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Use of lower temperature asphalt in pavement construction

Demonstration site construction, in service performance and specification

M Wayman, J C Nicholls, and I Carswell

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I Carswell	D Gershkoff
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Executive summary

The Highways Agency (HA), Mineral Products Association (MPA) and Refined Bitumen Association (RBA) have been sponsoring a Collaborative Research Programme at TRL for many years. In the 2013-14 programme, one of the tasks was to demonstrate the potential viability of lower temperature asphalt materials (LTAs) on the UK Strategic Road Network (SRN). This report covers the work undertaken on LTAs and covers the following objectives:

- To impartially observe a live demonstration of a lower temperature asphalt (LTA) material being laid alongside comparable hot mix asphalt (HMA) material.
- To visit sites where LTAs have been previously laid to assess in service performance.
- To gather and collate information on international experience with LTAs; the extent of their use and performance.

To address the first objective, a maintenance scheme to inlay the binder and surface courses on the A5 between Grendon and Mancetter in North Warwickshire in January 2014 was selected as a demonstration site. A stretch of the westbound carriageway of the A5, approximately 220 m in length, was inlaid 50:50 with a 110 m length of LTA and a 110 m length of conventional HMA. The LTA was produced using a patented 'injection foaming' LTA technology with a target mixing temperature of 90 °C to 100 °C. The corresponding HMA had a target mixing temperature of 165 °C to 175 °C. The production and laying of both binder and surface course layers and asphalt types were monitored and the laboratory properties of the four asphalt mixtures were tested.

The overall experience at the demonstration site was broadly comparable to an historic site which used the same type of LTA material. Considering the combined experience gathered from the two sites, the production and application was considered practically and technically achievable.

The main findings from the demonstration site were:

- The LTA could be laid successfully provided appropriate care was taken. There were similar comments from operatives about both LTA and HMA mixtures.
- LTA mixtures appear to require a higher level of control to ensure that adequate compaction is achieved.
- An increased proportion of reclaimed asphalt was successfully employed in the mixtures at lower target mixing temperatures.
- Temperature monitoring of the mat showed that neither the HMA nor LTA had cooled to ambient temperature at the time that the renewed section was reopened to traffic. The surface temperature of the HMA was around 60 °C and the LTA 30 °C at the time of reopening, whereas ambient was around 6 °C.
- Thermography was demonstrated to be a potentially useful tool. It can highlight potential inconsistencies (variability) in temperature across the mat and 'cold spots' that may later give rise to defects in the material.
- The carbon footprint calculation using asPECT v4.0 indicates an appreciable cradle-to-gate CO_2e saving in the region of 13-16 % associated with the use of LTA materials over their conventional HMA alternatives, which can purely be attributed to energy savings at the mixing plant.

- The works in total at Grendon on the night of the trial saved 0.7 tCO_2e by replacing approximately half of the conventional HMA with LTA alternatives.

Testing of laboratory prepared samples of both LTA and HMA materials gave comparable properties for compactibility, deformation resistance, stiffness, fatigue and fracture resistance. Water sensitivity testing indicated slightly higher susceptibility of LTA. However, samples taken from sites where the material had been laid previously have shown a large variation in voids. Similarly, the in situ density measurements on the binder course layer on the demonstration site showed greater variability in the LTA than the conventional HMA. This would seem to indicate that stricter quality control procedures may be needed on site for LTA materials.

Overall, assessment of this demonstration site and other trial sites supports the use of LTA mixtures in routine construction and maintenance of road pavements provided appropriate quality control measures are in place. As a result of the wide variety of available technologies to produce LTA mixtures, and the additional care that may be required during installation, sites should be more routinely monitored to confirm that materials are, and remain, suitable for routine use. It is also important to establish the criteria for their acceptance because these may differ from those for HMA and could also differ between different LTA technologies.

With regards to implementation by the Highways Agency in the UK, a roadmap is proposed, in line with current European thinking, which should encourage the wider, successful, use of LTA mixtures.

Abstract

Lower temperature asphalts (LTAs) have been identified as a way of reducing the energy required to produce and lay asphalt materials, the carbon footprint of pavement construction and maintenance, and exposure to fumes for workers. A demonstration site with sections of lower temperature asphalt surface and binder course mixtures has been laid and monitored for initial properties. The monitoring included physical properties of the materials, the temperatures of the mixture at various stages of the construction and the carbon footprint of the construction. The aim of the demonstration was to help establish criteria for specifying lower temperature asphalt mixtures within the framework of harmonised European standards for the production of asphalt and, if necessary, national requirements for the application of lower temperature asphalts. In addition, the initial and ongoing performance of the lower-temperature asphalts on this site, and on some other sites, has been investigated. The investigation has included obtaining advice on the durability obtained with lower temperature asphalts in the USA and Scandinavia, although with limited success because the materials have not yet been monitored for long enough.

1 Introduction

1.1 Objectives

One task within the 2013-14 Collaborative Research Programme, undertaken by TRL and sponsored by the Highways Agency, Mineral Products Association and Refined Bitumen Association, was to demonstrate the potential viability of lower temperature asphalt materials (LTAs) on the UK's strategic road network (SRN)[1]. The task had three sub-tasks:

1. To impartially observe a live demonstration of lower temperature asphalt material, preferably with a conventional hot mix asphalt (HMA) reference material to provide a direct comparison. Such a demonstration would provide an opportunity to observe construction from start to finish and to record material property data, take samples and record observations throughout the construction.
2. To visit sites where LTAs have been used historically, to assess their current performance.
3. To gather and collate information on international experience with LTAs; the extent of their use and performance.

This report presents the findings for each of these sub-tasks. The primary objective of the task was to review the performance of asphalt mixtures modified to reduce greenhouse gas emissions. This review was to provide a thorough understanding of the potential economic and environmental benefits that could be achieved prior to developing a specification and methods for design and application of these materials on the SRN. The output from the task was intended to be a road map to identify a future work plan for enabling low temperature emission (LTE) asphalt / low temperature asphalt (LTA) to be used on the SRN and any barriers that will need to be overcome.

1.2 Method of research

The following activities have been undertaken:

- A demonstration length containing both LTA and hot mix asphalt (HMA) sections has been laid and closely monitored for early-life performance.
- A review of existing data on the comparative life of LTA and HMA both nationally and in selected areas of the world (USA and Scandinavia) has been completed.
- A review of standards and specifications to identify the most efficient method for extending them to adequately cover LTA.

1.3 Technologies and processes involved

There are many different technologies and processes that are being promoted in order to produce LTA, with at least 35 having been identified (Mollenhauer, 2013). The demonstration site would have had to be very extensive to include all these different systems, particularly because many of them require specific modifications to the plant and/or specific additives for the bitumen or asphalt. The system offered for the

[1] The UK's strategic road network: http://www.highways.gov.uk/our-road-network/our-network/

demonstration used a proprietary foamed bitumen system to achieve a half-warm mix asphalt.

2 Scope of works at demonstration site

2.1 Site

The demonstration site was located within a longer maintenance scheme. The Grendon to Mancetter pavement scheme was located on a 1.1km stretch of the A5 that primarily involved surface course inlay. The demonstration site was a stretch on the westbound carriageway approximately 220 m in length (chainage 2960-3180 m) which was inlaid with proprietary LTA mixtures for the binder and surface course layers and an adjacent section which was constructed using conventional HMA mixtures. The laying and compaction were closely monitored, and materials were sampled and subjected to extensive laboratory testing. The site location is shown in Figure 2-1.

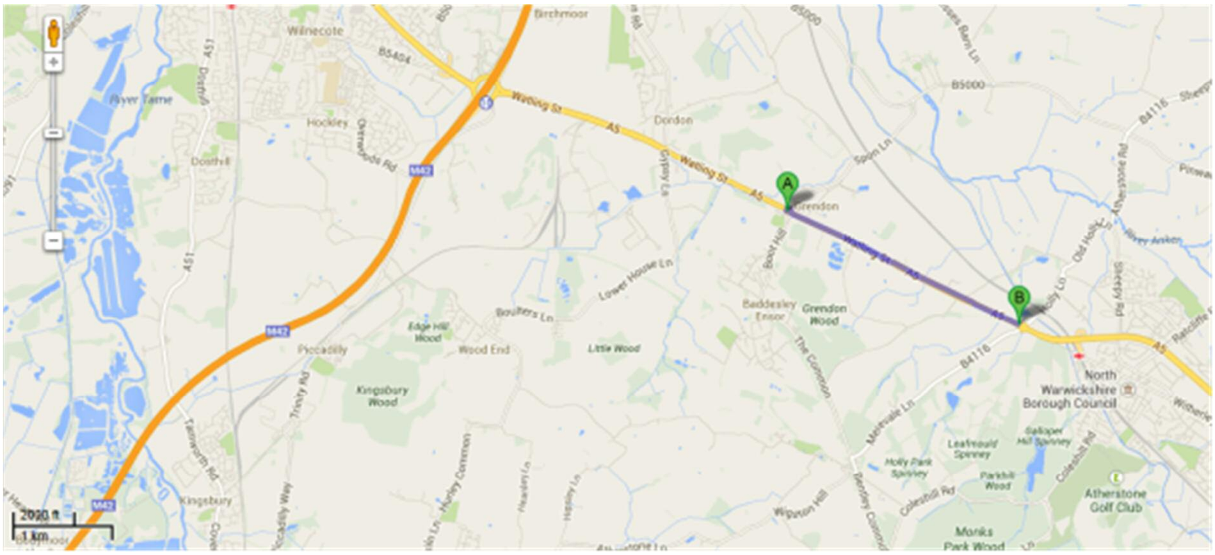

Figure 2-1: Approximate location of the A5 Grendon to Mancetter maintenance scheme

The maintenance took place on the night of the 17 January 2014. A section of the westbound carriageway, approximately 220 m in length, was inlaid with 110 m of LTA and 110 m of conventional HMA. The LTA employed a patented foam injection technology that was mixed at a target temperature of (95 ± 5) °C. The corresponding HMA was mixed at a target temperature of (170 ± 5) °C. All materials were supplied from a plant at Haughmond Hill in Shropshire. The material suppliers conducted extensive testing on material sampled at both the weighbridge and on site. The results of this testing, which followed a protocol agreed prior to the site trial, have been made available (Artamendi, 2014) and have been used in this report. Annual energy consumption data (Sabin, 2014) was made available to allow TRL to calculate the carbon footprint of the materials.

2.2 Asphalt mixtures

The mixtures used for the site were asphalt concretes complying with BS EN 13108-1 (CEN, 2006a) in categories AC 20 HDM bin 40/60 design for the binder course and AC 14 surf PMB PSV 65 for the surface course (PMB = polymer modified bitumen; PSV = polished stone value). The HMA mixtures were manufactured conventionally and the LTA mixtures using a patented 'injection foaming' LTA technique[2]. The target binder content of both binder course mixtures was 4.3 % and the target binder content of both surface course mixtures was 5.1 %.

The CE marks for the mixtures are given in Appendix A with the numbering of the mixtures for this report being:

- Mixture 1 LTA Binder course AC 20 HDM bin 40/60 design
- Mixture 2 LTA Surface course AC 14 surf PMB PSV 65
- Mixture 3 HMA Binder course AC 20 HDM bin 40/60 design
- Mixture 4 HMA Surface course AC 14 surf PMB PSV 65

The LTA mixtures were produced in 2.5 tonne batches for AC 20 bin and 2.0 tonne batches for AC 14 surf whereas the HMA mixtures were mixed in 3.0 tonne batches for AC 20 bin and 2.5 tonne batches for AC 14 surf. The mean production temperatures and maximum and minimum batch temperatures are presented in Table 2-1. Differences in production temperatures between the low temperature and hot materials were approximately 80 °C for the binder course mixtures and 60 °C for the surface course mixtures.

Table 2-1: Production temperatures

Mixture No.	Type	Course	Mixing temperature (°C)	
			Mean	Range
1	LTA	Binder	92	7 (88 – 95)
2	LTA	Surface	107	27 (92 – 119)
3	HMA	Binder	171	33 (149 – 182)
4	HMA	Surface	169	41 (141 – 182)

Various proportions of reclaimed asphalt (RA) were also incorporated into the mixtures as shown in Table 2-2. The proportion of RA incorporated into the LTA binder course mixture was 25 %. The target proportion of RA for the HMA binder was also 25 %, but the actual proportion incorporated was significantly less (6 %). This was thought to be due to a combination of the higher fines content of the binder course HMA material (relative to the HMA surface course material) and high moisture content of the feedstock RA, which would have required superheating of the aggregate (to dry the RA) to temperatures beyond acceptable production plant tolerances; as a result the proportion of RA in the binder course HMA was reduced. The amount of RA in both LTA and HMA surface course mixtures was approximately 16 %.

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[2] The patented LTA technique, whilst unique in its own right, could be described as falling within a distinct family of asphalt 'foaming' techniques. The techniques in this category are characterised by the method of injecting a small controlled amount of water into hot bitumen via foaming nozzles, immediately prior to coating the aggregate. This results in a large but temporary increase in the effective volume of binder which facilitates coating at lower temperatures. Some vapour remains in the bitumen during compaction, reducing effective viscosity and facilitating compaction. This family of foaming techniques is distinct from the other principal group of foaming techniques, which derives the water for foaming from a mineral source; either from a zeolite additive or residual moisture in the RA or sand components of the mixture (EAPA, 2014).

Table 2-2: Reclaimed asphalt contents

Mixture No.	Type	Course	Reclaimed asphalt (%)	
			Mean	Range
1	LTA	Binder	25.9	2.8 (24.4 – 27.2)
2	LTA	Surface	15.6	2.2 (14.9 – 17.1)
3	HMA	Binder	5.9	13.0 (0.0 – 13.0)
4	HMA	Surface	15.6	1.2 (15.2 – 16.4)

2.3 Site layout

Figure 2-2 shows a plan view of the area on the westbound carriageway (blue hatched area) that was inlaid.

Figure 2-2: Extract from site drawing indicating inlaid section WB

Figure 2-3 shows a longitudinal cross-section of the inlaid area, with distances measured on the night of the works. Distances are measured from the easternmost extremity of the section, at approximate road chainage 3180 m. The total length inlaid was approximately 220 m over pre-existing base (nominally 30 mm) and an hydraulically bound material (HBM) sub base. The HBM layer could be seen in places where the condition of the base was such that it was loose and/or de-bonded after planing-off (see Section 3). A 55 mm thick binder course was placed with the boundary between the LTA and HMA materials at site chainage 105 m. Above this course, a 45 mm thick surface course was laid with the boundary between the HMA and LTA mixtures at site chainage 92 m. GPS co-ordinates for the start of the site are provided in Appendix B.

To aid the future locating of the site, batches of radio frequency identification devices (RFID) tags were inserted at six locations to mark the key boundaries of the site (as indicated by the green labels in Figure 2-3).

2.4 Schedule of events and observed weather conditions

The works described took place on the night of the 17th (and morning of the 18th) January 2014. The ambient temperature was 4 °C when laying commenced at 00:20, it cooled slightly to reach a low of 3 °C at 01:30 and then steadily rose again to reach 5 °C at 02:40 and 6 °C at 04:15 when the road was reopened to traffic. The key events of the night took place during the timeframes indicated in Table 2-3. The weather was largely dry throughout the laying operation although light rain fell from 03:10 until well beyond the point when the site was reopened to traffic at 04:15.

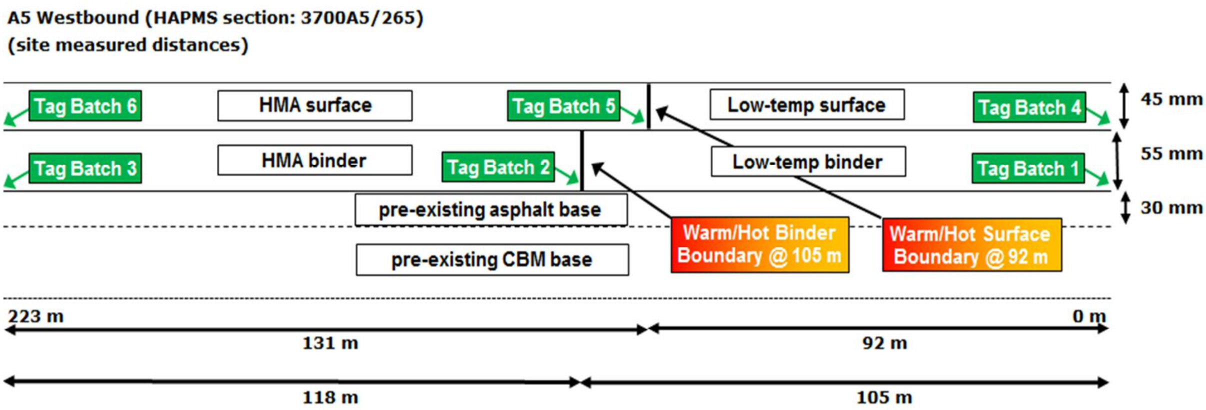

Figure 2-3: Cross sectional representation of completed works (with site measured distances and RFID tag locations indicated)

Table 2-3: Key events and timeframes

Time	Event
Friday 17th January 2014	
~14:00 – 16:00	Site visually surveyed
~21:00	Plant mixing commenced
21:50 – 22:09	LTA binder course material dispatched
~22:20 – 23:30	Planing-off
23:08 – 23:10	HMA binder course material dispatched
23:30	LTA arrives at site (subsequent loads arrive approximately 80 min after dispatch time)
Saturday 18th January 2014	
00:16 – 00:58	LTA surface material dispatched
00:20	Commence laying LTA binder
00:45	Commence laying HMA binder course
01:32 – 02:01	HMA surface course material dispatched
02:15	Commence laying LTA surface
02:55	Commence laying HMA surface
04:15	Site reopened to traffic
12:30 – 13:00	Site observed in daylight approximately 8 hours after reopening

3 Visual survey

3.1 Prior to commencement of works

A visual survey covering the full length of the site was undertaken in daylight prior to commencement of the resurfacing works. The aim was to record any defects that were present and that could possibly re-occur in the new surface due to any underlying structural problems in the pavement. A representation of the visual survey is shown in Figure 3-1, which also shows:

- The extent of the LTA and HMA sections, in both binder and surface courses.
- The approximate locations of the thermocouples, used to measure temperature over time as the fresh materials were laid, up to the end of the closure period, at the base of both the binder and the surface course layers (results from these measurements are presented in Section 4.4).

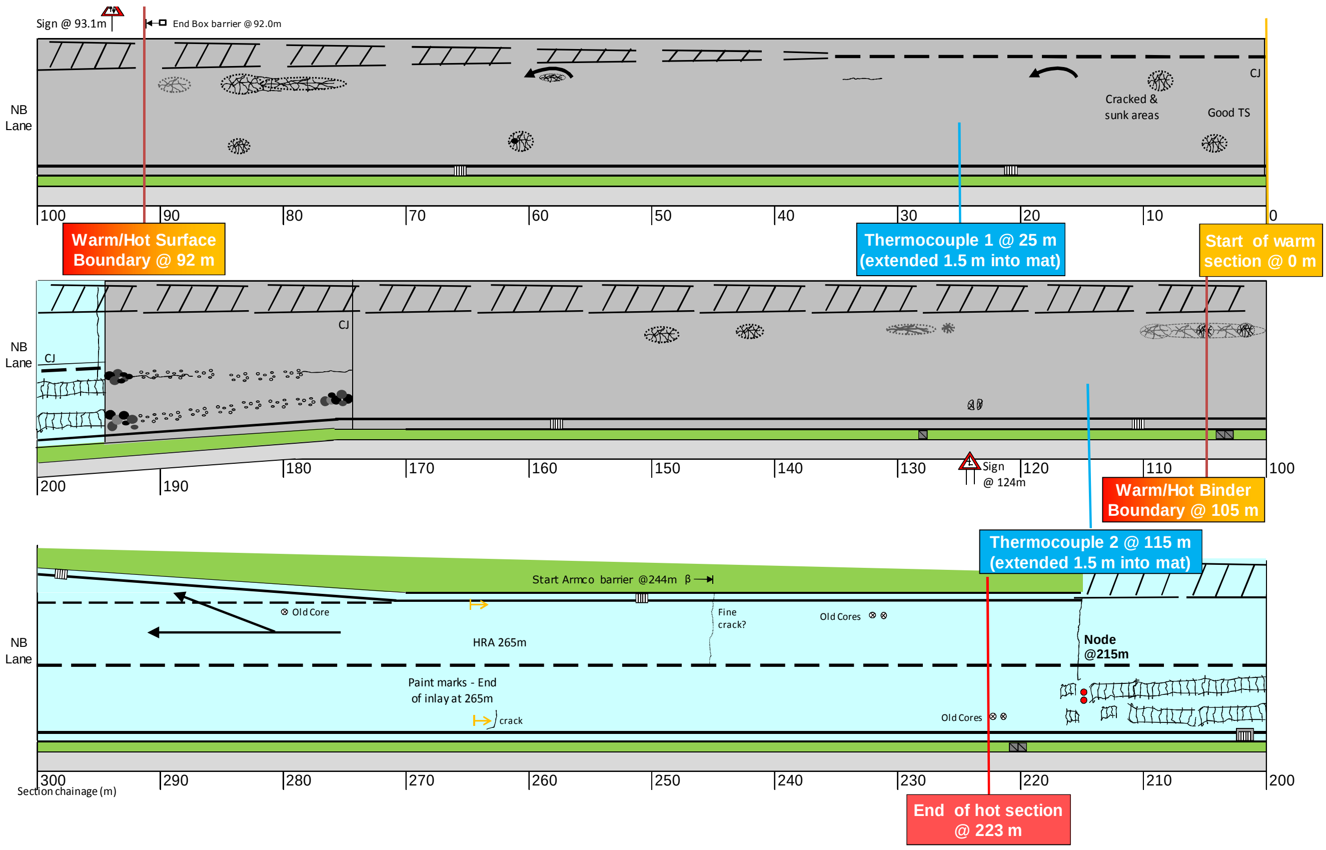

Figure 3-1: Visual survey representation (with other key site locations)

Photographs were taken during the pre-work visual survey and are shown in Section B.1 of Appendix B with the locations of the photographs shown in Figure 3-2. Photographs that indicate extensive cracking are reproduced in Figure 3-3 and Figure 3-4: Visual survey in advance of works showing both longitudinal and alligator cracking.

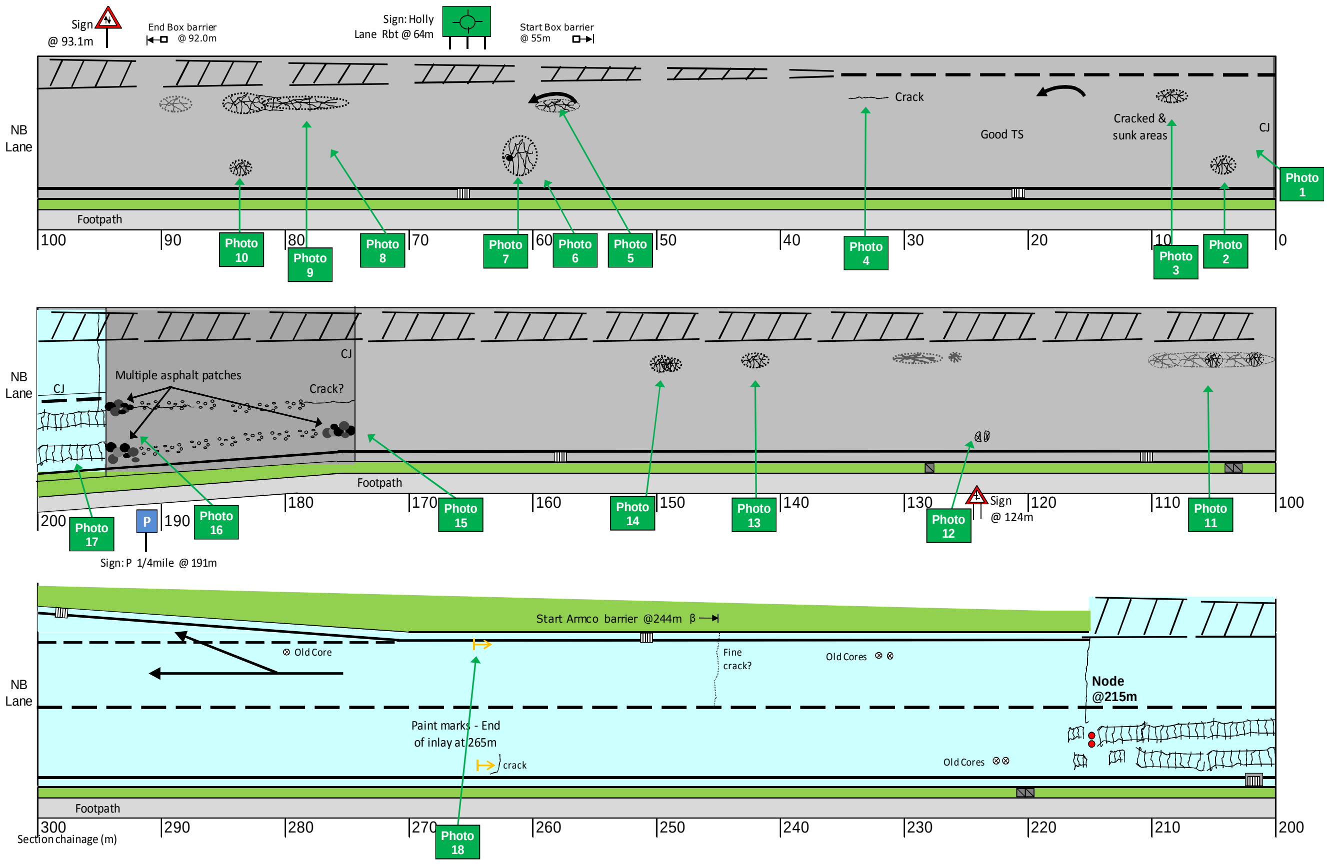

Figure 3-2: Visual survey photograph locations

(where "Photo x" is Figure B-x in Appendix B e.g. Photo 1 is presented as Figure B-1)

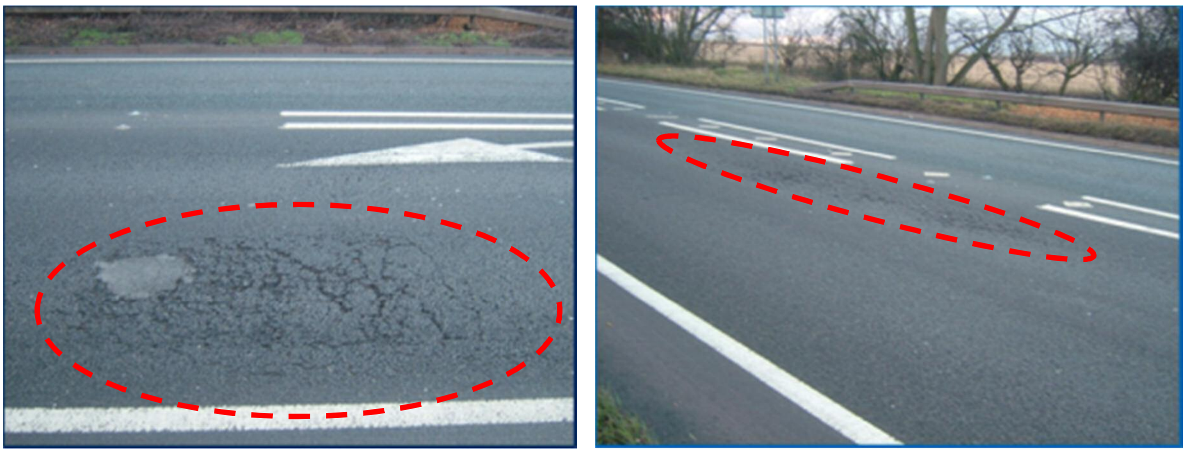

Figure 3-3: Visual survey in advance of works (1)

Figure 3-4: Visual survey in advance of works (2)

3.2 After planing

A limited number of photographs, taken after planing and prior to paving, are included in Section B.2 of Appendix B. The photographs reproduced in Figure 3-5 illustrate the key findings. Around 30 mm of pre-existing asphalt material above the HBM base remained after planing-off; in some places (e.g. at approximate chainage 3144-3156 m westbound) loose material remained after planing that could be removed with a shovel. Due to time constraints it was not possible to view the planed surface that was to be inlaid with HMA.

Figure 3-5: Photographs taken after planing in the section to be inlaid with LTA mixture

3.3 Eight hours after completion

Figure 3-6 to Figure 3-9 contain photographs taken at the site during the morning of 18 January 2014, approximately eight hours after the section was reopened to traffic. The boundary between the old and new material is clearly visible at both ends of the section. A contrast in 'evenness' after rolling is also apparent between the HMA and LTA sections. Possible reasons identified by the contractor and site observers include low ambient temperature, the time interval between mixing and compaction and the absence of a second heavy roller on site.

Figure 3-6: LTA completed section

Figure 3-7: Boundary of the LTA (left) with the existing surface (right)

Figure 3-8: Boundary between new LTA and HMA mixtures

Figure 3-9: HMA section and boundary to pre-existing surface (bottom-left)

3.4 Qualitative observations on the construction

A survey containing a few questions to ask the site operatives was prepared in advance of the visit to the demonstration site. Due to time constraints on site, it proved difficult to ask any individual operative more than one question at a time. The questions asked were:

1. Did you notice any differences between the respective surface and binder course materials laid throughout the night?
2. Were there any notable delays that might have impacted on workability?
3. How did the materials perform in relation to ease of machine and hand laying?
4. Any other comments?

The responses from the site gang are represented in the "word cloud" in Figure 3-10, with words that were mentioned more frequently being given greater prominence.

Figure 3-10: Word cloud representing the site gang's collective viewpoint

4 Material properties at plant and site

4.1 Material recipes

The measured mix proportions and average mixing temperatures are given in Table 4-1.

Table 4-1: Component materials proportions and mixing temperature

Component	LTA binder course	LTA surface course	HMA binder course	HMA surface course
Reclaimed asphalt planings (%)	25.52	15.62	5.89	15.60
20 mm aggregate (%)	24.34	0.00	25.21	0.00
14 mm aggregate (%)	11.69	30.31	11.29	30.81
10 mm aggregate (%)	9.27	17.13	14.64	16.69
6 mm aggregate (%)	0.00	8.48	6.72	9.08
<6 mm fine aggregate (%)	23.76	20.99	26.83	19.43
Reclaimed filler (%)	0.00	1.13	2.70	0.89
Imported filler (%)	1.93	1.48	2.72	2.75
Bitumen (%)	3.48	0.00	3.99	0.00
Polymer-modified bitumen (%)	0.00	4.86	0.00	4.76
TOTAL	100.00	100.00	100.00	100.00
Average mixing temperature (°C)	92	107	171	169

4.2 Material temperatures at weighbridge

The demonstration site required 13 truck-loads of asphalt. The quantities and mean despatch temperature for each truck are given in Table 4-2. The mean despatch temperatures for the LTA binder course are higher than anticipated considering the mix temperature range given in Table 4-3.

Using a weighted average, the mean temperature of the LTA binder course at the weighbridge was 96 °C and the HMA binder course was 172 °C, a difference of 76 °C. The mean temperature of the LTA surface course at the weighbridge was 99 °C and the HMA surface 166 °C, a difference of 67 °C.

4.3 Delivery and rolling temperatures

The mean material temperatures at delivery (laid) and during rolling are given in Table 4-2. It can be seen that the difference between laying (and rolling) temperatures for the hot and the lower temperature mixtures was between 85 °C and 90 °C.

Table 4-2: Material temperatures on dispatch from the plant

Truck No.	Dispatch time	Mixture type	Course	Quantity (t)	Mean temperature on dispatch (°C)
1	21:50	LTA	Binder	19.76	98
2	22:03	LTA	Binder	19.50	96
3	22:09	LTA	Binder	19.68	95
4	23:08	HMA	Binder	19.48	173
5	23:20	HMA	Binder	15.74	170
6	23:18	HMA	Binder	15.34	173
7	23:10	HMA	Binder	19.42	171
8	00:16	LTA	Surface	15.32	94
9	00:37	LTA	Surface	15.02	99
10	00:58	LTA	Surface	14.96	104
11	01:32	HMA	Surface	19.76	170
12	01:55	HMA	Surface	20.00	163
13	02:01	HMA	Surface	19.70	166

Table 4-3: Mean material temperatures (delivery and rolling)

Mixture No.	Temp- erature	Course	Mean temperature (°C)	
			Delivery	Rolling
1	LTA	Binder	80	70
2	LTA	Surface	85	65
3	HMA	Binder	170	155
4	HMA	Surface	170	155

4.4 Temperatures in the mat

4.4.1 Thermocouple measurements

Four thermocouples, each with 4 m wires stretching laterally into the mat, were placed:

- At the base of the binder course, in the HMA and LTA material sections (2 in total).
- At the top of the binder course, in the HMA and LTA material sections (2 in total).

The thermocouples were situated longitudinally at approximately 10 m into the section and at least 1 m from the edge of the carriageway (in the first wheel track once trafficking commenced). The locations of the thermocouples are indicated in Figure 3-1.

The measurements made are shown in Figure 4-1 for the LTA mixtures and Figure 4-2 for the HMA mixtures with the key events (start of laying each course, paving reaching the thermocouple and road opened) being identified. Spot infra-red temperatures (IRT - indicated in yellow boxes) of the surface of the material were also taken at key intervals throughout.

A small quantity of asphalt was taken from the paver and shovelled over the top to hold the thermocouple in place before paving commenced, hence a 'double-peak' is observed on the graph. Each thermocouple was attached to a data logger to record at one minute intervals throughout the remainder of the closure.

The figures show graphically the increased temperature and more rapid cooling that occurs with HMA compared to LTA mixtures. Note that the IRT spot temperature, shown yellow in Figure 4-1 and Figure 4-2, is on the surface whereas the thermocouples are under the binder and surface course layers. IRT surface temperatures are sometimes seen to exceed the mat temperatures. This is contradictory to what might be expected, since the thermal mass of the mat would be expected to cool at a lower rate than the surface. It is thought that the reverse is in fact observed due to the relative accuracy of the two temperature monitoring techniques (IRTs can be quite inaccurate and should therefore only be used to observe relative changes in temperature, rather than exact 'spot' temperatures).

It can be observed that the temperature of the asphalt had not reached ambient at the time of re-opening to traffic. However, this is not in contradiction to the requirements of BS 594987:2010 (BSI, 2010). At the time of opening, the temperature of the LTA - both under the base and binder courses, and at the surface - was lower than the corresponding temperatures for the HMA. As a result the LTA section may be less susceptible to early deformation.

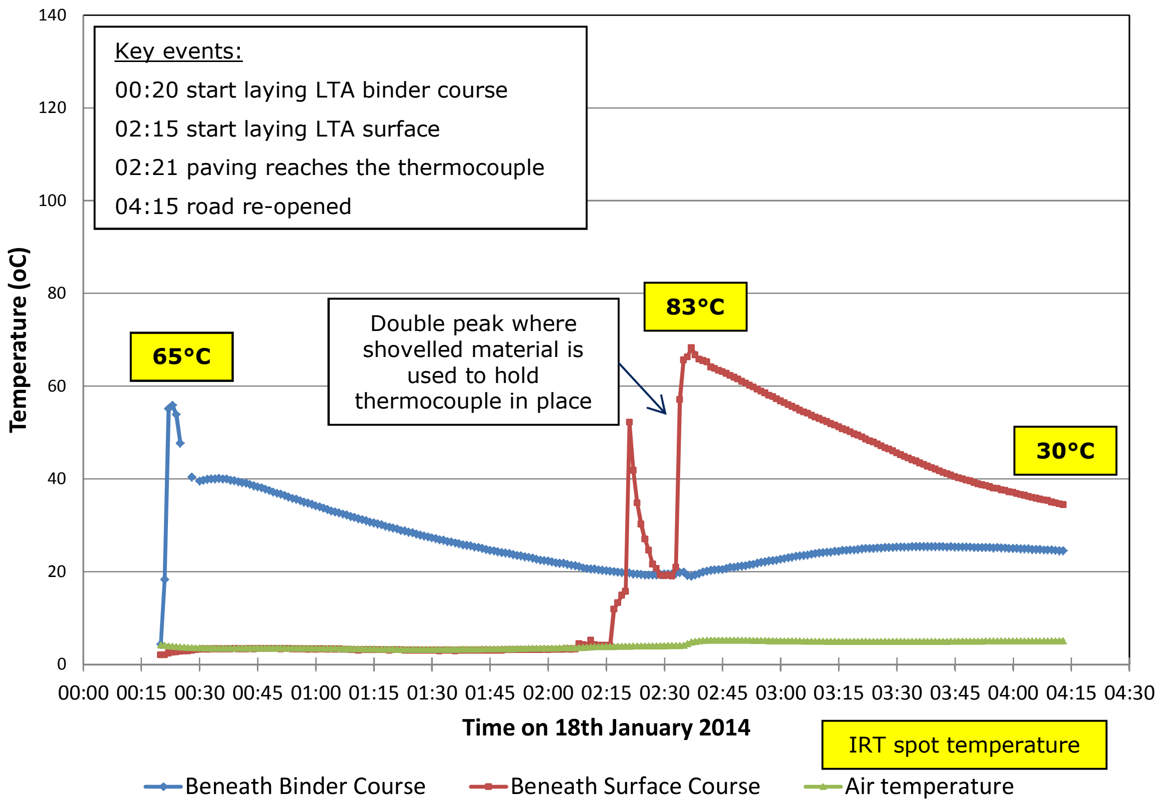

Figure 4-1: LTA mat temperature profiles (from thermocouples at approximate chainage 2985 m)

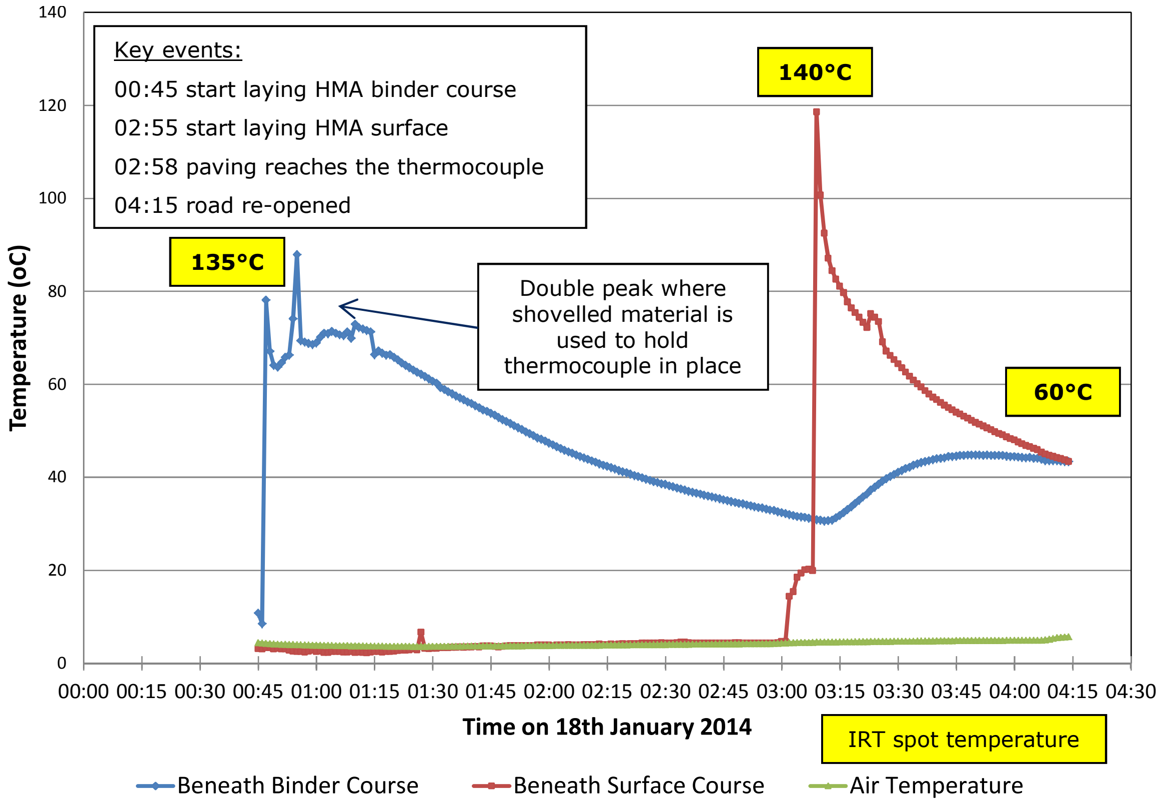

Figure 4-2: HMA mat temperature profiles (from thermocouples at approximate chainage 3075 m)

4.4.2 Thermography

In the UK, thermographic imaging is not commonly used for monitoring or assisting asphalt installation process. For the demonstration site construction, a thermal imaging camera was used to monitor the site and to assess how it might be used during installation on future schemes. A selection of the thermographic images taken throughout laying and compacting are presented in Appendix C. An example infrared image and its corresponding photograph are presented in Figure 4-3 to demonstrate the potential of this type of imaging and the resolution that it can provide during night work.

Figure 4-3: Example thermographic image and corresponding photograph

Bullas (2010) provides an introduction to approaches to using thermography in road construction in the United States and Sweden. Both countries work on the basic premise that variations in temperature (characterised by 'cold spots') cause variations in density across the mat. These low-density areas are deemed to have a tendency to fail prematurely through fatigue cracking or fretting. Cold spots are thought to arise when material has been residing in either trucks or pavers for excessive time periods, ultimately reflecting the efficiency of the contractors plant and site logistics from start to finish. Material that comes into contact with the sides of the truck or the paver (with high thermal conductivity) cools more quickly than the centre of the hot mass of asphalt. The longer the material is present in the equipment, the greater the tendency there is for it to cool. Ultimately, these cooler inclusions will pass through the paver and end up as lower-density cold spots on the road.

In the United States, Washington State used infrared cameras to assess the degree of thermal segregation across an asphalt mat whilst it was being laid. When a temperature differential of 25°F (~14 °C) between a particular location and its surrounding area is observed, a nuclear density measurement is required to be taken at that location. If consistently low densities are observed then a penalty of 15 % of the asphalt unit price can be levied on the contractor. In Sweden, bonuses are awarded and penalties are levied based on the consistency of temperature that is observed across the mat using a rear-facing thermographic imaging camera mounted on the paver. The thermographic camera is used to deliver a thermal image of the entire mat directly after paving. The image is then assessed for consistency of temperature, and the areas of excessively lower temperature, when compared to the average, classified as *"at risk"*. Financial incentives are awarded incrementally for low *at risk* proportions of the total area (<5 %) and penalties levied for high *at risk* proportions (>5 %).

It is important to note that neither measure essentially precludes the use of LTA because both measures function on the basis of measuring *consistency* of temperature rather than the *absolute* value. Furthermore, Newton's law of cooling states that an object with a higher temperature differential with the surrounding environment will cool more quickly than one with a lower temperature, accordingly HMA, with a higher starting temperature relative to ambient, will cool more quickly than LTA. Aside from this, workability of some LTAs derives from foam or other additives, so any lower temperature boundary would need to take these additional properties into account.

The images in Appendix C show some interesting features and trends over time. These can be summarised as follows:

- Differential cooling near the edges of equipment, which can give rise to cold spots, can be observed in Figures C2 and C5.
- Separate rips of the paver can be observed in Figures C9 and C19.
- Boundaries can be observed between different loads of asphalt placed next to each other in Figures C16 and C17.
- Variability in the temperature of paved asphalt across the mat can clearly be observed in Figures C3, C11, C19, C24, C31 and C34. To establish the range in temperature of variability with confidence will require the imaging technique to be refined in future use, however, the colours present in the images appear to indicate quite considerable ranges in temperature.

4.5 In situ tests

In situ testing was carried out by CET and included an estimation of the in-situ air voids content of the binder course mixtures using a nuclear density gauge. Measurements were also made on the surface course for pavement longitudinal surface regularity. Texture depth was not measured due to the weather conditions. The mean, maximum and minimum values of in-situ air voids contents are presented in Table 4-4.

Table 4-4: In-situ test results

Mixture No.	Mixture Type	Course	Air voids content (%)		Longitudinal surface regularity
			Mean	Range	
1	LTA	Binder	9.5	3.4 (7.4 – 10.8)	–
2	LTA	Surface	–	–	Complied
3	HMA	Binder	7.6	2.1 (6.6 -8.7)	–
4	HMA	Surface	–	–	Complied

It can be seen that in-situ air voids of both the LTA and HMA binder course mixtures were relatively high at >7 %. This level could be attributed to poor compaction and, to some extent, to poor workmanship on the day. Furthermore, higher in-situ air voids contents were found in the LTA mixture than the HMA mixture. The surface regularity complied with the specification requirements as detailed in Series 700 Table 7/2 of the *Specification for Highway Works*, SHW (HA *et al*., 2008).

5 Laboratory tests of material properties

5.1 Compositional analysis

Compositional analysis was carried out for a single sample of each mixture using the binder content by ignition method in accordance with BS EN 12697-39 (CEN, 2012a) with the results given in Section D.1 of Appendix D. All the mixtures complied with the producer's Declaration of Performance (DoP) in terms of grading and binder content.

5.2 Recovered binder properties

Samples of binder from the two binder course mixtures were recovered by rotary evaporator to BS EN 12697-3 (CEN, 2005a) and analysed for the binder properties of penetration to BS EN 1426 (CEN, 2007a) and softening point to BS EN 1427 (CEN, 2007b). The results are given in Table 5-1.

Table 5-1: Recovered binder properties

Mixture	Mixture Type	Course	Penetration (0.1 mm)	Softening Point (°C)
Mixture 1	LTA	Binder	28	60.2
Mixture 3	HMA	Binder	22	64.2

Although the results are too limited for a definitive conclusion, the values appear to support the hypothesis that the lower heating in the LTA results in less initial binder hardening with higher measured recovered penetrations and lower recovered softening points. However, the differing proportions of RA in the two mixtures, the recovery method and the repeatability of the penetration and softening point tests should all be considered before drawing any definitive conclusions.

5.3 Density and air voids content

The maximum densities of the mixtures were first determined in accordance with BS EN 12697-5 (CEN, 2009) using Method A, volumetric. Six cylindrical specimens of 100 mm diameter and 50 mm height were cored from 300 mm x 300 mm x 50 mm laboratory-manufactured slabs (bulk samples were taken on site and used to manufacture the slabs in the laboratory, using a reheating temperature of 130 °C for both HMA and LTA) and then used for the determination of the bulk density in accordance with BS EN 12697-6 (CEN, 2012b) three times using Procedure A, dry, Procedure C, sealed, and Procedure D, dimensions. The air voids contents were determined according to BS EN 12697-8 (CEN, 2003a) and the mean values are shown in Figure 5-1. The results for individual specimens are presented in Section D.2 of Appendix D.

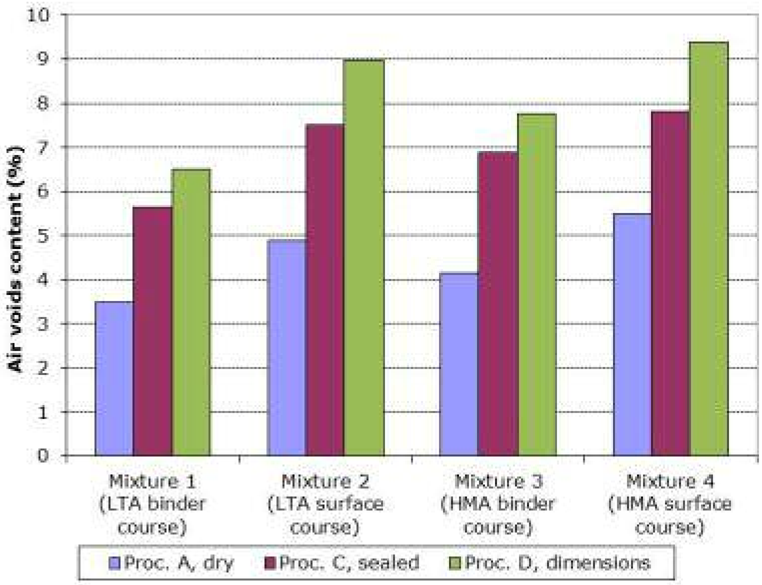

Figure 5-1: Air voids content of laboratory compacted specimens

Figure 5-1 shows that the air voids content depends on the procedure used for the determination of the bulk density. Similar air voids contents were obtained for the LTA and HMA mixtures, although for LTA materials the reheating procedure in the laboratory is the same as for the HMA as there is no longer the workability present from the original process. The LTA binder course material had significantly more RA compared to the HMA binder course which could lead to greater variability in the density of the material as the specific gravity of the aggregate(s) within the RA added may be different and more varied than the virgin material. Higher air voids contents were found for the surface course mixtures compared to the binder course materials. This would be expected as thin surface course materials tend to be more open to provide the required level of texture.

5.4 Water sensitivity

Resistance to moisture damage was evaluated by means of the water sensitivity test in accordance with BS EN 12697-12 (CEN, 2008) using Method A for the indirect tensile stiffness ratio, *ITSR*. Six cylindrical specimens cored from 300 mm x 300 mm x 50 mm slabs were split into two subsets with the dry subset being maintained at 20 °C and the wet subset being conditioned by applying a vacuum residual pressure of 6.7 kPa for 30 min followed by water conditioning at 40 °C for 70 h. Each specimen was tested for indirect tensile strength (Figure 5-2) at 20 °C. The temperature specified in BS EN 13108-20 (CEN, 2006b) for CE Marking is 15 °C, though the 5 °C difference is thought not to be significant within the repeatability of the test. *ITSR* was then determined using Equation 5.1 with the results shown in Figure 5-3 and individual *ITS* values for dry and wet specimens given in Section D.3 of Appendix D.

$$ITSR = \left(\frac{ITS_w}{ITS_d}\right) \times 100 \qquad (5.1)$$

where: *ITSR* is the indirect tensile strength ratio, in percent (%)
ITS_w is the mean indirect tensile strength of the wet group, in kilopascals (kPa)
ITS_d is the mean indirect tensile strength of the dry group, in kilopascals (kPa)

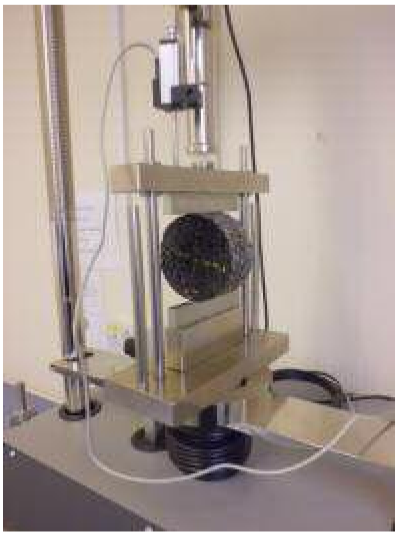

Figure 5-2: Indirect tensile strength test set-up

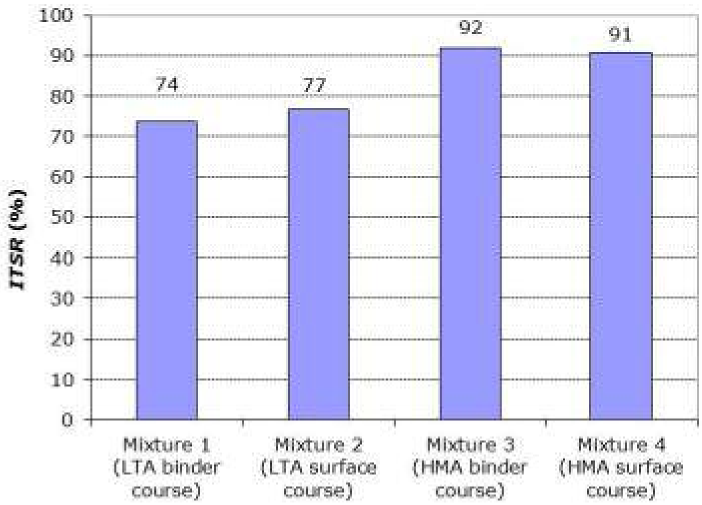

Figure 5-3: Water sensitivity test results at 20 °C

Figure 5-3 shows that the *ITSR* values for all the mixtures were above the specified level of 70 %, indicating adequate resistance to water damage. Furthermore, the *ITSR* value for the LTA binder course mixture was lower than that of the equivalent HMA mixture, possibly as a result of the increased amount of RA in the mixture. A possible explanation is the higher air voids contents of the LTA mixtures measured from site samples (Table 4-4), allow more water to enter the asphalt during the conditioning.

5.5 Permanent deformation

5.5.1 Cyclic compression

The resistance to permanent deformation was evaluated using the triaxial cyclic compression test (Figure 5-8) in accordance with BS EN 12697-25 (CEN, 2005b) to Method B with cylindrical specimens 100 mm in diameter and 60 mm in height cored from 300 mm x 300 mm x 100 mm slabs. The test conditions defined in BS EN 13108-20 (CEN, 2006b) are test temperatures of 40 °C and 50 °C, confining pressures of 50 kPa and 150 kPa and axial load pulses (peak-to-peak) of 200 kPa and 300 kPa for AC binder course and AC surface course mixtures, respectively. The load pulse used was a block pulse of 1 s loading and 1 s unloading while the frequency used was 0.5 Hz. The maximum number of load cycles applied to the specimen was 10,000 and four specimens from each of the two binder course mixtures were tested. The results are given in Section D.4 of Appendix D and are shown in Figure 5-4 for Mixture 1 (LTA binder course) and in Figure 5-5 for Mixture 3 (HMA binder course). Creep rates are calculated by fitting a straight line through the linear part of the creep curve.

The results show low creep rates for the two mixtures, indicating good resistance to permanent deformation. Furthermore, the LTA mixture had, on average, lower creep rates than the HMA mixture, indicating potential superior resistance to permanent deformation. However, higher variability was observed from the LTA mixture. Based on these results, Mixture 1 (LTA binder course) complies with the category $f_{c\ max\ 0,4}$ whereas Mixture 3 (HMA binder course) complies with the category $f_{c\ max\ 0,6}$, where the categories are defined in BS EN 13108-1 (CEN, 2006a).

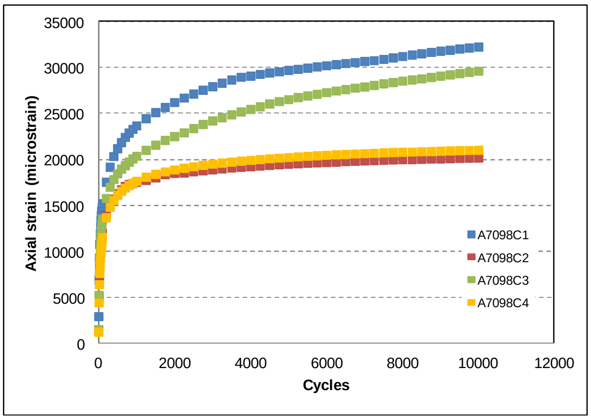

Figure 5-4: Creep curves for Mixture 1 (LTA binder course)

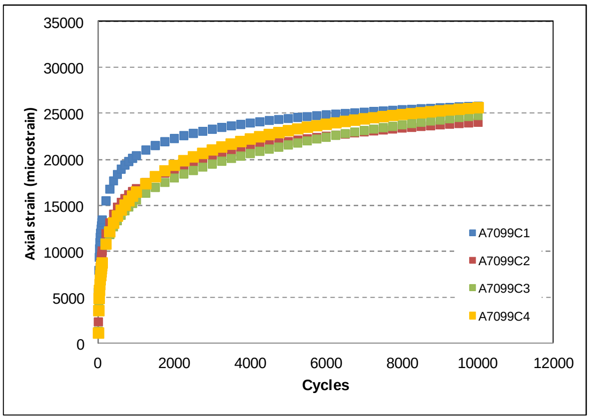

Figure 5-5: Creep curves for Mixture 3 (HMA binder course)

5.5.2 Wheel tracking

The resistance to permanent deformation was also evaluated using wheel-tracking in accordance with BS EN 12697-22 (CEN, 2007c) using both the large-size device and the small-size device to Procedure A.

- For testing with the large-size, the samples were compacted in accordance with BS EN 12697-33 (CEN, 2007d) using a single tyre pneumatic roller to the heavy compaction option. Only one replicate per mixture was used although the test normally requires two.
- For testing with the small-size to Procedure A, the samples were compacted in accordance with BS EN 12697-33 (CEN, 2007d) using a smooth steel roller. Procedure A is normally only used for hot rolled asphalt mixtures and only two replicates per mixture were tested although the test normally requires six.

The results are given in Section D.5 of Appendix D and shown in Figure 5-6 and Figure 5-7 for the large and small size test devices, respectively.

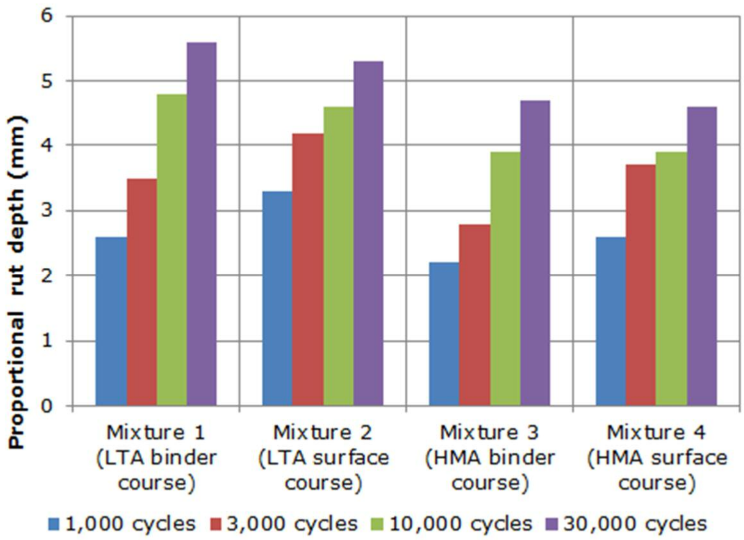

Figure 5-6: Wheel-tracking results for large size device

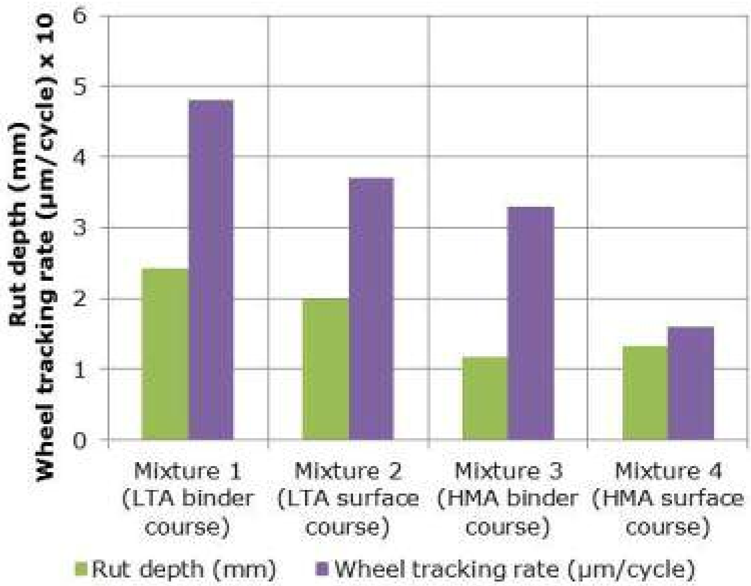

Figure 5-7: Wheel-tracking results for small size device to Procedure A

5.6 Stiffness

5.6.1 Indirect tension stiffness test

Stiffness modulus was determined in accordance with BS EN 12697-26 (CEN, 2012c) using Annex C for applying indirect tension to cylindrical specimens (IT-CY). The tests were undertaken on cylindrical specimens of 100 mm diameter and 50 mm height that had been cored from 300 mm x 300 mm x 50 mm slabs per mixture at 20 °C with a loading time of 124 ms, as specified in BS EN 13108-20 (CEN, 2006b). The mean stiffness values are shown in Figure 5-9 and the results from individual tests are given in Section D.6 of Appendix D.

Figure 5-8: Triaxial cyclic compression test set-up

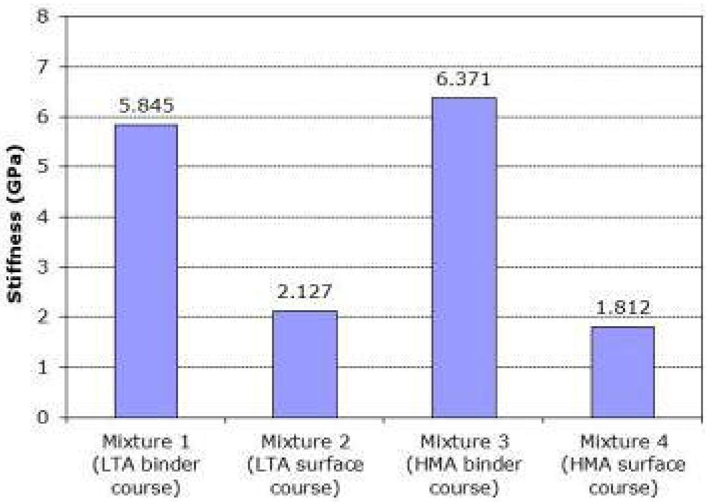

Figure 5-9: Stiffness modulus (IT-CY)

The results show similar stiffness values for the LTA and HMA binder course. It could be argued that there is less binder ageing for the LTA mixtures, as a result of the mixing process, and therefore the stiffness values could be expected to be lower as a result. However, small variations that are observed are fairly typical for any material subjected to stiffness testing. The results also show comparable stiffness values for the LTA and HMA surface course.

5.6.2 Four point bending stiffness test

Stiffness modulus was also determined in accordance with BS EN 12697-26 (CEN, 2012c) using Annex B for four point bending on prismatic specimens (4PB-PR), as shown in Figure 5-10. Five prismatic specimens of 400 mm x 50 mm x 50 mm were cut from 400 mm x 300 mm x 50 mm slabs for each mixture and tested under controlled strain mode at a target strain of 100 microstrain. One hundred loading cycles were applied at each combination of temperatures 20 °C, 15 °C and 10 °C and frequencies 0.5 Hz, 1.0 Hz, 2.5 Hz, 5.0 Hz, 8.0 Hz and 10.0 Hz to determine the stiffness at 100 cycles. BS EN 13108-20 (CEN, 2006b) gives test conditions of 20 °C and 8 Hz while 20 °C and 5 Hz are used in the UK for design purposes. Figure 5-11, Figure 5-12, and Figure 5-13 show the mean stiffness values at different temperatures and frequencies while the results from individual tests are presented in Section D.7 of Appendix D.

Figure 5-10: Four-point bending test set-up

The stiffness increased as the temperature decreased and as the frequency of loading increased. The differences between the stiffness values of the LTA and HMA were small, with the values of the LTA binder course mixture being slightly lower than that of the equivalent HMA mixture whilst the reverse was the case for the surface course mixtures.

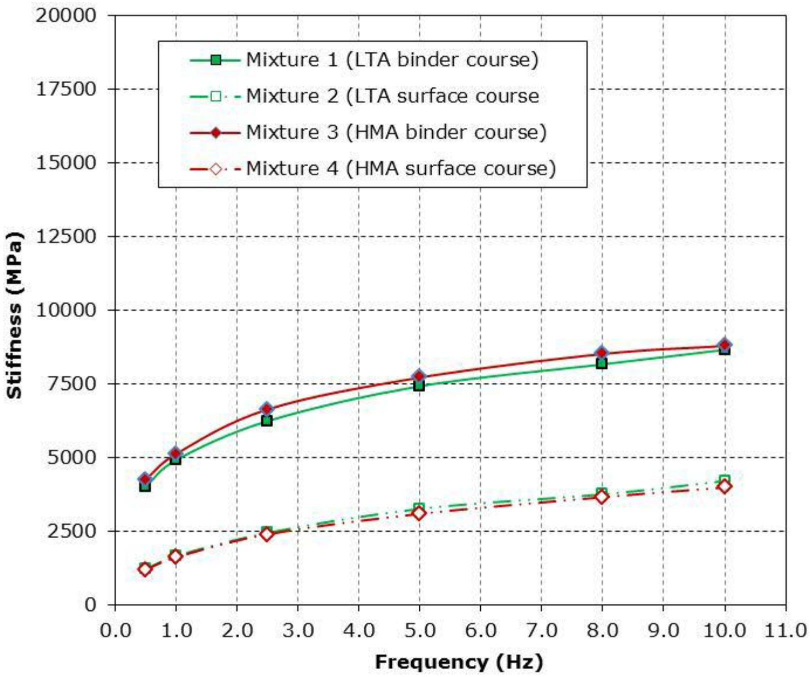

Figure 5-11: 4PB stiffness test results at 20 °C

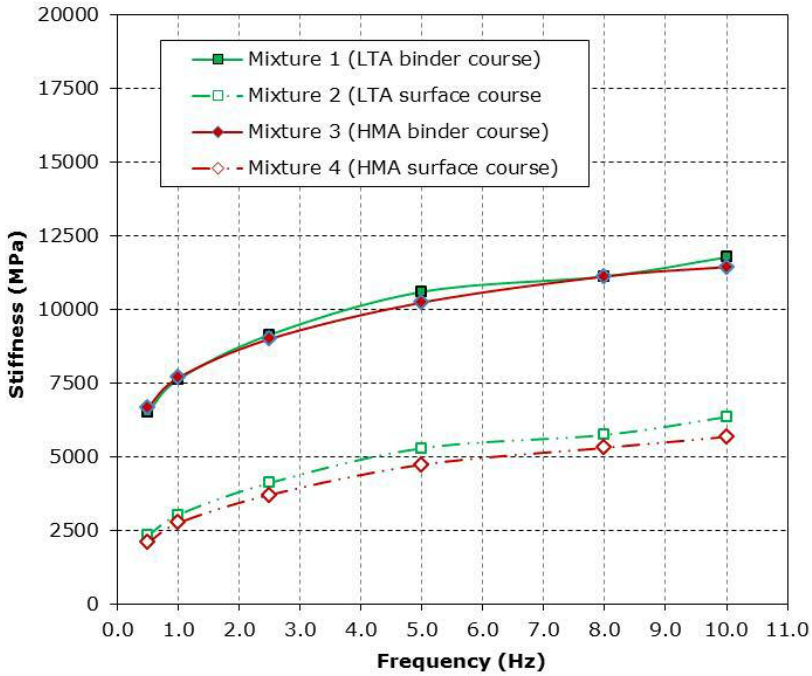

Figure 5-12: 4PB stiffness test results at 15 ^{0}C

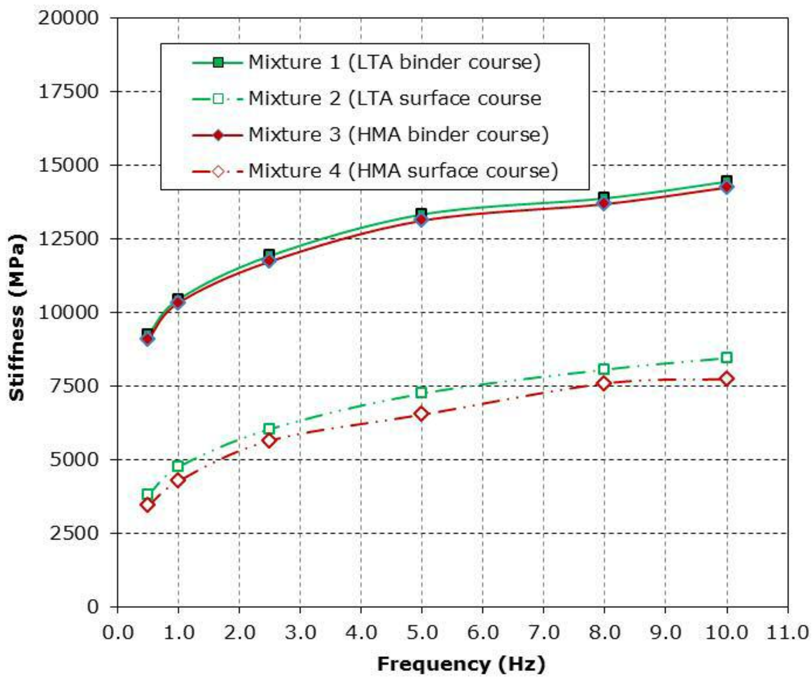

Figure 5-13: 4PB stiffness test results at 10 ^{0}C

5.7 Fatigue resistance

The fatigue resistance was determined in accordance with BS EN 12697-24 (CEN, 2012d) using Annex D for the four-point bending test on prismatic shaped specimens under constant strain (deformation) conditions. The tests were carried out at 20 °C and 30 Hz as given in BS EN 13108-20 (CEN, 2006b) for different strain levels, typically from 75 to 250 microstrain. The relationships between the strain (ε) and the number of cycles to failure (N_{50}), defined as the number of cycles to 50 % stiffness reduction, are plotted in Figure 5-14. It should be noted that a limited number of specimens were available for testing.

The coefficients for the power trend line, as shown in Equation 5.2, and the fatigue resistance in terms of microstrain at 10^6 cycles, ε_6, are given in Table 5-2 while the detailed results are given in Section D.8 of Appendix D.

Table 5-2 $$N_{50} = A\left(\frac{1}{\varepsilon}\right)^b \qquad (5.2)$$

where: A and b are regression constants determined from the power law equation fitted through experimental data (see equation D.2 in BS EN 12697-24).

Table 5-2: Resistance to fatigue at 10^6 cycles

Mixture	Mixture Type	Course	Trend line			ε_6 (microstrain)
			Constant	Power	R^2	
Mixture 1	LTA	Binder	5.42×10^{19}	0.691	86.8	103
Mixture 2	LTA	Surface	5.16×10^{11}	3.20	85.5	113
Mixture 3	HMA	Binder	1.66×10^{14}	4.00	99.6	69
Mixture 4	HMA	Surface	4.32×10^{14}	4.17	94.8	119

The higher the ε_6 value, the better the resistance to fatigue. The results indicate better fatigue resistance for the LTA binder course mixture than the HMA one whilst the difference between the LTA and HMA surface course mixtures was minimal. Due to the differing proportions of RA in the mixtures it is not possible to draw any definitive conclusions about resistance to fatigue.

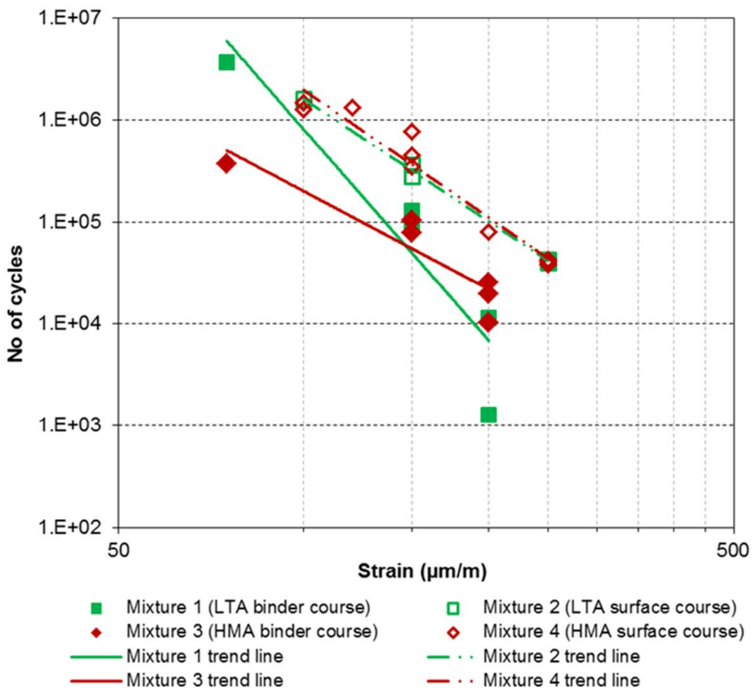

Figure 5-14: Laboratory fatigue results

6 Carbon footprint

6.1 Introduction/asPECT

One of the principal benefits of the LTA technologies is the energy savings that can be realised via lower temperature mixing. This benefit can be expressed using the graph in Figure 6-1, which splits LTA into three sub categories based on temperature. These are: warm mix asphalt (WMA); half-warm mix asphalt (HWMA); and cold mix asphalt (CMA).

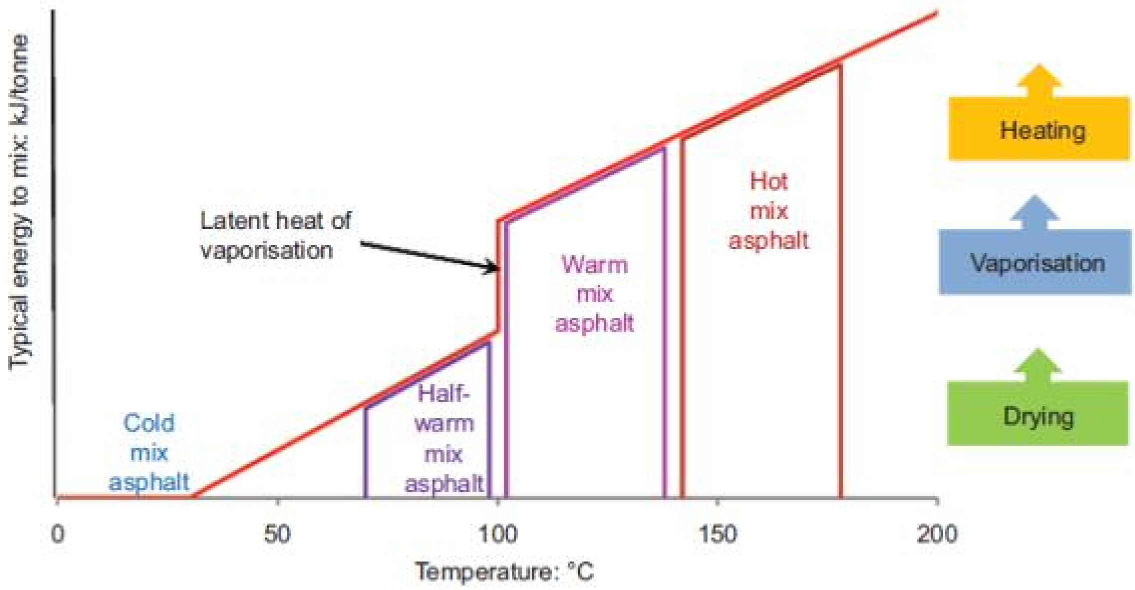

Figure 6-1: Classification of LTA technologies by temperature range (extracted from Nicholls & James, 2011)

Conventional HMA is usually produced at temperatures of 140 °C to 180 °C, warm mix asphalt (WMA) at 100 °C to 140 °C and half-warm asphalt (HWMA) at 70 °C to 100 °C. Production at a lower temperature directly translates to energy savings for WMAs and HWMAs when compared to conventional HMAs. HWMAs also have the significant added benefit of not requiring the complete removal of moisture from the aggregate (or RA), consequently steam is not driven off by reaching temperatures in excess of boiling point and the latent heat of vaporisation does not need to be overcome. Table 4-2 lists the material temperatures at the weighbridge and this shows that the LTA mixtures used at the demonstration site fall into the HWMA category. The HMA surface and binder both fall comfortably within the HMA classification.

The contribution to climate change of the mixtures used can be analysed using the life cycle based approach of asPECT (the asphalt Pavement Embodied Carbon Tool; Wayman *et al*., 2014), which was subjected to a minor update during the course of this research. This approach not only considers the plant energy consumption in heating, mixing and peripheral activities, but also the acquisition, transport and processing of constituent materials and installation at site, and thus evaluates any potential trade-offs between these steps. The life cycle steps covered by asPECT are presented in Figure 6-2.

Life-cycle stage		Description
1	**Raw Material Acquisition**	Acquiring raw materials from the natural environment with the input of energy
2	**Raw Material Transport**	Transporting acquired raw materials to processing
3	**Raw Material Processing**	Crude oil refining, rock crushing and grading, recycled and secondary material reprocessing
4	**Processed Material Transport**	Transporting processed raw materials site of manufacture of bitumen bound highway components
5	**Road Component Production**	Production of bitumen bound mixtures
6	**Material Transport to Site**	Delivery of materials to site
7	**Site Preparation, Laying and Compacting**	Placing materials at the construction site, mobilisation of plant and labour
8	**Scheme Specific Works**	Installation of other specified materials e.g. geosystems and material specific traffic management etc.
9	**Maintenance**	Interventions to maintain the road. Re-surfacing, surface dressing works, patching, haunching etc.
10	**End of Life**	Dismantling and material management

Use

Figure 6-2: Life cycle steps covered by asPECT

6.2 Parameters, data collection and assumptions

The approach taken to quantifying the contribution of the seven life cycle steps is detailed in this section.

6.2.1 Steps 1-3 Acquisition, intermediate transport and processing of raw materials

The batch compositions for the mixtures produced are presented in Table 6-1.

Table 6-1: Component materials proportions and mixing temperature

Component	LTA binder course	LTA surface course	HMA binder course	HMA surface course
Aggregate (%)	69.06	76.91	84.69	76.01
Reclaimed asphalt planings (%)	25.52	15.62	5.89	15.60
Reclaimed filler (%)	0.00	1.13	2.70	0.89
Imported filler (%)	1.93	1.48	2.72	2.75
Bitumen (%)	3.48	0.00	3.99	0.00
Polymer-modified bitumen (%)	0.00	4.86	0.00	4.76
TOTAL	100.00	100.00	100.00	100.00

The CO_2e generated by Steps 1-3 for the asphalts investigated are covered by 'cradle-to-gate' default emissions factors. The values used for aggregate, reclaimed asphalt planings and imported filler were provided by Sabin (2014). The value for reclaimed filler was set to zero in line with the asPECT Protocol Section 2.5.1.7. The values for bitumen and PMB where sourced from Appendix D of the asPECT Protocol (Wayman *et al*., 2014). The values used are presented in Table 6-2.

Table 6-2: Cradle to gate CO_2e values for constituents

Constituent	CO_2e (kg/t)
Aggregate	7.00
Reclaimed asphalt planings	2.98
Reclaimed filler	0.00
Imported filler	7.90
Bitumen	190
Polymer-modified bitumen	370

6.2.2 Step 4 Transport to plant

The haulage distances for the different mixture constituents are presented in Table 6-3.

Table 6-3: Haulage distances for constituents

Constituent	One–way haulage distance (km)	Mode
Aggregate	70	Rigid >17 t
Reclaimed asphalt planings	0	N/A
Reclaimed filler	0	N/A
Imported filler	100	Articulated >3.5-33 t
Bitumen	100	Articulated >3.5-33 t
Polymer-modified bitumen	100	Articulated >3.5-33 t

6.2.3 Step 5 Plant operations: heating and mixing

A complete year of production with associated energy and water consumption data was provided for the Haughmond Hill asphalt plant by Sabin (2014), detailing in excess of 100,000 tonnes of asphalt production by continuous process. This provided the base data for the additional analysis required for the 233.68 t of material used during the demonstration. Four further mixtures were added to the pre-existing regular mixtures at the plant to reflect the specific mixture recipes used at the demonstration site, using the compositions presented in Table 6-1. For the two HMA mixtures, a production rate of 158 tonnes per hour was used (the pre-existing rate for asphalt concrete mixtures). For the LTA mixtures, a notional production rate of 258 tonnes per hour was calculated using the procedure laid down in Section 2.8.3 of the asPECT Protocol, using a standard process rate of 140 tonnes per hour, a standard product energy of 14.8 L of fuel oil per t, and non-standard product energy for the LTA of 8 L per t. The product energies are indicative of 'bundles' of materials using the same technology, rather than being specific to individual recipes, and individual recycled contents. These two production rates facilitated calculation of the cradle-to-gate CO_2e footprints for the four asphalt materials using Section 2.8.1 of the asPECT Protocol.

6.2.4 Step 6 Transport to site

The haulage distance from asphalt plant to site was 88 km one-way. The journey was undertaken by rigid 8-wheeled trucks (>17 t) carrying the loads specified in Table 4-2 and returning the same distance empty.

6.2.5 Step 7 Installation

In line with the asPECT protocol, laying and compacting impacts were included at a rate of 4.7 kgCO_2e per tonne of asphalt.

6.3 Results

Using the parameters specified in Section 6.2, the cradle-to-gate, cradle-to-site and total CO_2e footprints were calculated for the works carried out at the demonstration site and are presented in Table 6-4. The contributions of the different life cycle steps to the overall footprints are presented in Figure 6-3.

Table 6-4: Calculated CO_2e footprints for the four mixtures used

Component	LTA binder course	LTA surface course	HMA binder course	HMA surface course
Cradle-to-gate CO_2e footprint (kgCO_2e per t)	27.65	38.93	35.24	45.21
Cradle-to-site CO_2e footprint (kgCO_2e per t)	42.61	53.89	50.20	60.17
Total CO_2e footprint (kgCO_2e)	2511	2441	3513	3578

Clear savings are observed for the LTA mixtures relative to the corresponding HMA mixtures. Based on the cradle-to-gate footprints, the saving is 14 % for the surface course mixtures and 22 % for the binder course mixtures. It should be noted that only the surface course mixtures have similar RA contents, therefore the former figure is more accurate. The total CO_2e footprint for the works is calculated at 12.0 tonnes. If all 233.68 t of materials used on the works were LTA then the total footprint would have been 11.1 t CO_2e, relative to 12.8 t for all HMA, a saving of 1.6 t CO_2e. This saving is equivalent to undertaking a 1450 km one-way journey in an average-laden heavy goods vehicle (Defra, 2014), or the energy required to run 3 typical 250 W motorway lights for their entire average 4,000 h lifetime (*ibid*.).

One further analysis was conducted where all of the recycled content was removed from the mixtures – by back calculating on the basis of the RA soluble binder content of 4.9 % and assumed 100 % activity – to give the theoretical 0 % RA mix compositions in Table 6-5. This analysis yielded the CO_2e footprints in Table 6-6.

The results in Table 6-6 allow determination of the benefits of using the LTA technology purely on the basis of energy savings. Based on the cradle-to-gate footprints, a saving of 16 % CO_2e is realised by utilising the LTA binder course asphalt in place of the HMA binder course asphalt. A saving of 13 % CO_2e is realised by using the LTA surface course material over the conventional HMA surface course material; the relative saving is lower due to the higher contribution of PMB to the surface course mixtures.

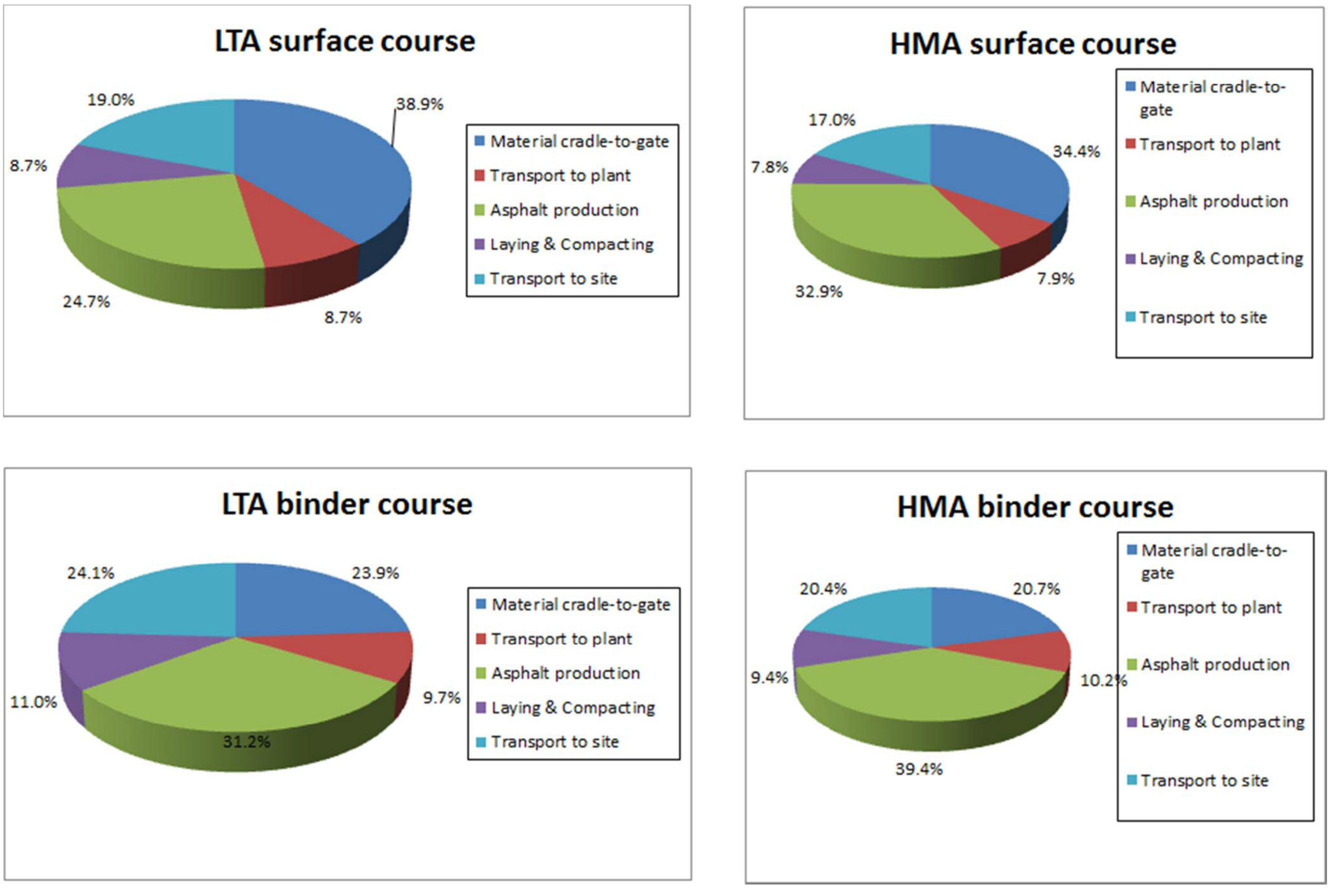

Figure 6-3: Relative contributions of the life cycle steps to the overall footprints

Table 6-5: Theoretical mixture compositions with no reclaimed asphalt

Component	LTA binder course	LTA surface course	HMA binder course	HMA surface course
Aggregate (%)	93.35	91.74	90.31	90.84
Reclaimed asphalt planings (%)	0.00	0.00	0.00	0.00
Reclaimed filler (%)	0.00	1.13	2.70	0.89
Imported filler (%)	1.93	1.48	2.72	2.75
Bitumen (%)	4.75	0.00	4.29	0.00
Polymer-modified bitumen (%)	0.00	5.66	0.00	5.56
TOTAL	100.00	100.00	100.00	100.00

Table 6-6: Theoretical footprints based purely on energy savings

Component	LTA binder course	LTA surface course	HMA binder course	HMA surface course
Cradle-to-gate CO_2e footprint ($kgCO_2e$ per t)	30.19	41.29	35.83	47.58
Cradle-to-site CO_2e footprint ($kgCO_2e$ per t)	45.15	56.25	50.79	62.54
Total CO_2e footprint ($kgCO_2e$)	2661	2548	3554	3718

7 Previous sites

7.1 National

7.1.1 Overview

There are an increasing number of sites where some form of LTA has been used. A summary of LTA sites known to the authors is given in Table 7-1, Table 7-2 and Table 7-3. The information included in these tables is too extensive to be included in a single table and so has been split up with the following columns:

- Table 7-1: Source; type; supplier; product; and length.
- Table 7-2: Materials and construction information.
- Table 7-3: Traffic; lane; date of construction; and performance data.

These column titles give the following information:

- Road: Road number or road name.
- Location: Section of major road with the LTA section or the town in which a more minor road with LTA is located.
- Source: Where the authors gained the information from.
- Type: The type of LTA (warm, semi-warm, cold and cold recycled).
- Supplier: Company supplying the LTA.
- Product: The proprietary name of the LTA.
- Length: The length of LTA.
- Materials and construction information: Layer(s) with LTA, layer thicknesses, mixture categories, additives and maximum nominal aggregate size.
- Traffic: Annual average daily traffic (AADT) level.
- Lane: Lane for multi-lane roads such as motorways.
- Date of construction: Date LTA was laid.
- Performance data: Types of data on performance available.

The full set of data is not available from all the sites listed. Of the sites, about half are on the HA Network whilst the rest are on county or private roads.

Further details of two of the sites are given in Sections 7.1.2 and 7.1.3.

Table 7-1: Details of previous sites (Part 1 of 3)

Road	Location	Source	Type	Supplier	Product	Length (km)
A1M	Shincliffe to Belmont Bridge – Northbound carriageway between J61 and 62 in Durham (Area 14)	HA departure	Semi-warm	AI	Life asphalt	Patches
M55	J3-1 SB (Area 13)	HA departure	Warm	Tarmac	Sasobit	–
M6	J30-31 NB	HA departure	Warm	Tarmac	Sasobit	–
St. Johns Hill	Shrewsbury	Industry contact	Semi-warm	AI	Life asphalt	–
Middleton Road	Bringhurst	Industry contact	Warm Cold	Tarmac	–	0.3
Meadow Lane	Bromsgrove	Industry contact	Semi-warm	AI	Life asphalt	–
A21	Sevenoaks	Past TRL site	Cold recycled	–	–	–
A38	Peartree to Drybridge	Past TRL site	Cold recycled	–	–	8
A46	Between roundabouts at A422 at Shottery and the A3400 at Bishopton	Past TRL site	Cold recycled	–	ViaFoam	2
M6	A34 Walsall Junction J7 Great Barr	Industry contact	Warm	Cemex	Sasobit	–
M4	Between Bristol and Bath	Industry contact	Warm	Cemex	Sasobit	–
A90	Fraserburgh Trunk Road Snabs to Star Farm chainage 270 to 800 and 2550 to 2670	Industry contact	Cold	Tayside Contracts	Tayset	670
A66	EB carriageway of the A66 between the A67 Bowes Junction and the B6277 Cross Lanes junction	HA departure	Semi-warm	AI	Life asphalt	Patches
A1/M1	Link road	Possible departure	Warm	Tarmac	Sasobit	–
A444	Burton-on-Trent	Industry contact	Semi-warm	MQP	LEA	–
Residential road	Dudley BC	Industry contact	Semi-warm	MQP	LEA	–
Private road	Dordon	Industry contact	Semi-warm	MQP	LEA	–
2 arterial roads	Birmingham PFI	Industry contact	Semi-warm	MQP	LEA	–
High Street	Broughton Astley, Leicestershire	Industry contact	Semi-warm	MQP	LEA	–

Table 7-2: Details of previous sites (Part 2 of 3)

Road	Location	Materials and construction information
A1M	Shincliffe to Belmont Bridge - Northbound carriageway between J61 and 62 in Durham (Area 14)	200 mm of AC32 HDM base 40/60 material laid in two 100 mm layers, 100 mm layer of AC20 HDM bin 40/60
M55	J3-1 SB (Area 13)	100 mm deep bituminous inlay
M6	J30-31 NB	150 mm deep bituminous inlay
St. Johns Hill	Shrewsbury	10 mm close-graded surface course 100/150
Middleton Road	Bringhurst	60 mm BC and 40 mm SC
Meadow Lane	Bromsgrove	40 mm inlay using 14 mm CGSC 40/60 with a 65PSV
A21	Sevenoaks	2x100 mm thick layers combining 3 FB, 2 lime, 6 PFA, and 2 OPC
A38	Peartree to Drybridge	200 mm removed and replaced with 170 mm of in-situ recycled materials hot mix binder and BC
A46	Between roundabouts at A422 at Shottery and the A3400 at Bishopton	Planed off the existing 190 mm asphalt, crack and seat existing CBM and overlaid with ViaFoam as a base course and a conventional HMA binder course and a thin surfacing
M6	A34 Walsall Junction J7 Great Barr	AC32 HDM, AC20 HDM and 14 mm Viapave; base layer contained 40/60 + Sasobit and the binder course and surface course both contained Olexobit 100 + Sasobit
M4	Between Bristol and Bath	Shell S Grade Binder
A90	Fraserburgh Trunk Road Snabs to Star Farm chainage 270 to 800 and 2550 to 2670	1600 t Slow Visco-Elastic (SVE) as defined in TRL 611, including RA
A66	EB carriageway of the A66 between the A67 Bowes Junction and the B6277 Cross Lanes junction	Patches consist of 200 mm of AC32 HDM base 40/60 material laid in two 100 mm layers, a 65 mm layer of AC20 HDM bin 40/60 material and a 35 mm layer of thin surfacing
A1/M1	Link road	2500 t
A444	Burton-on-Trent	1673 t of AC 32 Dense Base 100/150 LEA and AC 20 Dense Bin 100/150 LEA; binder course left open to traffic for two weeks prior to surface course installation
Residential road	Dudley BC	220 t of AC 20 HD Binder LEA 40/60
Private road	Dordon	Waste recycling depot with extensive HGV usage surfaced using 568 t of AC 32 Dense Base LEA 100/150 and 99 t of AC 20 Dense Binder LEA 100/150
2 arterial roads	Birmingham PFI	Surfaced with 1,546 t of AC 32 HDM Bin 40/60 LEA
High Street	Broughton Astley, Leicestershire	Village high street 110 t of AC 32 HDM Base 40/60 LEA

Table 7-3: Details of previous sites (Part 3 of 3)

Road	Location	Traffic (AADT)	Lane	Date of construction	Performance data
A1M	Shincliffe to Belmont Bridge - Northbound carriageway between J61 and 62 in Durham (Area 14)	30,044 (11 % HGV)	1	May 2013	On-site LWD on lower 100 mm
M55	J3-1 SB (Area 13)	29,146	1	Feb. 2013	–
M6	J30-31 NB	65,759	1	July 2013	–
St. Johns Hill	Shrewsbury	–	1	April 2009	–
Middleton Road	Bringhurst	–	1	March 2011	ITSM on cores
Meadow Lane	Bromsgrove	–	1	May 2013	–
A21	Sevenoaks	–	–	May 2002	ITSM on cores
A38	Peartree to Drybridge	19,708 (14 % HGV)	EB	–	–
A46	Between roundabouts at A422 at Shottery and the A3400 at Bishopton	–	–	–	FWD
M6	A34 Walsall Junction J7 Great Barr	–	1 + 2 on/off slips	Dec. 2003	Gradlab results
M4	Between Bristol and Bath	–		–	–
A90	Fraserburgh Trunk Road Snabs to Star Farm chainage 270 to 800 and 2550 to 2670	–	2 and layby	June 2010	LWD, DSM, ITSM
A66	EB carriageway of the A66 between the A67 Bowes Junction and the B6277 Cross Lanes junction	6512 (27.1 % HGV)	–	June 2012	LWD + 2 year monitoring
A1/M1	Link road	–	–	–	–
A444	Burton-on-Trent	–	–	–	ITSM, resistance to permanent deformation, voids, wheel tracking
Residential road	Dudley BC	–	–	–	
Private road	Dordon	–	–	–	
2 arterial roads	Birmingham PFI	–	–	–	
High Street	Broughton Astley, Leicestershire	–	–	–	

7.1.2 A1(M) at Shincliffe

Similar mixtures to those applied on the A5 Grendon demonstration site had been used previously on the A1(M) at Shincliffe, County Durham, where LTA mixtures had been applied in the binder course and base in May 2013 but without control HMA mixtures. The site was visited in April 2014 and twelve cores extracted. Copies of the core logs are reproduced in Section E.1 of Appendix E.

The binder course and base layers of the cores were tested for bulk density in accordance with BS EN 12697-6 Procedure B (SSD) (CEN, 2012b) and stiffness in accordance with BS EN 12697-26 (CEN, 2012c) using Annex C for applying indirect tension to cylindrical specimens (IT-CY). Two cores samples of both layers were also tested for maximum density in accordance with BS EN 12697-5 (CEN, 2009) and the air voids content of all samples determined in accordance with BS EN 12697-8 (CEN, 2003a) using the mean maximum density for the relevant layer. The individual density test results are given in Section E.2 of Appendix E and the statistics given in Table 7-4 while the individual test stiffness results are given in Section E.3 of Appendix E.

Table 7-4: Statistics of air voids content results from cores

Core No.	Binder course			Base		
	Bulk density (Mg/m^3)	Max. density (Mg/m^3)	Air voids content (%)	Bulk density (Mg/m^3)	Max. density (Mg/m^3)	Air voids content (%)
Mean	2.386	2.670	10.6	2.338	2.542	8.0
Maximum	2.486	–	16.2	2.451	–	13.1
Minimum	2.238	–	6.9	2.209	–	3.6
Range	0.248	–	9.3	0.242	–	9.5
Standard deviation	0.077	–	2.9	0.068	–	2.7

Plotting the stiffness against the core densities for both layers (Figure 7-1) shows that, in general, higher density relates to higher stiffness although the relationship is not that consistent (the correlations are weak).

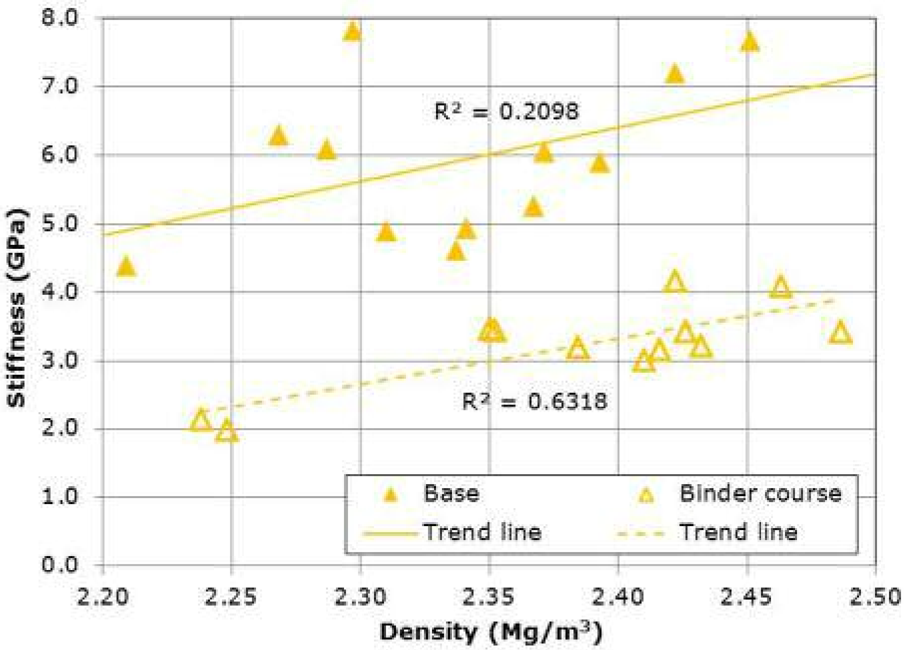

Figure 7-1: Relationship between stiffness and density of cores

There appears to be a threshold level of air voids content, above which there is a detrimental effect on material stiffness properties. The primary concern is the variability in the density of the laid material and the results from Shincliffe appear to echo the experience on the A5 Grendon demonstration site. The cause of this variability may be two fold; that is, solely related to inadequate temperature at the time of compaction; and/or the time that has elapsed since the process at the asphalt plant has reduced the workability of the material to an extent where full compaction is difficult to achieve. The precise reasons for poor compaction are not definitively known, but they do emphasise the importance of good quality control in terms of workability window, compactive effort and material temperature.

7.1.3 Middleton Road, Bringhurst

The site selected was a section of Middleton Road, Bringhurst, Leicestershire (Nicholls *et al*., 2014). The road required the replacement of both the binder and surface courses. The trial length compromised one lane that was divided into ten sections, each 75 m long. For the surface course, the trial materials consisted of both conventional hot mix asphalt and half-warm mix asphalt options of both hot rolled asphalt and asphalt concrete. For the binder course, the material options were conventional hot mix asphalt, half-warm mix asphalt and cold mix asphalt options of asphalt concrete. The conventional hot mix asphalts were included as the controls.

The deformation resistance of the materials was checked using the relevant option from BS EN 12697-22 (BSI, 2003). The results for the LTA surface courses were as good as, or better than, the equivalent HMA controls. The binder course materials could not be compared with the hot mix control, but the results indicated equivalent behaviour to HMA and were well within the specification limits set for HMA. These results indicate that the LTA mixtures have good durability in terms of deformation resistance.

The stiffness modulus was also monitored using the indirect tensile method to BS EN 12697-26 (BSI, 2012) and the stiffness values for half-warm asphalt concrete showed equivalence to those for HMA AC whilst the stiffness values for half-warm hot rolled asphalt was slightly higher than those for HMA HRA. All materials demonstrated comparable performance in terms of stiffness. In addition, the cold mix material showed a significant increase in stiffness after two weeks curing at 40^{o}C (Nicholls *et al*., 2014).

The results also indicated that the materials could be durable, although confirmation would be needed from in-service experience of actual performance.

7.2 International

7.2.1 Introduction

A review of international experience on the durability of low temperature asphalt was initiated through direct contact with key industry sources in the USA and Scandinavia. The review was undertaken between August 2013 and March 2014. The findings of the review are presented below with separate sections for the USA and Scandinavia. Any views expressed in this chapter are those of the international contacts.

7.2.2 USA

7.2.2.1 NCHRP research into low temperature asphalt

The National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board (TRB) conducts research in problem areas that affect highway planning, design, construction, operation, and maintenance nationwide in the USA. With the increasing use of low temperature asphalt, particularly warm mix asphalt (WMA) as shown in Figure 7-2, their remit includes low temperature asphalt and its relative durability compared to hot mix asphalt (HMA).

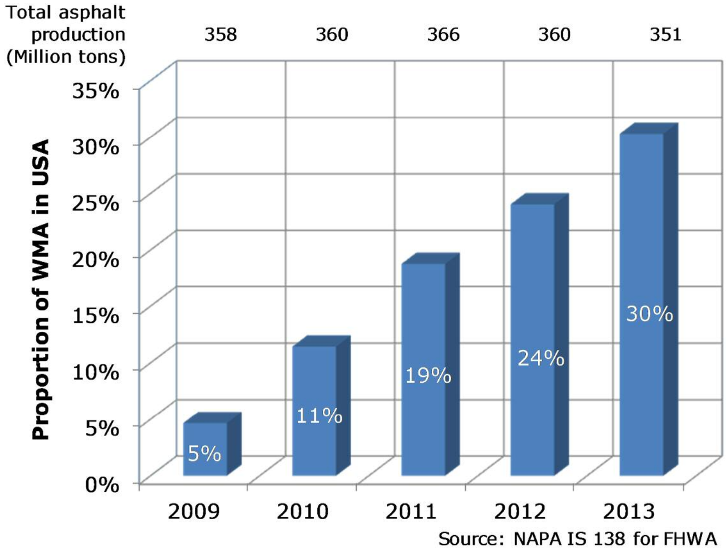

Figure 7-2: Development in the production of warm mix asphalt in USA

The NCHRP projects related to WMA are the most significant work in this area comparing the relative performance of WMA and HMA in the USA. The WMA Technical Group has been very successful in getting WMA research needs statements funded through the NCHRP programme.

The NCHRP Projects funded as a result of WMA Technical Working Group efforts are:

9-43	Mix Design Practices for WMA
9-47	Engineering Properties, Emissions, and Field Performance of WMA Technologies
9-47A	Properties and Performance of WMA Technologies
9-49	Performance of WMA Technologies: Stage I – Moisture Susceptibility
9-49A	Performance of WMA Technologies: Stage II – Long-Term Field Performance
9-52	Short-Term Laboratory Conditioning of Asphalt Mixtures
9-53	Properties of Foamed Asphalt for Warm Mix Asphalt Applications
9-54	Long-Term Ageing of Asphalt Mixtures for Performance Testing and Prediction
9-55	Recycled Asphalt Shingles in Asphalt Mixtures with WMA Technologies
20-07 (311)	Development of a WMA Tech. Evaluation Program

The programme has a total cost of $6,022,501, about £3,875,000 or €4,550,000 at current exchange rates. Of particular note are projects 9-47A and 9-49A which monitor field performance of WMA pavements with HMA control sections. The information for all the asphalt related NCHRP projects listed above can be accessed by clicking on the

Research Field 9 – Bituminous Materials link on the site www.trb.org/NCHRP/Public/NCHRPProjects.aspx.

A useful document that has been cited in several of these webpages is the three volume "Collected critical literature reviews from NCHRP Projects 9-47, 9-47A, 9-49, 9-49A and 9-53" which can be downloaded as Part I; Part II; and Part III. This draft document has been reviewed with the specific aim of identifying comparative site performance for different systems. Project summaries (taken from the internet) for the projects which include observations on field performance have been reproduced in Appendix F *. Case studies from NCHRP Projects 9-47, 9-47A, 9-49, 9-49A and 9-53 are included as Appendix G.

7.2.2.2 Comparative field studies

The main details of comparisons of site performance are given in Appendix G. These have been summarised in terms of in situ performance in Table 7-5 and Table 7-6.

Table 7-5: Summary of US durability data for WMA from NCHRP Project 9-47A (

Reference	Site	Systems	Age	Condition
–	NCAT test track	Evotherm™ ET	500,000 ESAL	Rut depths less than 1.5 mm on all sections
Reyes *et al.*, 2009	North Burnaby Ready Mix Plant & Coquitlam Sand & Gravel Pit, Western Canada	Astec Double Barrel Green	2 years	Visual condition index of: 7.5 with 15 % RA 8.2 with 15 % RA & 5 % RAS 7.9 with 50 % RA
Chowdhury and Button, 2008	70 sites (various)	Various	Up to 5 years	No negative performance
Hurley and Prowell, 2006	St Louis, Missouri and Milwaukee, Wisconsin	Aspha-min®, Evotherm™ ET and Sasobit®	4 months	Maximum rut depth of 1.1 mm for all sections
D'Angleo *et al.*, 2008	Toll road southwest of Paris, France	Aspha-min®	4 years	Comparable with HMA
	Seven field trials in Germany	Sasobit®, Asphaltan® B, Aspha-min® and Sübit®	3 to 7 years	The same or better performance than the HMA sections
	28 sections in Norway	WAM-Foam	2 to 8 years	Considerable deterioration from studded tyres with similar damage in HMA sections

* The text, in Appendix F and Appendix G, has been "translated" as far as practicable to use UK English and SI units throughout.

Table 7-5: Summary of US durability data for WMA from NCHRP Project 9-47A (cont.)

Reference	Site	Systems	Age	Condition
Davidson, 2008	Canada	Sasobit®, WAM Foam, Astec Double Barrel Green, Aspha-min®, Evotherm™ ET and DAT	Up to 3 years	All performing well
Hodo *et al*., 2009	Chattanooga, Tennessee	Astec Double Barrel Green	1 year	No signs of distress
Mogawer *et al*., 2009	Massachusetts	Sasobit®	Almost 1 year	No visible distresses
Wielinski *et al*., 2009	Two sites in Indio, California	Astec Double Barrel Green	1 year	Performing well with no visible distresses
Barros and Dmytrow, 2009	California	Sasobit®	2 year	Still performing well
West, 2009	13 projects across Alabama, Texas, Michigan, Wisconsin, Florida, Tennessee, Ohio, South Carolina and Nebraska	Unspecified	1 to 4 years	Visually, HMA and WMA had the same amount of rutting Crack resistance of WMA is equal to (and in some cases better) than HMA No signs of moisture damage
Hurley *et al*., 2009a	Michigan	Sasobit®	2 years	No cracking Rutting non-existent to minimal
Hurley *et al*., 2010a	Hall Street, St Louis, Milwaukee	Evotherm™ ET, Sasobit® and Aspha-min®	2 years	The average rutting ranged from 0.5 to 1.1 mm Small reflective cracks were observed in the sections Possible beginning of moisture damage for Aspha-min® and Evotherm™ ET
Kvasnak *et al*., 2009	Franklin, Tennessee	Astec DBG, Evotherm™ DAT, Sasobit® and Advera® WMA	1 year	Some spots in the control and Advera® WMA sections where binder had bled Some ravelling exhibited in all of the sections
Jones, 2009	Aromas, California	Advera®, Evotherm™ and Sasobit®	170,000 ESAL to 734,014 ESAL	Rutting of Advera® and Evotherm™ slightly higher than Control Three WMA systems did not significantly influence the rutting performance of the mixture

Table 7-5: Summary of US durability data for WMA from NCHRP Project 9-47A (cont.)

Reference	Site	Systems	Age	Condition
			3,048,400 ESAL to 13,608,800 ESAL	Control and Evotherm™ rutted at a notably faster rate than Advera® and Sasobit® Trafficking terminated on Advera® and Sasobit® before failure No section showed any indication of moisture damage

Table 7-6: Summary of US durability data for WMA from NCHRP Project 9-49A c

Reference	Site	Systems	Age	Condition
Estakhri *et al.*, 2010; Button *et al.*, 2007	San Antonio Loop 368*, Texas	Evotherm™ ET	1 year	HMA had bitumen absorption while WMA did not
			3 years	Some cracking in both WMA and HMA No rutting in either WMA or HMA
Estakhri *et al.*, 2010	Austin SH 71, Texas	Evotherm™ DAT	1 year	Performed well with no signs of distress in HMA or WMA
	Lufkin FM 324, Texas	Sasobit®, Evotherm™ DAT, Rediset® and Advera®	1 year	Performing well No evidence of rutting or cracking
	Fort Worth BU 287 Project, Texas	Evotherm™ DAT	1 year	Performing well with no rutting or cracking
Kvasnak *et al.*, 2010	SR-79, Tarrant City, Alabama	Evotherm™ DAT	1st visit	Segregation issues for both HMA and WMA No cracking and other distress
			2nd visit	Cracks in WMA and patches in HMA
			3rd visit = 1 year	Indirect tensile strength of WMA similar to HMA
Prowell *et al.*, 2007; Chowdhury and Button, 2008	NCAT test sections	Evotherm™ ET	500,000 ESAL	WMA and HMA showed excellent field performance in terms of rutting
Hurley and Prowell, 2005; Chowdhury and Button, 2008	Olano demonstration project, Florida	Aspha-min®	1 year	No distress in either HMA or WMA
Sholar and Nash, 2009	SR-417 project, Florida*	Aspha-min®	3 years	No difference in performance between HMA and WMA
	US-2 (SR-600) project, Florida	Evotherm™ DAT	1 year	No practical differences between WMA and HMA
Sholar and Nash, 2009; Copeland *et al.*, 2010	SR-11, Flagler County, Florida	Astec Double Barrel Green	1 year	No practical difference in rutting, cracking or ride rating between HMA and WMA

Table 7-6: Summary of US durability data for WMA from NCHRP Project 9-49A cont.)

Reference	Site	Systems	Age	Condition
Kvasnak *et al.*, 2010	SR-46, Franklin, Tennessee	Advera® WMA, Astec DBG®, Evotherm™ DAT and Sasobit®	1 year	HMA, DBG and Evotherm™ DAT had ravelling along centreline; Sasobit® less affected; Advera® more severe HMA had highest indirect tensile strength; Advera® and Sasobit® significantly lower Despite ravelling, distress was neither severe nor extensive
Burke, 2006	MD Route 925*, Maryland	Sasobit®	1 year	Both HMA and WMA performed well with no signs of deterioration or distress smooth texture and minimal amount of segregation
			5 years	Some segregation and centreline cracking on both HMA and WMA
Kim *et al.*, 2010	Antelope County Nebraska Trial Sections	Evotherm™ WMA, Advera® WMA, Sasobit® WMA*	1 and 2 years	WMA and HMA performed well without any major distresses Rut depth and roughness of WMA and HMA similar
Hurley *et al.*, 2009	Iron Mountain M95 Project, Michigan	Sasobit® WMA	2 years	Minor pop-outs of coarse aggregate particles in Sasobit® Density of Sasobit® similar to HMA The indirect tensile strengths had increased for both Sasobit® and HMA No visual stripping from either section
Hurley *et al.*, 2010	Hall Street, Missuri	Asphamin®, Sasobit® and Evotherm™ ET	2 years	Limited number of cracks (reflective in nature and apparently tight) in each section Performed well with minimal rutting and cracking in WMA and HMA
Hurley *et al.*, 2009; Sargand *et al.*, 2009; Nazzal *et al.*, 2011	SR 541, Kimbolton, Ohio	Evotherm™, Sasobit® and Aspha-min®	46 months	WMA exhibited low levels of ravelling; Evotherm™ the least and Sasobit® the greatest IRI values for WMA similar to that of HMA Based on MEPDG, Evotherm™ and Sasobit® need rehabilitation sooner than HMA No measureable rutting No performance problems

* Not included in list of systems used, but referred to in later text.

Table 7-6: Summary of US durability data for WMA from NCHRP Project 9-49A cont.)

Reference	Site	Systems	Age	Condition
Diefenderfer, 2010	Highland County, Rappahannock County and York County, Virginia	Sasobit® and Evotherm™ ET	2 years	No significant distresses in WMA or HMA Air voids content for WMA and HMA not significantly differently Recovered binder suggested that Sasobit® aged at slightly reduced rate than HMA; no difference between HMA and Evotherm™
Cheng *et al.*, 2010	Santa Clara project, California	Sasobit®	2 years	Still "looked good"
	I-5 District 10	Astec Double Barrel Green and Evotherm™	2 years	No signs of distress
Aschenbrener *et al.*, 2011	I-70 in Silverthorne, Colorado	Advera®, Sasobit® and Evotherm™ DAT	3 years	WMA comparable to HMA in terms of rutting, cracking and ravelling Performance excellent despite very harsh winter climate

*Sites at least three years old – see further data in Table 7-7

This review generally shows equivalence between WMA and HMA, although none of the data are for sites that have been in service for an age near the expected life of an asphalt surfacing of between 10 and 20 years. The longest reported monitoring was for 5 years (apart from that identified in a study tour of Europe by a US group that is included in their review, which went up to 8 years) whilst most were for a single year.

Of the lower-temperature systems evaluated, the vast majority are additive based systems, with the most commonly trialled ones appearing to be Evotherm™ (in its various forms), Astec Double Barrel Green, Sasobit®, Aspha-min® and Advera® WMA. However, with the properties "measured" for potential differences mostly being qualitative observations rather than quantitative properties, it was difficult to identify any differences in their performance. The additive-centric focus of the NCHRP review seems somewhat contradictory to the findings of a survey conducted by NAPA (2014) and funded by the FWHA that determined plant foaming to represent 87 % of the WMA market and additives 13 %, although it was the most extensive review available of warm mix systems from the United States.

7.2.2.3 Trials of sites over three years old

The trials with data for at least three years from Table 7-6 are listed in Table 7-7 with the additional details of mix design, weather conditions and traffic, where known. The older sites from Table 7-5 are not included because the same additional data was not provided. There are significant gaps in this information that were not capable of being extracted from the available papers. However, the data are still insufficient to make any firm conclusions about the relative long-term durability of low temperature mixtures relative to that of hot mix asphalt.

Table 7-7: Summary of US durability data for WMA from NCHRP Project 9-49A

Site	Existing pavement	Overlay	Mix design	Temperature	Laid	Weather	Traffic
San Antonio Loop 368, Texas (Estakhri *et al.*, 2010; Button *et al.*, 2007)	Cold-milled asphalt surface seal coated with AC-15P and a Grade 4 pre-coated aggregate	51 mm In-place density 94.2 % (HMA) & 93.4 % (WMA)	Item 341, Type C dense graded Valero PG 76-22 Aggregate: 88 % Vulcan Helotes LS (SAC B) & 12 % Field Sand Anti-strip: 0.75 % liquid for HMA, none for WMA Bitumen content 4.8 % (HMA) & 4.2 % (WMA) Evotherm™ ET	Compaction 115 ºC (WMA) and 149 ºC, (HMA)	August & September 2006 Night time Hauled distance 20 miles (c.25 min)	–	Four-lane carriageway divided by median with curb and gutter Businesses along each side
SR-417 project, Florida (Sholar and Nash, 2009)	–	–	FC-5 open graded friction course Polymer-modified PG 76-22 bitumen in HMA & WMA Aspha-min®	Mixing 160 ºC (HMA) & 132 ºC (WMA)	February 2006	–	–
MD Route 925, Maryland (Burke, 2006)	–	–	15 % RA PG 64-22 bitumen Sasobit®	Behind paver 154 ºC to 176 ºC (HMA) & 132 ºC (WMA)	2005	–	–

Table 7-7: Summary of US durability data for WMA from NCHRP Project 9-49A (cont.)

Site	Existing pavement	Overlay	Mix design	Temperature	Laid	Weather	Traffic
SR 541, Kimbolton, Ohio (Hurley *et al.*, 2009; Sargand *et al.*, 2009; Nazzal *et al.*, 2011)	31.8 mm asphalt surface, 44.5 mm asphalt intermediate layer, 127 mm granular base and 102 mm granular material Two 38 mm asphalt overlays	19 mm HMA levelling course plus 32 mm surface course in 4 sections	Ohio DOT Item 441, Type 1 surface mix 9.5 mm NMAS PG 70-22 modified binder with 15 % RA and limestone aggregate Evotherm™, Sasobit® and Aspha-min®	Compaction 110 ºC to 127 ºC (WMA)	September 2006 Haul distance 21 miles (c.25 min)	Due to weather delays (rain), constructed over three week period	Two-lane rural highway with limited traffic
I-70 in Silverthorne, Colorado (Aschenbrener *et al.*, 2011)	Existing (255 – 330) mm asphalt 64 mm milled and replaced	–	CDOT Grading SX, 12.5 mm PG 58-28 bitumen Crushed river rock aggregate 6.3 % bitumen content, 3.6 % VTM, 16.8 % WMA Advera®, Sasobit® and Evotherm™ DAT	Compaction 17 ºC to 28 ºC cooler for WMA than HMA	July & August 2007 Haul distance 5 to 15 miles (c.10 to 25 min)	Extreme winter conditions 2,680 m to 3,380 m above sea level. Over 900 mm precipitation annually inc. over 5 m of snowfall	30,000 AADT with 10 % trucks Three uphill, eastbound lanes (three downhill, westbound lanes in 2008

7.2.3 Scandinavia

7.2.3.1 Denmark

A representative from Skanska reported that, when comparing the different choice of pavement types and solutions in Scandinavia, it was important to be aware of the different climatic conditions in the Scandinavian countries, resulting in different expected life time performance. As an example, there are no mountains in Denmark (the highest hill in Denmark, called "Himmelbjerget" (which translated to English would be "Sky Mountain") is only 147 m above sea level, and often there are only a few weeks of snow during winter time). Thus studded tyres are never used in Denmark whereas, in the other Scandinavian countries, studded tyres are widely used in the winter, which affects the pavement life time performance dramatically. In Denmark, a typical surface course in the countryside or on minor city roads would be a soft AC 8d, which often lasts for more than 20 to 25 years, whereas a Finnish AC 16d surface course may need repair or replacement after three to four years due to wear from studded tyres. Therefore, comparison of life time performance/experience between different countries may be difficult.

Cold asphalt mixtures (especially base course materials) have been trialled (on a low scale) in Denmark since the 1980s, but normally the trials concluded that the unavoidable water content from the emulsion and cold aggregates resulted in too high air voids content and that the mixture could not fulfil the needed functional properties such as stability and durability. Half-warm mixes have been used on a more regular basis in the northern part of Scandinavia for low trafficked roads, possibly where HMA is not practically available or where a lower pavement quality still is an improvement compared to unbound materials road surfaces. Warm Mix Asphalt has been used to a limited extent in Denmark for some years. Different techniques have been used on a trial basis for some years and seem to work well. The systems trialled include binder additives (wax types), surfactants and foam. WMA is not yet used on a regular basis and, therefore, no general specifications exist.

However, Denmark has always aimed for the principle that other methods, techniques and/or materials may be used so long as all the requirements specified for standard HMA are fulfilled and the general long warranty period is maintained in order to support development.

The expectation is that, in the future, a certain proportion of all Danish asphalt mixtures will be produced as WMA (mixture temperature <130 °C) in order to obtain a more "green" approach. So far, the demand for WMA from customers has been very limited. The intention to be more "green" is relevant to Danish municipalities, but with the very limited amount of money available for pavement rehabilitation, the interest for "most-square-meters-per-invested-money" has typically overruled the green choice because many of the systems are slightly more expensive than the standard HMA due to cost of additives. For this reason, foam systems are expected to be the future solution.

A representative from Danish Roads Institute reported that DRI visited some paving work being undertaken in 2011 in order to take infra-red photographs and get a better understanding of the early attempts in the WMA technology (based on wax and surface active component additives but not zeolites or foam). No report or technical note has been produced to date and the project was dormant in 2013, to be resumed in 2014. Some of the asphalt contractors incorporated foaming facilities in a few asphalt plants prior to the 2012 construction season. They have been using the material on a very small scale (to get acquainted with the technique) in base layers. Denmark has been a little slow to adopt foaming technology because little is perceived to be gained by in situ mixing, when the geographical spread of asphalt plants in Denmark means that only short transport distances are required plant to site. There has also been some reluctance to add water to asphalt mixtures through the foaming technology and the consequences that this may have, given the prevailing weather conditions of rain and freeze-thaw in winter. The main reservations concerning water arise from not yet fully understanding how water from emulsion escapes the mixtures, the pore structure it may leave behind, and whether water ingress can occur at a later date through these pores which might be subject to freeze-thaw processes.

It was the DRI representative's view that it is too early for Denmark to have (local) specifications for this technique as asphalt contractor trials are no more than three years old, so no real durability data is available at this stage. The present technical evaluation from a road administrator's point of view is that the major impact of this technology is on road workers' health (i.e. reduced fumes). Depending on the technology, it is questionable when additives are used whether or not there will be energy savings and the suppliers of additives regulate the price so that currently there is no economic advantage for the road administration.

7.2.3.2 Norway

A representative from Veiteknisk Institutt reported that Veidekke (a Norwegian technical centre for R & D, quality control and documentation of asphalt) paved a lot of roads in Norway between 2001 and 2004 using the WAM Foam technique developed together with Shell Bitumen. These roads had been monitored by both Road Authorities and Veidekke. They have been compared with other, comparable roads paved at around the same time. There was some variation in the development of ruts and other forms of damage for both WMA and HMA, but on average it was concluded that the performance was equal.

Veidekke used the technology between 2005 and 2010 when the level of road construction was low. However, they paved eleven field trials using different techniques in 2011 which, after two years, seemed to have all performed similarly. In 2012 and 2013, Veidekke laid trials, one of which was in a tunnel, with polymer modified binders (SBS) that look good. The reduction in bitumen foam was 93 % and 94 % when the temperature was reduced by 40 °C. In 2013, three companies paved approximately 250,000 tons of WMA based on three different foaming techniques. The road authorities awarded bonus payments for the use of low temperature asphalt in 2013 and 2014. Some details of the trials are given in Section H.1 of Appendix H.

A national working group has been established in Norway on low temperature asphalt with participants from contractors, government and other organisations to follow up and promote WMA.

7.2.3.3 Sweden

A representative from Road and Transport Research Institute (VTI) reported that requirements for cold asphalt were removed from the specifications a few years ago but now the Road Transportation Administration (TRV) is willing to introduce the requirements again to reduce carbon dioxide, but did not give any information relevant to durability. Some details of trials in Sweden are given in Section H.2 of Appendix H.

8 Discussion

8.1 Construction

The construction of the LTA mixtures on the demonstration site proved no more difficult than that with the HMA mixtures. However, there was a clear visual difference in finish (Section 3.3) that could have arisen due to site specific conditions. The absence of a second heavy roller on site may have been a factor with regards to the ability to consistently achieve uniform compaction of the LTA mixture.

The main difference, apart from the temperature, seems to be that the LTA mixtures achieved more variable levels of compaction. Inadequate compaction can lead to higher voids, lower density and potentially lower stiffness. At both the demonstration site on the A5 Grendon and on the earlier site on the A1(M) Shincliffe, variable levels of compaction were noted. Results obtained from tests conducted on laboratory manufactured samples suggest comparable performance with HMA is achievable.

In order to ensure satisfactory performance and durability of LTA mixtures, the level of production control and workmanship may need to be raised to a higher level than is currently observed. This needs to be considered in the next steps to facilitate wider take-up of LTA materials in the UK (Section 8.4.2).

8.2 Material properties

8.2.1 Overview

An overview of the comparative results of the material properties is given in Table 8-1.

The relative properties in terms of the change from HMA to LTA, at least for these mixtures assessed in the demonstration, can be summarised as:

- Compactibility: Similar voids measured from laboratory compacted samples but greater variability in voids in LTA samples taken directly from site.
- Water sensitivity: Slightly higher susceptibility to water for LTA materials, although the statistical significance not checked.
- Deformation resistance: Creep values were comparable for LTA and HMA but were more variable for the LTA material; wheel tracking of laboratory prepared samples showed less deformation resistance for the LTA samples.
- Stiffness: Stiffness values for the HMA and LTA materials were similar for both binder and surface course.
- Fatigue: Similar for both materials but LTA binder course appears to be more strain susceptible.

The laboratory manufactured samples would suggest performance of LTAs comparable with that of HMAs is achievable.

Table 8-1: Overview of mean test properties

Property		Binder course		Surface course	
		Mixture 1 (LTA)	Mixture 3 (HMA)	Mixture 2 (LTA)	Mixture 4 (HMA)
Air voids content (%)	Dry	3.5	4.2	4.9	5.5
	Sealed	5.6	6.9	7.5	7.8
	Dimensions	6.5	7.8	9.0	9.4
Water sensitivity (ITSR) (%)		74	92	77	91
Triaxial creep rate (μstrain/cycle)		0.35	0.41	–	–
Wheel tracking	Large device, proportional rut depth (%) at 30,000 cycles	5.6	4.7	5.3	4.6
	Small device, mean WTR_{Air} (μm/cycle)	0.48	0.33	0.37	0.16
	Small device, rut depth (mm), after 1000 cycles	2.4	1.2	2.0	1.3
Stiffness (GPa)	IT-CY	5.84	6.37	2.13	1.81
	4PB	Dependant on temperature and frequency (see Section 5.6.2)			
Fatigue ε_6 (μstrain)		103	69	113	119

8.2.2 Carbon footprint

The carbon footprint analysis of the mixtures used at the A5 site using asPECT v4.0 demonstrated some appreciable CO_2e savings. CO_2e savings derived from both energy savings at the plant (the lower heating and drying energy of the LTA asphalt mixtures) and the recycled content that was incorporated. Direct comparisons were possible for the surface course materials which both had a recycled content of 15.6 %; in relation to these mixtures a saving of 13 % could be attributed to lower plant energy consumption and a further 5 % saving due to the recycled content. This demonstrates the importance of pursuing both recycling and LTA technologies. In particular, LTA technologies which do not have to overcome the latent heat of vaporisation during heating may realise considerable benefits compared to those mixed above 100 °C. In the latter instance, increasing RA content will realise a greater yield in terms of overall benefit.

To maximise energy efficiency during production of asphalt, operations should be carefully planned to avoid repeatedly switching between hot and lower-temperature mixtures.

8.3 Factors influencing the selection of low temperature asphalt

8.3.1 Dependence on choice of system

The temperature range at which asphalt can be mixed is dependent on the ability of the binder to completely coat all aggregate particles. The techniques and admixtures used for LTA need to create a mechanism by which that coating can occur at lower than normal temperatures, whether by reducing the viscosity at the mixing temperature, emulsifying the bitumen, increasing the binder volume by foaming or some other method.

The temperature range over which asphalt can be successfully compacted will also depend on the mechanical properties of the mix; it needs to be sufficiently stiff to maintain its integrity within the compaction equipment but the aggregate particles need to be sufficiently mobile to move into a more compact orientation without damage. The temperature range for compaction needs to be sufficiently wide to allow the required level of compaction across the whole mat and the bottom end of the range needs to be above the temperature that the pavement may reach in its working life (Nicholls and Daines, 1993), if strength development is purely temperature-related (i.e. not due to emulsion or foam technologies)

Therefore, the reduction in temperature that a LTA technology can achieve for a mixture needs to be determined and may change between different mixtures using the same system. The effectiveness of mixing and compaction at the reduced temperature needs to be assessed because inadequate mixing or compaction will result in less durable asphalt.

Another concern is the possibility that the water that is introduced into the material in order to allow the temperature reduction is not fully removed. Furthermore, the lower temperatures used mean that any residual moisture present in the aggregates are likely to cause issues. The effect of any water present will depend on the water sensitivity of the aggregate/binder combination and the ease with which such moisture can, or can be forced to, leave the mixture.

8.3.2 Medium-term durability data

Ideally, there would be extensive durability data available for each system, along with its carbon footprint and cost, so that a rational choice can be made between systems. However, there is only limited and relatively short term information available on a subset of the systems currently available. The data that is available indicates a broad equivalence between LTA and HMA.

Ideally, a systematic compilation of the data available on each system, including any detrimental aspects, should be compiled so that the expected performance can be established. This activity could be undertaken by or for the supplier, but any compilation which ignores negative aspects of the system will invalidate the findings. Such reviews could then be combined to produce guidance on the durability produced with different LTA technologies, which could then be compared. Also, any conflicting data could be investigated to see if there are other factors affecting the performance.

8.3.3 Long-term durability

There are no data on the condition of sites with LTA that have been in place for ten or more years, the minimum expected life of a typical HMA mixture, because the uptake of LTA technologies was too recent. Therefore, the longer-term durability of LTA cannot be assessed as yet from in-service performance.

8.3.4 Workmanship

The main issues of workmanship for LTA are similar to those for HMA. The mixture needs to be heated to the required temperature for mixing but not too much higher, transported in insulated wagons for a limited time, placed on the substrate by paver or hand-laid and given sufficient compaction to provide a low air voids content and a good profile. However, operatives will need to learn the "look" of these materials at each stage before they will be able to provide the best workmanship. The familiarity stage is typical for the introduction of any 'new' material. This was the case, for example, when thin surfacing systems and high modulus base and binder materials were introduced.

The aspect that, perhaps, requires the most care with LTA systems is compaction, particularly the compaction of joints. Although both the mixing and compaction temperatures are reduced, the available temperature range, and hence time, during which compaction can be undertaken is significantly shortened. The compaction of joints, generally a weak spot in any paving, is an issue requiring particular care.

At least until the performance of LTA is fully documented and understood, monitoring of the performance is required in order to ensure equivalence with the conventional HMA. Such monitoring will be vital if the LTA systems are to get wider acceptability within the highway industry.

8.4 The way forward

8.4.1 CEN Roadmap for European standards

A roadmap for incorporating LTA mixtures within the BS EN 13108 series was accepted in April 2014 by Working Group 1 (WG1) of Comité Européen de Normalisation (CEN) technical Committee 227 (TC227), where WG1 is responsible for bituminous mixtures. The road map is needed because BS EN 13108 was originally drafted with HMA mixtures in mind, HMA being the predominant material at the time and all asphalt was assumed to be HMA. Since that time, warm mix asphalt, half-warm mix asphalt and cold mix asphalt products have been developed and placed on the market. The status of such mixtures was uncertain because the product standards do not state whether or not they are included. The only explicit requirement in BS EN 13108 that would have excluded such LTA mixtures was for a minimum temperature, but that was removed in the 2008 amendments.

The roadmap implies that:

- The asphalt product standards will cover the relevant types of LTA mixture for all standards when using hot bitumen (i.e. not emulsified).
- The draft product standard for emulsion-based asphalts will need to be completed.
- The Assessment and Verification of Constancy of Performance (AVCP) – Type Testing and Factory Production Control - standards will need to have additional requirements or Annexes for emulsion-based asphalts, primarily to deal with curing and testing protocols.
- The test methods will be retitled "Bituminous mixtures – Test Methods – Part …" and the scope refined, when necessary, with regard to the mixture types to which they apply.
- Additional test method standards are to be produced to cover the sample preparation and curing procedures which may be required for some LTA mixtures.
- Additional test method standards are to be produced to cover properties relevant only for some LTA mixtures.

The time scale for the completion of the roadmap is considerable because the necessary changes are not incorporated into the current revision of the BS EN 13108 and the next revision of BS EN 13108 will not be completed before 2025.

8.4.2 Possible UK roadmaps for wider use of lower temperature asphalt

8.4.2.1 Options considered

Currently, the use of LTA on the SRN requires a departure from standards. In order to increase the take-up and application of these products, three alternative options for a UK Roadmap are discussed. These options are:

- The development of a national specification (Section 8.4.2.2).
- A certification system based primarily on laboratory properties (Section 8.4.2.3).
- A self-certification system based on type approval installation trials (Section 8.4.2.4).

If required, a system could be developed combining aspects from two or more of these options. However, any system would need to be complementary to the existing and future harmonised CEN standards. Therefore, clear guidelines need to be drawn up as to which mixture types are comprehensively covered by current documents (including BS EN 13108, BS 594987 and the Specification for Highway Works [SHW]), which mixture types are partially covered and which mixture types are not covered at all. If partial coverage, the guidance should include which aspects are and which are not covered.

Regardless of the option taken forward, any documents developed as part of the UK roadmap will require regular revision as the CEN Roadmap comes into play. However, the CEN Roadmap will only apply to the mixture "in the back of the lorry" and not as placed. As such, a considerable amount of the UK Roadmap will need to remain in place.

8.4.2.2 Development of a national specification

A proposed specification for different categories of LTA (PPR666, Nicholls *et al.*, 2013) has been drafted for use in procuring such mixtures prior to the BS EN 13108 series being revised to specifically include them (though not necessarily in a temperature categorised format). Limited details are given on national implementation and application because of the potential performance differences between different LTA technologies, and hence their applicability for routine use.

If the specification in PPR666 is to be developed further, the requirements will need to be tightened up for the different LTA technologies. The starting point will be a methodology to group different systems together by the approach they take rather than treating each system separately because this could introduce the appearance of a proprietary bias. However, because different technologies may require different requirements on at least some aspects, the result will be either a complicated new single clause in the SHW with each section having to define which technology or technologies it applies to or a series of similar new clauses, each relevant to a different technology. If multiple clauses are drafted, ideally all clauses would be published together unless there were definite reasons for staged publication, such as the differing extent of data on different technologies.

The introduction of completely new systems utilising a completely new technology will require extending the clause(s) once that technology is considered to have been proven. However, any delay could be seen as a barrier to trade. The approach currently set out in PPR666 and implicitly in much of the CEN Roadmap assumes that the properties of LTA mixtures can be measured using the same test procedures as those for HMA. Whilst that is generally true for the test procedures, it is not the case with many of the laboratory preparation procedures. As far as possible, the test methods should be the same in order to provide confidence in the LTA being equivalent to HMA mixtures. However, the preparation procedures will need to be refined and revised in order to make them appropriate for all potential LTA systems.

8.4.2.3 Certification of laboratory test properties

LTA systems could be certified by an external body. A scheme would need to be developed to assess the performance of different systems which would be primarily based on laboratory or pilot-scale trials but could also include site trials. For systems considered to be covered by a harmonised CEN standard, many of the properties would already be covered by the CE Marking, but the properties of the laid material will need to be checked for all systems in order to ensure the capability to achieve satisfactory installation and provide adequate durability. The certificate would need to define any constraints (environmental, trafficking, travelling time, etc.) that may need to be applied for that system.

Because the performance is assessed on the basis of laboratory test results, the relevance of tests developed for HMA mixtures (and preparation procedures) is again a concern. However, the use of pilot-scale and site trials should limit the need for relevant laboratory preparation procedures. The need to use a certificated system for LTA would need to be incorporated into the SHW.

8.4.2.4 Type approval installation trials

The approach for self-certification using a type approval installation trial (TAIT) is similar to product certification except that the performance is primarily based on the performance of the pavement at a number of site trials rather than the properties of the asphalt mixture. The documentation could be produced internally by the supplier, although the supplier would need an external body to prepare the report to demonstrate its independence. The minimum data required from the site trials will need to be given in the SHW together with guidance on how to determine the constraints on the demonstrated suitability of use for that system and any other constraints on its use. The need to use an LTA system with a TAIT relevant to the intended site would also need to be incorporated into the SHW.

8.4.2.5 Comparison of options

The principal advantages and disadvantages of three approaches are listed in Table 8-2 with a code of one to three (to indicate strength) either (to indicate an advantage) or (to indicate a disadvantage). The following seven aspects are covered in the table.

- <u>Applicability to new techniques:</u> The ease with which the approach can accommodate a totally new technique; the national specification approach will require new sub-clauses and possibly laboratory preparation procedures drafted; the laboratory certification approach may require laboratory preparation procedures to be drafted; the TAIT approach should not require any changes.
- <u>Standardised preparation procedures</u>: The standardisation of laboratory procedures for the preparation of samples for testing; the national specification and laboratory certification approaches will require them; the TAIT approach should not (although laboratory tests could be included).

- Central documentation: The extent to which specifications and associated documentation to define the approach will need to be drafted and subsequently updated; the national specification approach would require full documentation; the laboratory certification approach would require the full assessment and interpretation methodologies drafted; the TAIT approach would only require the assessment methodology drafted.
- Cost to supplier: The cost for a supplier to get approval of their system over and above normal costs in supplying the material; the national specification approach does not require approval; the laboratory certification approach requires considerable extra laboratory tests; the TAIT approach requires additional monitoring.
- Assurance for client: The assurance that is given where the approach is fully complied with; all approaches should provide assurance; the national specification and laboratory certification approaches provide assurance about the properties attained; the TAIT approach provides assurance of performance on site.
- Implementation time: The time that is required for a system to be capable of being applied on the SRN; the national specification approach can be used at any time; the laboratory certification approach requires extensive laboratory testing; the TAIT approach requires time for the sites to be laid and monitored for the required period.
- Validation: The extent to which complying systems have been validated in use; the national specification and laboratory certification approaches are validated against laboratory performance; the TAIT approach is validated against site performance.

Table 8-2: Advantages and disadvantages of each approach

Aspect	National specification	Laboratory certification	TAIT
Applicability to new techniques	👎	👍	👍👍👍
Standardised preparation procedures	👎👎	👎👎	–
Central documentation	👎👎👎	👎👎	👎
Cost to supplier	–	👎👎👎	👎
Assurance for client	👍	👍	👍👍
Implementation time	👍	👎👎	👎👎👎
Validation	👎	👎	👍👍👍

The approach with the greatest advantages appears to be the TAIT process.

9 Conclusions

The demonstration site on the A5 Grendon has confirmed previous experience on other sites that the production and application of both LTA and HMA mixtures are similar and can be achieved in practice with the right amount of care and checks in place.

The following conclusions were drawn from the demonstration site:

1. The LTA could be laid successfully provided appropriate care was taken. There were similar comments from operatives about both LTA and HMA mixtures.
2. LTA mixtures appear to require a higher level of control to ensure that adequate compaction is achieved.
3. An increased proportion of reclaimed asphalt was successfully employed in the mixtures at lower target mixing temperatures.
4. Temperature monitoring of the mat showed that neither the HMA nor LTA had cooled to ambient temperature at the time that the renewed section was reopened to traffic. The surface temperature of the HMA was around 60 °C and the LTA 30 °C at the time of reopening, whereas ambient was around 6 °C. Temperature monitoring of the mat showed the LTA had cooled to about 25 °C in the mat with a surface temperature of 30 °C at opening. The corresponding HMA mat and surface temperature were about 45 °C and 60 °C respectively.
5. Thermography was demonstrated to be a potentially useful tool. It can highlight potential inconsistencies (variability) in temperature across the mat and 'cold spots' that may later give rise to defects in the material.
6. The carbon footprint calculation using asPECT v4.0 indicates a cradle-to-gate CO_2e saving in the region of 13-16 % associated with the use of LTA materials over their conventional HMA alternatives, which can purely be attributed to energy savings at the mixing plant. The works in total at Grendon on the night of the trial saved 0.7 tCO_2e by replacing approximately half of the conventional HMA with LTA alternatives. If LTAs had replaced all conventional materials used then the saving would have been in the region of 1.6 tCO_2e.

Testing of laboratory prepared samples of both LTA and HMA materials gave comparable properties for compactibility, deformation resistance and stiffness. Water sensitivity testing indicated slightly higher susceptibility of LTA. However, samples taken from sites where the material had been laid previously has shown a large variation in air voids content, and hence stiffness, for the LTA materials. Similarly, the in situ density measurements on the binder course layer on the demonstration site showed greater variability in the LTA compared with the conventional HMA. This would seem to indicate that stricter quality control procedures may be needed on site for LTA materials. The limited amount of data gathered with regard to fatigue meant that meaningful conclusions could not be drawn.

The review of available data on the durability of LTA systems both nationally, in the USA and in Scandinavia found that the initial performance is generally equivalent to that of HMA, but that sections had to monitored over longer timescales than are currently possible to confirm the longer-term durability.

Overall, the monitoring of sites supports the use of LTA mixtures in routine construction and maintenance of road pavements with appropriate quality control measures in place.

As a result of the wide variation in technologies to produce LTA mixtures, and the additional care that may be required during installation, sites should be monitored to confirm that materials are suitable for routine use. It is also important to establish the criteria for their acceptance because these may differ from those for HMA and could also differ between various LTA technologies.

With regard to implementation by the Highways Agency in the UK, a number of options for a roadmap are presented that could be used to encourage the wider use of LTA mixtures on the SRN. The key routes to implementation are:

- The development of a national specification;
- A certification system based on primarily on laboratory properties; and
- A self-certification system based on type approval installation trials.

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References

Artamendi, I (2014). Low temperature asphalt trial: A5 Grendon. *Report Ref. SL/001/2014* [email]. Personal communication. 20th May 2014.

Bullas, J C (2009). Thermographic imaging and improving bituminous materials. Atkins: Southampton. [Available at: http://www.academia.edu/1739272/Thermographic-Imaging_of_New_Bituminous_Construction, last accessed September 2014].

British Standards Institution (2010). Asphalt for roads and other paved areas – Specification for transport, laying, compaction and type testing protocols. *BS 594987:2010.* London: British Standards Institution.

Comité Européen de Normalisation (2003a). Bituminous mixtures – Test methods for hot mix asphalt – Part 8: Determination of void characteristics of bituminous specimens. *BS EN 12697-8:2003*. London: British Standards Institution.

Comité Européen de Normalisation (2003). Bituminous mixtures – Test methods for hot mix asphalt – Part 23: Determination of the indirect tensile strength of bituminous specimens. *BS EN 12697-23:2003*. London: British Standards Institution.

Comité Européen de Normalisation (2005a). Bituminous mixtures – Test methods for hot mix asphalt – Part 3: Binder recovery; Rotary evaporator. *BS EN 12697-3:2005*. London: British Standards Institution.

Comité Européen de Normalisation (2005b). Bituminous mixtures – Test methods for hot mix asphalt – Part 25: Cyclic compression test. *BS EN 12697-25:2005*. London: British Standards Institution.

Comité Européen de Normalisation (2006a). Bituminous mixtures – Material specifications – Part 1: Asphalt concrete. *BS EN 13108-1:2006*. London: British Standards Institution.

Comité Européen de Normalisation (2006b). Bituminous mixtures – Material specifications – Part 20: Type testing. *BS EN 13108-20:2006*. London: British Standards Institution.

Comité Européen de Normalisation (2007a). Bitumen and bituminous binders – Determination of needle penetration. *BS EN 1426:2007*. London: British Standards Institution.

Comité Européen de Normalisation (2007b). Bitumen and bituminous binders – Determination of softening point – Ring and ball method. *BS EN 1427:2007*. London: British Standards Institution.

Comité Européen de Normalisation (2007c). Bituminous mixtures – Test methods for hot mix asphalt – Part 22: Wheel tracking. *BS EN 12697-22:2003+A1:2007*. London: British Standards Institution.

Comité Européen de Normalisation (2007d). Bituminous mixtures – Test methods for hot mix asphalt – Part 33: Specimen prepared by roller compactor. *BS EN 12697-33:2003+A1:2007*. London: British Standards Institution.

Comité Européen de Normalisation (2008). Bituminous mixtures – Test methods for hot mix asphalt – Part 12: Determination of water sensitivity of bituminous specimens. *BS EN 12697-12:2008*. London: British Standards Institution.

Comité Européen de Normalisation (2009). Bituminous mixtures – Test methods for hot mix asphalt – Part 5: Determination of the maximum density. *BS EN 12697-5:2009*. London: British Standards Institution.

Comité Européen de Normalisation (2010). Bituminous mixtures – Test methods for hot mix asphalt – Part 40: Crack propagation by semi-circular bending test. *BS EN 12697-44:2010*. London: British Standards Institution.

Comité Européen de Normalisation (2012a). Bituminous mixtures – Test methods for hot mix asphalt – Part 39: Binder content by ignition. *BS EN 12697-39:2012*. London: British Standards Institution.

Comité Européen de Normalisation (2012b). Bituminous mixtures – Test methods for hot mix asphalt – Part 6: Determination of bulk density of bituminous specimens. *BS EN 12697-6:2012*. London: British Standards Institution.

Comité Européen de Normalisation (2012c). Bituminous mixtures – Test methods for hot mix asphalt – Part 26: Stiffness. *BS EN 12697-26:2012*. London: British Standards Institution.

Comité Européen de Normalisation (2012d). Bituminous mixtures – Test methods for hot mix asphalt – Part 24: Resistance to fatigue. *BS EN 12697-24:2012*. London: British Standards Institution.

Defra (2014). Government Greenhouse Gas Conversion Factors for Company Reporting. London: Defra. [Available at: http://www.ukconversionfactors-carbonsmart.co.uk/, last accessed September 2014].

Environmental Working Group (2011). Full Lifecycle Greenhouse Gas Emissions from Common Proteins and Vegetables. Washington: EWG. [Available at: http://www.ewg.org/meateatersguide/a-meat-eaters-guide-to-climate-change-health-what-you-eat-matters/climate-and-environmental-impacts, last accessed September 2014].

European Asphalt Paving Association (EAPA) (2014). The use of warm mix asphalt. Brussels: EAPA. [Available at: http://www.eapa.org/userfiles/2/Publications/-EAPA%20paper%20-%20Warm%20Mix%20Asphalt%20-%20version%202014.pdf, last accessed September 2014].

Highways Agency, Transport Scotland, Welsh Assembly Government and The Department for Regional Development Northern Ireland (2008). Road pavements – Bituminous bound materials. *Manual of Contract Documents for Highway Works, Volume 1: Specification for Highway Works, Series 900*. London: The Stationery Office, London. [Available at: www.dft.gov.uk/ha/standards/mchw/vol1/pdfs/ series 0900.pdf, last accessed May 2014].

Mollenhauer, K, C Nicholls, A Varveri, A Tabaković, C McNally and A Gibney (2014). Effects of constituent materials, recycled and secondary sources materials and construction conditions on pavements durability derived from literature and site data review. *EARN deliverable D3*. www.trl.co.uk/solutions/road-rail-infrastructure/sustainable-infrastructure/earn/.

National Asphalt Pavement Association (NAPA) (2014). Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009-2013. [Available at: http://www.asphaltpavement.org/PDFs/IS138/IS138-2013 RAP-RAS-WMA Survey Final, last accessed February 2015].

Nicholls, J C, and M E Daines (1993). Acceptable weather conditions for laying bituminous materials. *TRL Project Report PR13*. Crowthorne: TRL Limited.

Nicholls, J C and D James (2011). Literature review of lower temperature asphalt systems. Proceedings of the Institution of Civil Engineers – Construction Materials. London: Thomas Telford.

Nicholls, J C, H K Bailey, N Ghazireh and D H Day (2013). Specification for low temperature asphalt mixtures. *TRL Report TRL666*. Crowthorne: TRL Limited.

Nicholls, J C, N Ghazireh and D H Day (2014). Site trials and specification for lower temperature asphalts. *Proceedings of the Institution of Civil Engineers – Construction Materials*. London: Thomas Telford.

Sabin, P (2014). Energy consumption data for Haughmond Hill asphalt plant in 2012 [email]. Personal communication. 8th July 2014.

Wayman, M, Schiavi-Mellor, I & Cordell, B (2014). Protocol for the calculation of whole life cycle greenhouse gas emissions generated by asphalt. *TRL Report PPR575 (version 4.0)*. Crowthorne: TRL Limited.

Appendix A CE mark reports

A.1 Mixture 1, LTA Binder course

CE

0086

Aggregate Industries UK Ltd, Bardon Hill, Coalville, Leicestershire, LE67 1TL
0086-CPR-533859
2014
CNSUPERLASTING1920A-1/1342051

EN 13108-1
Asphalt concrete for roads and other trafficked areas
AC 20 HDM bin 40/60 des NS
Haughmond Hill Asphalt
MRSUPERLASTING1920A-1/1342051

Grading (passing)	
31,5 mm sieve	100%
20 mm sieve	95%
14 mm sieve	75%
6,3 mm sieve	47%
2 mm sieve	30%
0,25 mm sieve	15%
0,063 mm sieve	7.0%
Binder Content	$B_{min4,6}$(4.6 %)
Temperature of the mixture	80-110°C
Void Content	
- minimum	NPD
- maximum	NPD
Voids content after 10 Gyrations	
- minimum	NPD
Stiffness	
- minimum	NPD
- maximum	NPD
Resistance to permanent deformation (ssd)	
- small size device: max. wheel tracking slope	NPD
- small size device: max. proportional rut depth	NPD
Resistance to permanent deformation (lsd)	
- large size device: proportional rut depth	NPD
Resistance to fatigue	NPD
Water sensitivity	NPD
Resistance to permanent deformation in triaxial compression	NPD
Reaction to fire	NPD
Dangerous substances	NPD
Resistance to abrasion by studded tyres	NPD
Resistance to fuel for application on airfields	NPD
Resistance to de-icing fluids for application on airfields	NPD
Marshall Values for application on airfields	
- Minimum Stability	NPD
- Maximum Stability	NPD
- Flow	NPD
- Quotient	NPD
Voids filled with bitumen (BS EN 13108-20:2006 D.2)	
- minimum	NPD
- maximum	NPD
Voids in Mineral aggregate	
- minimum	NPD

No Performance Determined (NPD) for the following properties

Additional Information:
The binder content detailed on the above certificate is declared in accordance with EN13108; the actual material target binder content is 4.4%

Valid From: 23/05/14

A.2 Mixture 2, LTA Surface course

Product: **Hitex AC 14 Surf PMB PSV65 13108-1 SUPERLASTING**
Aggregate Industries Product Code: SUPERLASTING8634H

AGGREGATE INDUSTRIES

CE

0086

Aggregate Industries UK Ltd, Bardon Hill, Coalville, Leicestershire, LE67 1TL
0086-CPR-533859
2014
CNSUPERLASTING8634H-1/1342051

EN 13108-1
Asphalt concrete for roads and other trafficked areas
AC 14 surf pmb PSV 65
Haughmond Hill Asphalt
MRSUPERLASTING8634H-1/1342051

Grading (passing)	
20 mm sieve	100%
14 mm sieve	95%
10 mm sieve	67%
6,3 mm sieve	45%
2 mm sieve	24%
0,063 mm sieve	6.5%
Binder Content	$B_{min5,4}$(5,4 %)
Temperature of the mixture	80-110°C
Void Content	
- minimum	NPD
- maximum	NPD
Voids content after 10 Gyrations	
- minimum	NPD
Stiffness	
- minimum	NPD
- maximum	NPD
Resistance to permanent deformation (ssd)	
- small size device: max. wheel tracking slope	NPD
- small size device: max. proportional rut depth	NPD
Resistance to permanent deformation (lsd)	
- large size device: proportional rut depth	NPD
Resistance to fatigue	NPD
Water sensitivity	NPD
Resistance to permanent deformation in triaxial compression	NPD
Reaction to fire	NPD
Dangerous substances	NPD
Resistance to abrasion by studded tyres	NPD
Resistance to fuel for application on airfields	NPD
Resistance to de-icing fluids for application on airfields	NPD
Marshall Values for application on airfields	
- Minimum Stability	NPD
- Maximum Stability	NPD
- Flow	NPD
- Quotient	NPD
Voids filled with bitumen (BS EN 13108-20:2006 D.2)	
- minimum	NPD
- maximum	NPD
Voids in Mineral aggregate	
- minimum	NPD

No Performance Determined (NPD) for the following properties

Additional Information:
The binder content detailed on the above certificate is declared in accordance with EN13108, the actual material target binder content is 5.1%
SHW Binder by Volume = .0%
EME2 Richness Modulus = .00%

Valid From: 23/05/14

A.3 Mixture 3, HMA Binder course

Product: AC 20 HDM bin 40/60 des BS EN13108-1 HS
Aggregate Industries Product Code: 1920A

AGGREGATE INDUSTRIES

CE

0086

Aggregate Industries UK Ltd, Bardon Hill, Coalville, Leicestershire, LE67 1TL
0086-CPR-533859
2013
CN1920A-2/1342051

EN 13108-1
Asphalt concrete for roads and other trafficked areas
AC 20 HDM bin 40/60 des HS
Haughmond Hill Asphalt
MR1920A-2/1342051

Grading (passing)	
31,5 mm sieve	100%
20 mm sieve	95%
14 mm sieve	75%
6,3 mm sieve	47%
2 mm sieve	30%
0,25 mm sieve	15%
0,063 mm sieve	7.0%
Binder Content	$B_{min4,4}$ (4,4 %)
Temperature of the mixture	150-190°C

No Performance Determined (NPD) for the following properties

Void Content	*NPD*	*Voids Content after 10 Gyrations*	*NPD*
Stiffness	*NPD*	*Resistance to permanent deformation (ssd)*	*NPD*
Resistance to permanent deformation (lsd)	*NPD*	*Resistance to fatigue*	*NPD*
Water Sensitivity	*NPD*	*Resistance to permanent deformation in triaxial compression test*	*NPD*
Reaction to fire	*NPD*	*Dangerous substances*	*NPD*
Resistance to abrasion by studded tyres	*NPD*	*Resistance to fuel for application on airfields*	*NPD*
Resistance to de-icing fluids for application on airfields	*NPD*	*Marshall Values for application on airfields*	*NPD*
Voids filled with bitumen	*NPD*	*Voids in Mineral aggregate*	*NPD*

Additional Information:

Chris Hudson
Director of Asphalt Materials

Valid From: 01/01/14

Issue Date: 08/05/2014

A.4 Mixture 4, HMA Surface course

Product: Hitex AC 14 surf PMB BS EN13108-1 PSV65
Aggregate Industries Product Code: 8634H

AGGREGATE INDUSTRIES

CE

0086

Aggregate Industries UK Ltd, Bardon Hill, Coalville, Leicestershire, LE67 1TL
0086-CPR-533859
2013
CN8634H-2/1342051

EN 13108-1
Asphalt concrete for roads and other trafficked areas
AC 14 surf pmb PSV 65
Haughmond Hill Asphalt
MR8634H-2/1342051

Grading (passing)	
20 mm sieve	100%
14 mm sieve	95%
10 mm sieve	67%
6,3 mm sieve	45%
2 mm sieve	24%
0,063 mm sieve	6.5%
Binder Content	$B_{min5,6}$ (5,6 %)
Temperature of the mixture	150-190°C

No Performance Determined (NPD) for the following properties

Void Content	*NPD*	*Voids Content after 10 Gyrations*	*NPD*
Stiffness	*NPD*	*Resistance to permanent deformation (ssd)*	*NPD*
Resistance to permanent deformation (isd)	*NPD*	*Resistance to fatigue*	*NPD*
Water Sensitivity	*NPD*	*Resistance to permanent deformation in triaxial compression test*	*NPD*
Reaction to fire	*NPD*	*Dangerous substances*	*NPD*
Resistance to abrasion by studded tyres	*NPD*	*Resistance to fuel for application on airfields*	*NPD*
Resistance to de-icing fluids for application on airfields	*NPD*	*Marshall Values for application on airfields*	*NPD*
Voids filled with bitumen	*NPD*	*Voids in Mineral aggregate*	*NPD*

Additional Information:

Chris Hudson
Director of Asphalt Materials

Valid From: 01/01/14

Issue Date: 08/05/2014

Appendix B Photographs of demonstration site

Note: distances in Appendices B and C are measured from the easternmost extremity of the section, at approximate chainage 3180 m, with exact location (latitude 52.5826944°, longitude 001.5643611°), measured from the footway. The westernmost extremity of the section lies at (latitude 52.5834167°, longitude 001.5672778°).

B.1 Defects in original surfacing before planing

Figure B-1: General NB view at section start (Section 1900A5/170, ch. 0 m)

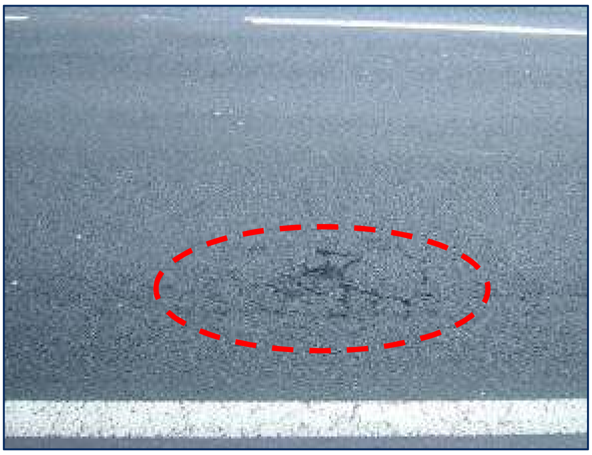

Figure B-2: General SB view, new TS (Section 1900A5/170, ch. 0 m)

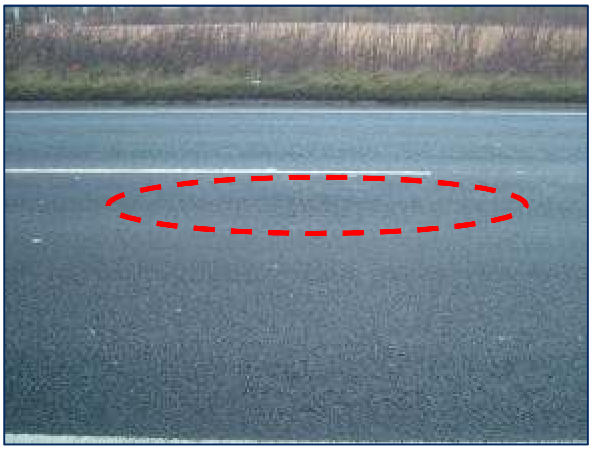

Figure B-3: General NB view, new TS (Section 1900A5/171, ch. 0 m)

Figure B-4: New TS changes to old surface (Section 1900A5/171, ch. 0 m)

Figure B-5: L crack(s) in OS edge of SB lane (Section 1900A5/171, ch. 0 m)

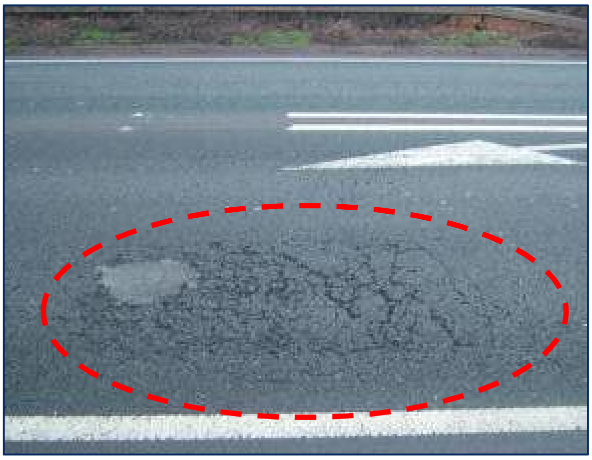

Figure B-6: L+T cracks in SB lane (Section 1900A5/171, ch. 0 m)

Figure B-7: General SB view - poor surface dressing (Section 1900A5/171, ch. 0 m)

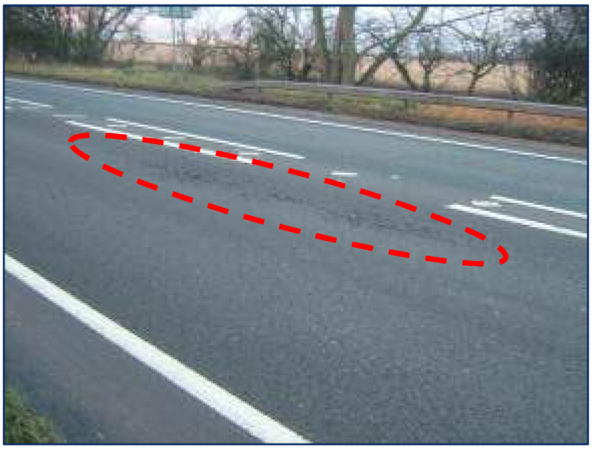

Figure B-8: T crack in SB lane (Section 1900A5/171, ch. 0 m)

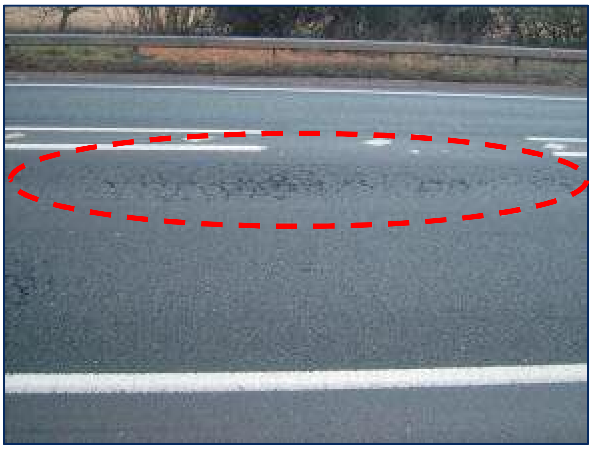

Figure B-9: Nodes at start of Section (NB lane) (Section 1900A5/157, ch. 0 m)

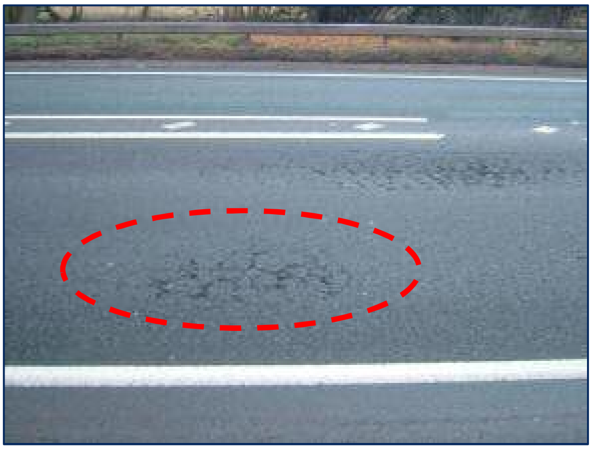

Figure B-10: Transverse cracks (NB lane) (Section 1900A5/157, ch. 17 m)

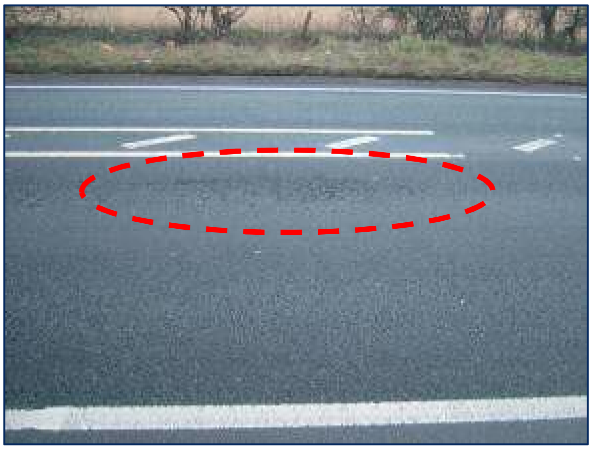

Figure B-11: T cracks (NB lane) 2229 (Section 1900A5/157, ch. 25 m)

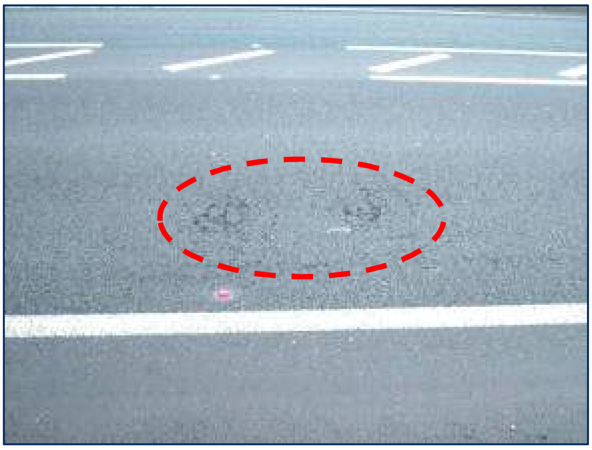

Figure B-12: L+T cracks (NB lane) 2230 (Section 1900A5/157, ch. 39 m)

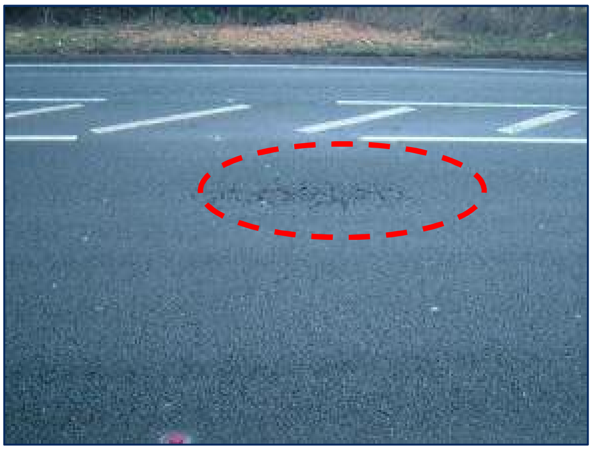

Figure B-13: (Section 1900A5/157, ch. 50 m)

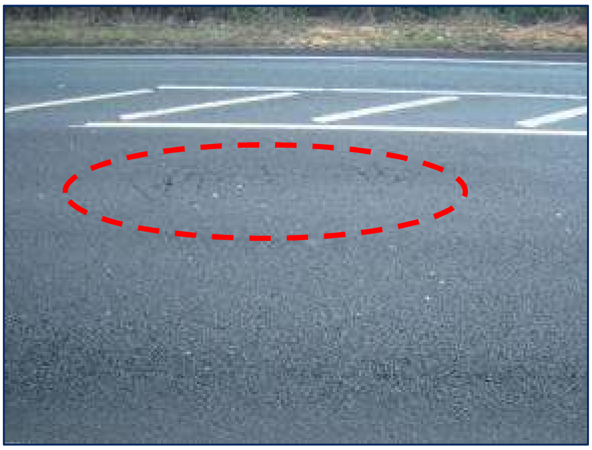

Figure B-14: (Section 1900A5/157, ch. 50 m)

Figure B-15: L crack in OS edge of SB lane (Section 1900A5/157, ch. 0 m)

Figure B-16: Section 1900A5/157, ch. 0 m

Figure B-17: Section 1900A5/157, ch. 0 m

Figure B-18: Section 1900A5/157, ch. 0 m

B.2 Planed surface and general photographs of paver

Figure B-19: Section 1900A5/157, ch. 77 m

Figure B-20: Section 1900A5/157, ch. 77 m

Figure 21: Section 1900A5/157, ch. 109 m

Figure B-22: Section 1900A5/157, ch. 126 m

Figure B-23: Section 1900A5/157, ch. 126 m

Figure B-24: Section 1900A5/157, ch. 0 m

Figure B-25: Section 1900A5/157, ch. 0 m

Figure B-26: Section 1900A5/157, ch. 0 m

Figure B-27: Section 1900A5/157, ch. 0 m

Figure B-28: Section 1900A5/157, ch. 0 m

Figure B-29: Section 1900A5/157, ch. 0 m

Appendix C Thermographic images

C.1 Binder course (LTA and HMA mixtures)

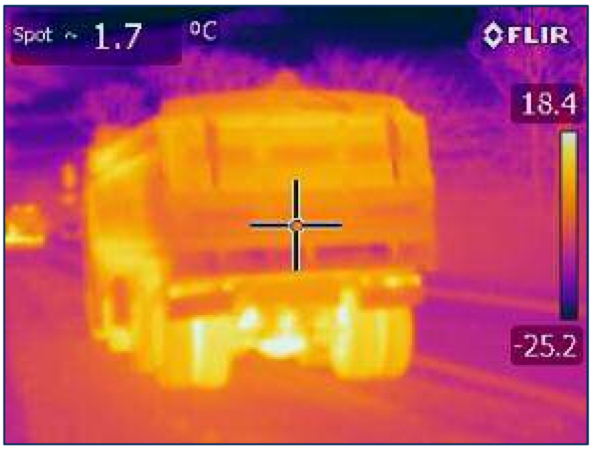

Figure C-1

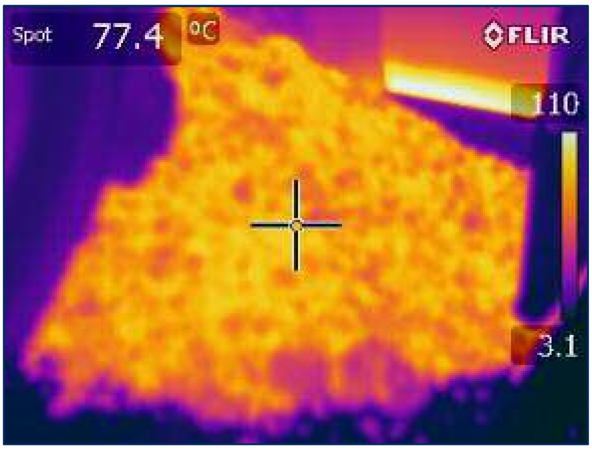

Figure C-2

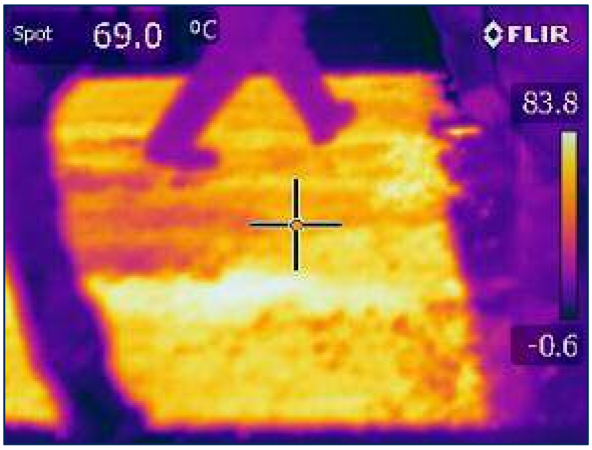

Figure C-3

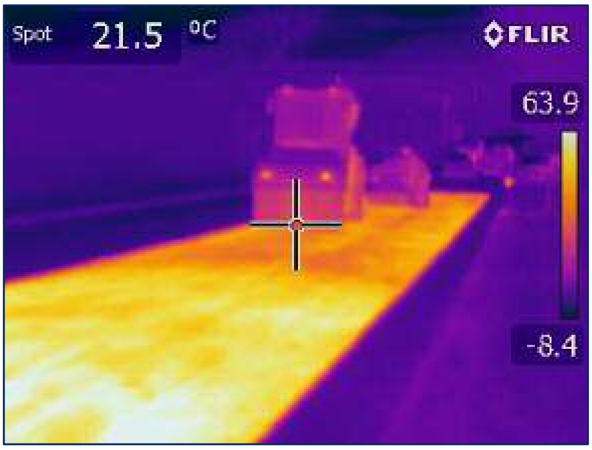

Figure C-4

Figure C-5

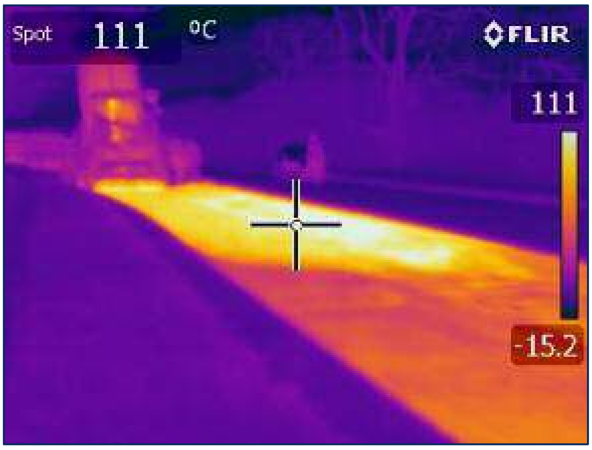

Figure C-6

Figure C-7

Figure C-8

Figure C-9

Figure C-10

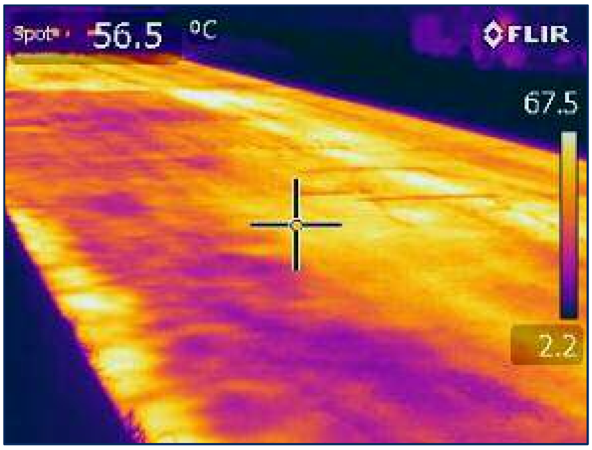

Figure C-11

Figure C-12

C.2 Surface course (LTA and HMA mixtures)

Figure C-13

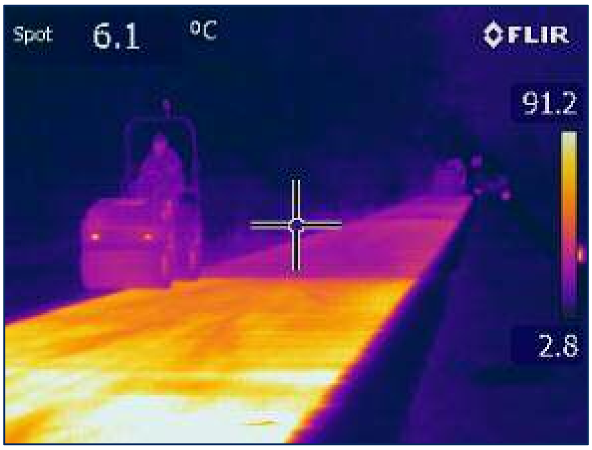

Figure C-14

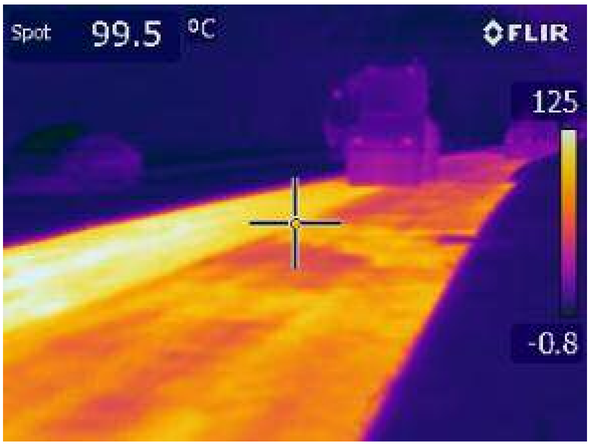

Figure C-15

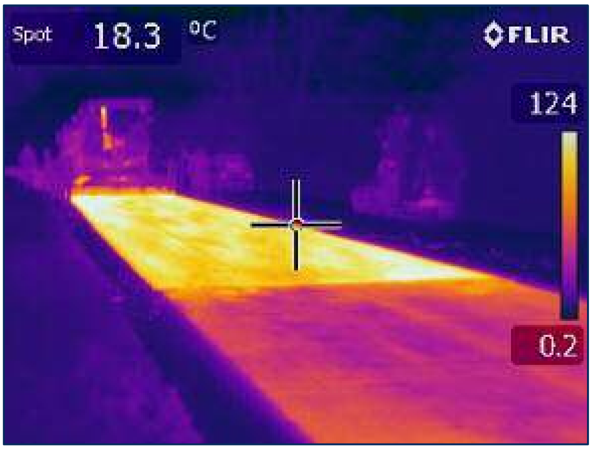

Figure C-16

Figure C-17

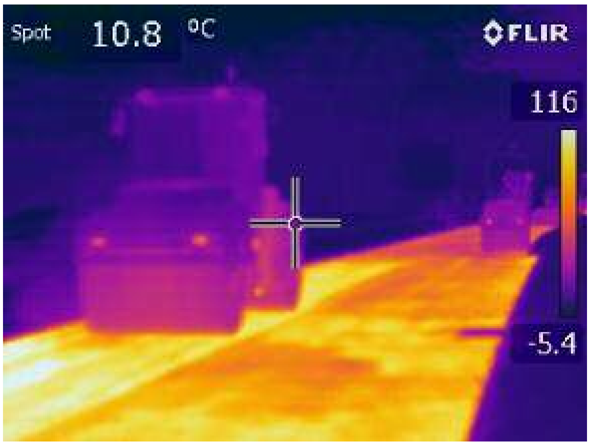

Figure C-18

C.3 LTA binder course at ch. 25 m over time

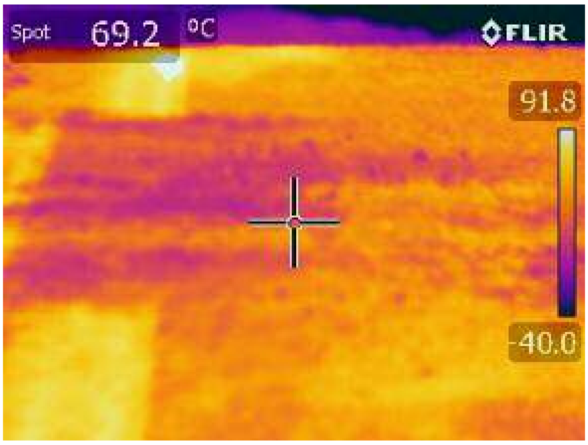

Figure C-19: After 20 s

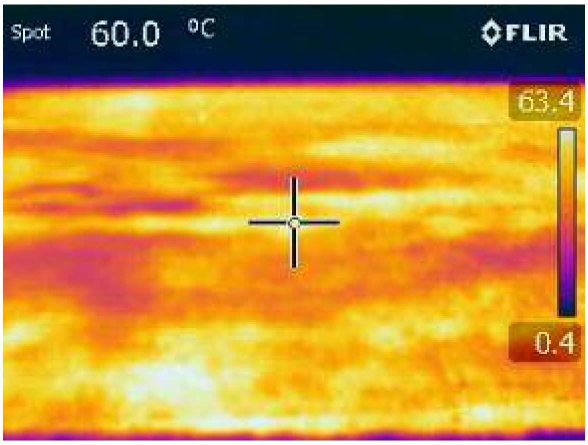

Figure C-20: After 15 min

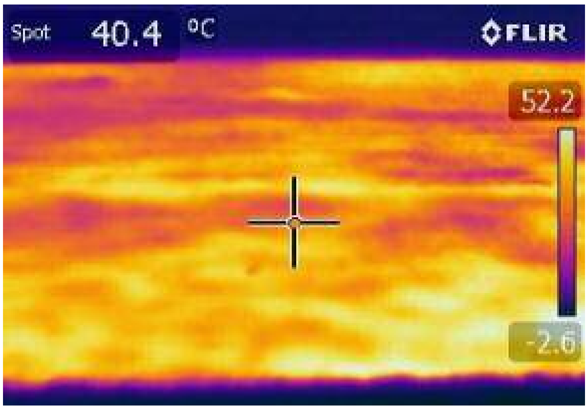

Figure C-21: After 30 min

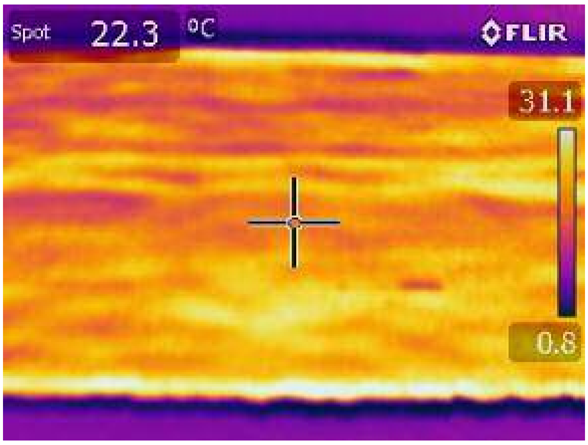

Figure C-22: After 45 min

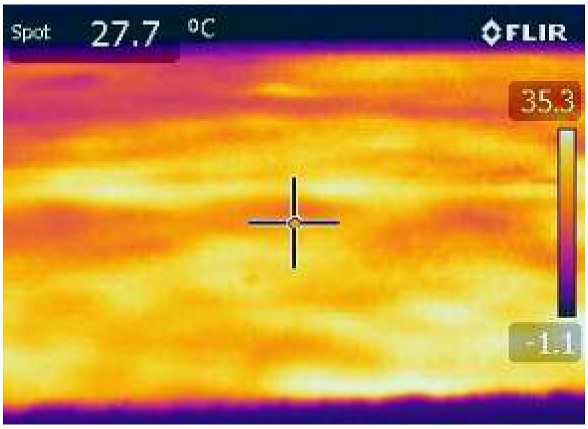

Figure C-23: After 60 min

C.4 LTA binder course at ch. 75 m over time

Figure C-24: After 35s

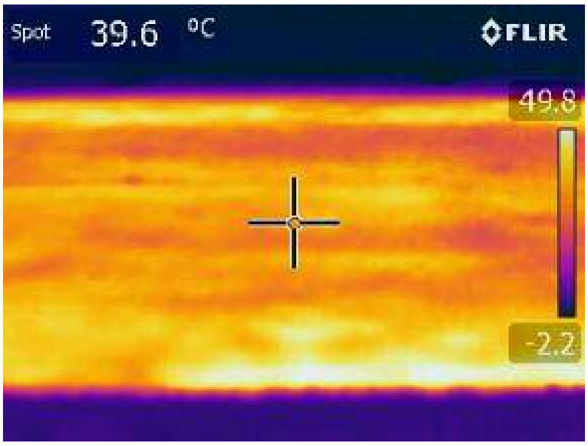

Figure C-26: After 35 min

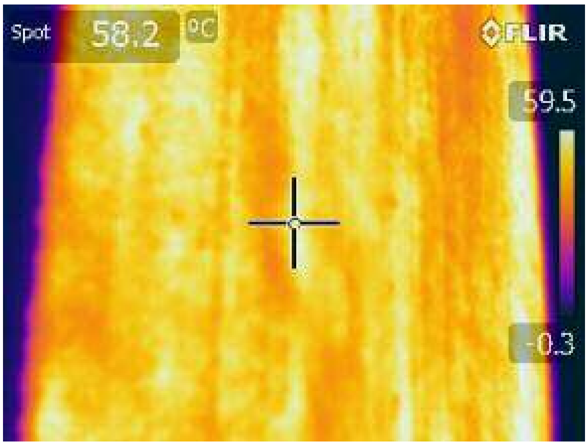

Figure C-25: After 15 min

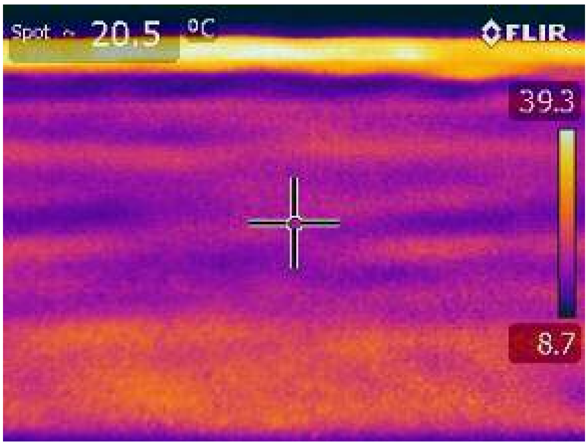

Figure C-27: After 50 min

C.5 HMA binder course at ch. 125 m over time

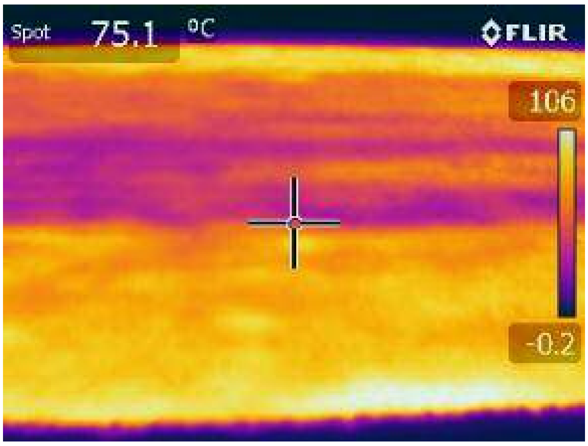

Figure C-28: After 11s

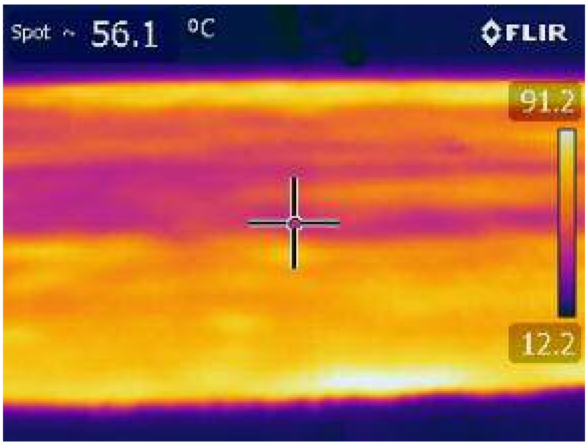

Figure C-29: After 15 min

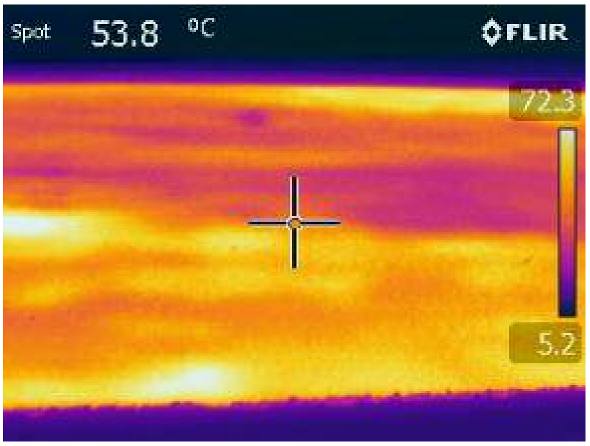

Figure C-30: After 35 s

C.6 LTA surface course at ch. 25 m over time

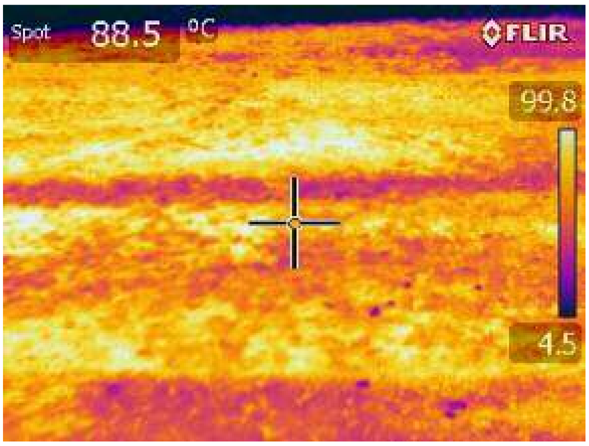

Figure C-31: After 2 min 33 s

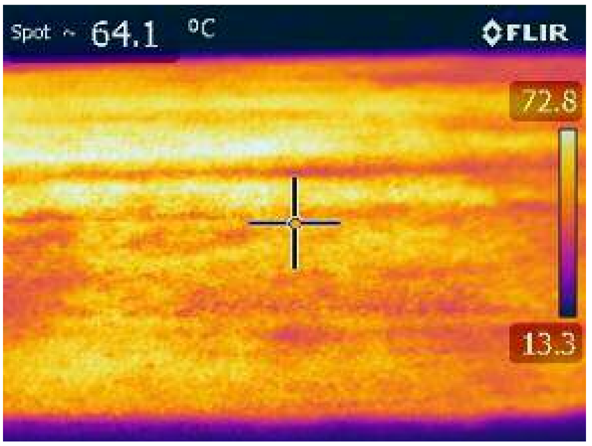

Figure C-32: After 15 min

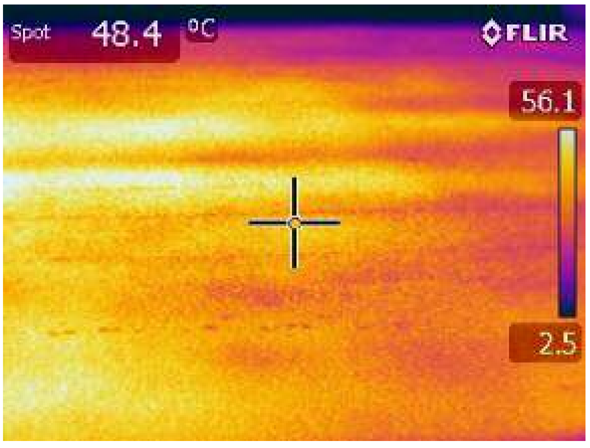

Figure C-33: After 35 min

C.7 LTA surface course at ch. 25 m over time

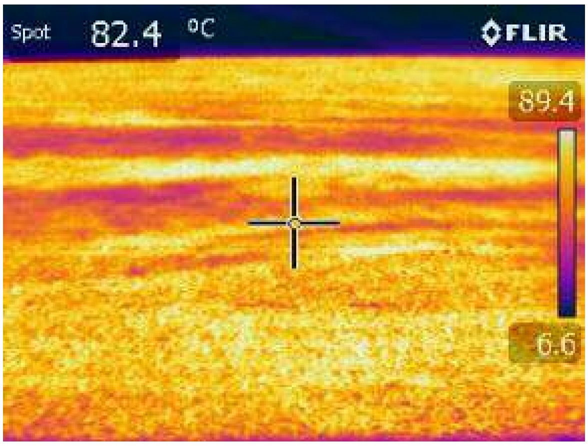

Figure C-34: After 2 min 52 s

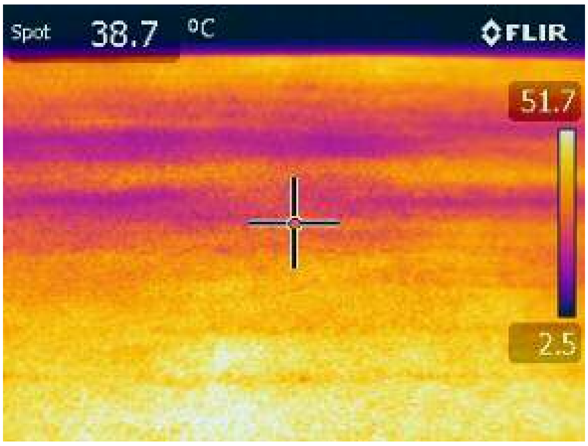

Figure C-35: After 23 min

Appendix D Laboratory results

D.1 Compositional analysis

Table D-1: Compositional analysis of mixtures

Sieve size (mm)	Proportion passing (%)					
	Binder course			Surface course		
	LTA	HMA	Limits	LTA	HMA	Limits
31.5	100	100	98 – 100	100	100	–
20	99	99	86 – 100	100	100	98 – 100
14	80	74	66 – 84	91	96	87 – 100
10	64	63	–	65	72	60 – 74
6.3	46	44	38 – 56	43	47	38 – 74
4	40	37	–	33	35	27 – 41
2	30	27	23 – 37	23	25	18 – 30
1	23	21	–	18	18	–
0.500	18	16	–	14	15	–
0.250	13	12	10 – 20	11	11	–
0.125	9	9	–	8	9	–
0.063	6.7	6.9	4.0 – 10.0	5.8	6.7	4.5 – 8.5
Binder content (%)	4.7	4.2	3.7 – 4.9	5.6	5.4	4.6 – 5.6

D.2 Density and air voids content of laboratory prepared samples

Table D-2: Density and air voids content results

Mix-ture	Sample	Max. density (Mg/m³)	Bulk density (Mg/m³)			Air voids content (%)		
			Proc. A	Proc. C	Proc. D	Proc. A	Proc. C	Proc. D
Mixture 1 (LTA binder course)	1	2.574	2.489	2.435	2.422	3.3	5.4	5.9
	2	2.574	2.483	2.434	2.395	3.5	5.4	7.0
	3	2.574	2.492	2.432	2.433	3.2	5.5	5.5
	4	2.574	2.478	2.418	2.384	3.7	6.1	7.4
	5	2.574	2.481	2.433	2.402	3.6	5.5	6.7
	6	2.574	2.481	2.421	2.410	3.6	5.9	6.4
	Mean	**2.574**	**2.484**	**2.429**	**2.408**	**3.5**	**5.6**	**6.5**
Mixture 2 (LTA surface course)	1	2.528	2.406	2.346	2.316	4.8	7.2	8.4
	2	2.528	2.397	2.316	2.267	5.2	8.4	10.3
	3	2.528	2.417	2.356	2.320	4.4	6.8	8.2
	4	2.528	2.413	2.343	2.320	4.5	7.3	8.2
	5	2.528	2.400	2.351	2.292	5.1	7.0	9.3
	6	2.528	2.394	2.317	2.291	5.3	8.3	9.4
	Mean	**2.528**	**2.405**	**2.338**	**2.301**	**4.9**	**7.5**	**9.0**

Mixture	Sample	Max. density (Mg/m³)	Bulk density (Mg/m³)			Air voids content (%)		
			Proc. A	Proc. C	Proc. D	Proc. A	Proc. C	Proc. D
Mixture 3 (HMA binder course)	1	2.587	2.483	2.396	2.369	4.0	7.4	8.4
	2	2.587	2.482	2.424	2.412	4.0	6.3	6.7
	3	2.587	2.480	2.414	2.386	4.1	6.7	7.8
	4	2.587	2.483	2.419	2.410	4.0	6.5	6.8
	5	2.587	2.476	2.394	2.361	4.3	7.5	8.7
	6	2.587	2.471	2.408	2.375	4.5	6.9	8.2
	Mean	**2.587**	**2.479**	**2.409**	**2.386**	**4.2**	**6.9**	**7.8**
Mixture 4 (HMA surface course)	1	2.535	2.392	2.331	2.297	5.6	8.0	9.4
	2	2.535	2.412	2.351	2.323	4.8	7.3	8.4
	3	2.535	2.396	2.348	2.298	5.5	7.4	9.3
	4	2.535	2.389	2.328	2.296	5.8	8.2	9.4
	5	2.535	2.383	2.317	2.267	6.0	8.6	10.6
	6	2.535	2.402	2.347	2.304	5.2	7.4	9.1
	Mean	**2.535**	**2.396**	**2.337**	**2.298**	**5.5**	**7.8**	**9.4**

D.3 Water sensitivity results

Table D-3: Water sensitivity results

Mixture	Samples	Dry		Wet		*ITSR*
		Density (Mg/m³)	ITS_d (kPa)	Density (Mg/m³)	ITS_d (kPa)	(%)
Mixture 1 (LTA binder course)	1/1 & 1/4	2.422	1711	2.433	1374	
	1/2 & 1/5	2.395	1689	2.384	1191	
	1/3 & 1/6	2.410	1789	2.402	1263	
	Mean	**2.409**	**1730**	**2.406**	**1276**	**74**
Mixture 2 (LTA surface course)	2/1 & 2/4	2.316	1018	2.320	834	
	2/2 & 2/5	2.267	970	2.292	849	
	2/3 & 2/6	2.320	1125	2.291	708	
	Mean	**2.301**	**1038**	**2.301**	**797**	**77**
Mixture 3 (HMA binder course)	3/1 & 3/4	2.396	1543	2.412	1494	
	3/2 & 3/5	2.410	1602	2.386	1555	
	3/3 & 3/6	2.375	1620	2.361	1326	
	Mean	**2.394**	**1588**	**2.386**	**1458**	**92**
Mixture 4 (HMA surface course)	4/1 & 4/4	2.297	932	2.323	844	
	4/2 & 4/5	2.296	937	2.298	915	
	4/3 & 4/6	2.304	1018	2.267	860	
	Mean	**2.299**	**962**	**2.296**	**873**	**91**

D.4 Cyclic compression results

Table D-4: Creep rate values of binder course mixtures

Mixture	Specimen No.	Density (Mg/m^3)	Air voids content (%)	Creep rate (microstrain/cycle)
Mixture 1 (LTA binder course)	A7098/C1	2.483	3.5	0.52
	A7098/C2	2.508	2.6	0.13
	A7098/C3	2.498	3.0	0.61
	A7098/C4	2.507	2.6	0.15
	Mean	**2.499**	**2.9**	**0.35**
Mixture 3 (HMA binder course)	A7098/C1	2.482	4.0	0.24
	A7098/C2	2.479	4.2	0.38
	A7098/C3	2.484	4.0	0.58
	A7098/C4	2.461	4.9	0.44
	Mean	**2.477**	**4.3**	**0.41**

D.5 Wheel-tracking results

Table D-5: Wheel-tracking results with large-size device

Property		Mixture 1	Mixture 2	Mixture 3	Mixture 4
Asphalt type		LTA		HMA	
Course		Binder	Surface	Binder	Surface
Compaction temperature (°C)		116.8	117.3	118.9	117.8
Bulk Density (kg/m^3)		2444	2356	2432	2365
Maximum density (kg/m^3)		2593	2569	2593	2569
Target air voids content (%)		5.0	7.0	5.0	7.0
Air voids content (%)		5.7	8.3	6.2	7.9
Test temperature (°C)		60	60	60	60
Mean specimen thickness (mm)		101.6	52.8	102.4	53.6
Proportional rut depth (%)	@ 1,000 cycles	2.6	3.3	2.2	2.6
	@ 3,000 cycles	3.5	4.2	2.8	3.7
	@ 10,000 cycles	4.8	4.6	3.9	3.9
	@30,000 cycles	5.6	5.3	4.7	4.6

Table D-6: Wheel-tracking results with small-size device to Procedure A

Property		Mixture 1		Mixture 2		Mixture 3		Mixture 4	
Asphalt type		LTA				HMA			
Course		Binder		Surface		Binder		Surface	
Sample		M1/1	M1/2	M2/1	M2/2	M3/1	M3/2	M4/1	M4/1
Specimen thickness (mm)		50	50	50	50	50	50	50	50
Density (Mg/m³)		2.451	2.449	2.387	2.392	2.453	2.444	2.399	2.4
Void Content, Vm (%)		5.5	5.6	7.1	6.9	5.4	5.7	6.6	6.6
Wheel-tracking rate (μm/cycle)	TR_{Air}	0.67	0.63	0.47	0.53	0.53	0.36	0.19	0.23
	WTR_{Air}	0.48		0.37		0.33		0.16	
Rut depth @ 1000 cycles (mm)	Ind.	2.4	2.43	1.97	1.98	1.94	1.47	1.32	1.33
	Mean	2.42		1.975		1.17		1.325	

D.6 Stiffness (CY-IT) results

Table D-7: CY-IT stiffness results

Material	Specimen No	Max. density (Mg/m³)	Density (Mg/m³)	Air voids content (%)	Stiffness (MPa)
Mixture 1 (LTA binder course)	A7098/A3	2.574	2.435	5.4	6011
	A7098/B2	2.574	2.418	6.1	4950
	A7098/B4	2.574	2.421	5.9	6574
	Mean	**2.574**	**2.425**	**5.8**	**5845**
Mixture 2 (LTA surface course)	A7100/A4	2.528	2.316	8.4	1873
	A7100/B1	2.528	2.356	6.8	2217
	A7100/B3	2.528	2.351	7.0	2290
	Mean	**2.528**	**2.341**	**7.4**	**2127**
Mixture 3 (HMA binder course)	A7099/A4	2.587	2.424	6.3	6836
	A7099/B1	2.587	2.414	6.7	6191
	A7099/B3	2.587	2.394	7.5	6085
	Mean	**2.587**	**2.411**	**6.8**	**6371**
Mixture 4 (HMA surface course)	A7101/A3	2.535	2.331	8.0	1800
	A7101/B1	2.535	2.348	7.4	1871
	A7101/B2	2.535	2.328	8.2	1766
	Mean	**2.535**	**2.336**	**7.9**	**1812**

D.7 Stiffness (4PB-PR) results

Table D-8: 4PB-PR stiffness results at 20 °C

Material	Replicate	Frequency (Hz)					
		0.5	1.0	2.5	5.0	8.0	10.0
Mixture 1 (LTA binder course)	1	4095	5014	6516	7716	8452	9288
	2	2748	3358	4302	5209	5541	6052
	3	4589	5684	7177	8641	9378	9698
	4	4643	5670	7187	8171	9388	9806
	5	3943	4806	5950	7317	8009	8379
	Mean	**4004**	**4906**	**6226**	**7411**	**8154**	**8645**
Mixture 2 (LTA surface course)	1	1224	1667	2461	3285	3744	4318
	2	1272	1723	2542	3422	3892	4339
	3	1153	1594	2371	3162	3643	4076
	4	1181	1632	2385	3242	3682	4128
	5	1190	1614	2396	3131	3750	4109
	Mean	**1204**	**1646**	**2431**	**3248**	**3742**	**4194**
Mixture 3 (HMA binder course)	1	4511	5485	7133	8285	9094	9296
	2	3924	4769	6086	7366	7812	8338
	3	4515	5441	7023	8118	9145	9344
	4	3370	4026	5304	5942	6823	6904
	5	4899	5845	7581	8804	9642	9992
	Mean	**4244**	**5113**	**6625**	**7703**	**8503**	**8775**
Mixture 4 (HMA surface course)	1	1157	1555	2300	3030	3560	3804
	2	1273	1702	2534	3141	3933	4121
	3	1149	1557	2305	2967	3620	3897
	4	1146	1554	2331	3023	3568	3959
	5	1214	1660	2444	3233	3531	4090
	Mean	**1188**	**1606**	**2383**	**3079**	**3642**	**3974**

Table D-9: 4PB-PR stiffness results at 15 °C

Material	Replicate	Frequency (Hz) 0.5	1.0	2.5	5.0	8.0	10.0
Mixture 1 (LTA binder course)	1	6979	8173	9694	11269	11882	12539
	2	4673	5531	6611	7663	8099	8568
	3	7226	8372	10088	11763	12283	12879
	4	7390	8583	10316	11793	12306	13170
	5	6238	7418	8924	10446	10980	11626
	Mean	**6501**	**7615**	**9127**	**10587**	**11110**	**11756**
Mixture 2 (LTA surface course)	1	2345	3084	4200	5382	5874	6501
	2	2316	3090	4210	5430	5893	6391
	3	2323	2952	3963	5109	5570	6253
	4	2313	3028	4121	5341	5794	6341
	5	2241	2940	4002	5142	5535	6216
	Mean	**2308**	**3019**	**4099**	**5281**	**5733**	**6340**
Mixture 3 (HMA binder course)	1	7197	8277	9586	11087	11953	12264
	2	5969	6905	8302	9127	10186	10424
	3	6968	8135	9480	10849	11849	12141
	4	5691	6456	7642	8537	9304	9527
	5	7516	8574	9916	11514	12243	12793
	Mean	**6668**	**7669**	**8985**	**10223**	**11107**	**11430**
Mixture 4 (HMA surface course)	1	2080	2746	3748	4884	5337	5710
	2	2167	2885	3778	4882	5392	5895
	3	2027	2686	3660	4645	5296	5624
	4	2017	2689	3594	4583	5147	5470
	5	2047	2711	3692	4618	5298	5632
	Mean	**2068**	**2743**	**3694**	**4722**	**5294**	**5666**

Table D-10: 4PB-PR stiffness results at 10 °C

Material	Replicate	Frequency (Hz)					
		0.5	1.0	2.5	5.0	8.0	10.0
Mixture 1 (LTA binder course)	1	9449	10593	12238	13559	14049	14792
	2	6364	7284	8357	9406	9830	10299
	3	10647	12230	13843	15361	16170	16574
	4	10495	11733	13397	15042	15578	16002
	5	9237	10322	11718	13220	13693	14458
	Mean	**9238**	**10432**	**11911**	**13318**	**13864**	**14425**
Mixture 2 (LTA surface course)	1	3739	4721	6018	7496	7969	8360
	2	3685	4730	5962	7322	7834	8533
	3	3927	4887	6287	7338	8351	8700
	4	3714	4560	5686	6936	7811	8131
	5	3902	4803	6187	7092	8266	8482
	Mean	**3793**	**4740**	**6028**	**7237**	**8046**	**8441**
Mixture 3 (HMA binder course)	1	9842	11217	12558	14038	14669	15298
	2	8238	9235	10720	11927	12381	13164
	3	10064	11156	12974	14571	15148	15732
	4	7786	8868	9888	11075	11551	11924
	5	9475	11102	12448	13918	14601	15020
	Mean	**9081**	**10316**	**11718**	**13106**	**13670**	**14228**
Mixture 4 (HMA surface course)	1	3371	4226	5539	6535	7472	7518
	2	3456	4359	5763	6471	7714	7838
	3	3335	4163	5517	6507	7456	7727
	4	3501	4296	5757	6488	7662	7898
	5	3431	4283	5613	6590	7577	7659
	Mean	**3419**	**4265**	**5638**	**6518**	**7576**	**7728**

D.8 Fatigue results

Table D-11: 4PB-PR fatigue results

Material	Sample	Max. density (Mg/m³)	Density (Mg/m³)	Air voids content (%)	Strain (μstrain)	Initial stiffness (MPa)	Cycles
Mixture 1 (LTA binder course)	1	2.574	2.338	9.2	150	9298	128293
	2	2.574	2.299	10.7	200	5381	11434
	3	2.574	2.392	7.1	150	10443	98551
	4	2.574	2.352	8.6	75	10801	3700000
	5	2.574	2.327	9.6	200	9945	1275
Mixture 2 (LTA surface course)	1	2.528	2.261	10.6	100	5470	1612550
	2	2.528	2.276	10.0	150	5612	368747
	3	2.528	2.248	11.1	150	5275	282274
	4	2.528	2.278	9.9	250	5426	42952
	5	2.528	2.269	10.2	250	5296	39732
Mixture 3 (HMA binder course)	1	2.587	2.321	10.3	150	10553	104903
	2	2.587	2.339	9.6	200	10863	10138
	3	2.587	2.322	10.2	200	8647	19809
	4	2.587	2.341	9.5	150	10008	79029
	5	2.587	2.320	10.3	200	9630	25201
	6	2.587	2.343	9.4	75	11481	375322
Mixture 4 (HMA surface course)	1	2.535	2.231	12.0	200	4537	79929
	2	2.535	2.231	12.0	250	4674	40544
	3	2.535	2.262	10.8	250	4952	38000
	4	2.535	2.266	10.6	150	5084	352884
	5	2.535	2.240	11.7	100	5284	1292968
	6	2.535	2.250	11.2	250	4905	42576
	7	2.535	2.250	11.3	150	5258	777736
	8	2.535	2.236	11.8	150	5250	448585
	9	2.535	2.254	11.1	120	5262	1325581
	10	2.535	2.277	10.2	100	5407	1489286

Appendix E Results from A1(M) Shincliffe

E.1 Core logs from A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	40	40	TS	14	GS	Very Voided	Intact	Y	-VE
2	40	104	64	DBM	20	GNT	Very Voided	Intact	Y	-VE
3	104	213	109	DBM	20	LST	Very Voided	Intact	Y	-VE
4	213	290	167	DBM	32	LST	Damage at base	De-Bonded	Y	-VE
5	290	399	109	DBM	32	LST	Sound	-	Y	-VE
6										
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7

Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150		
Project Code:	11112687 1		
Client:		**Coring Date:**	N/K
Project:	A1(M)	**TRL LMS Ref:**	133111 / 1
Location:		**Core Ref:**	1
		Logged by:	PH
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**	
Checked by:			

TRL Limited,
Crowthorne House,
Nine Mile Ride,
Wokingham.
RG40 3GA.
Tel: 01344 773131

Top of core photo:

Figure E-1: Core133111, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	40	40	TS	14	GS	Sound	Intact	Y	-VE
2	40	105	65	DBM	20	GNT	Very Voided	Intact	Y	-VE
3	105	200	95	DBM	32	LST	Very Voided	Intact	Y	-VE
4	200	284	84	DBM	32	LST	Very Voided	De-Bonded	Y	-VE
5	284	370	86	DBM	32	LST	Sound	-	N	-VE
6										
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7

Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150		
Project Code:	11112687 1		
Client:		**Coring Date:**	N/K
Project:	A1(M)	**TRL LMS Ref:**	133112 / 1
Location:		**Core Ref:**	2
		Logged by:	PH
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**	
Checked by:			

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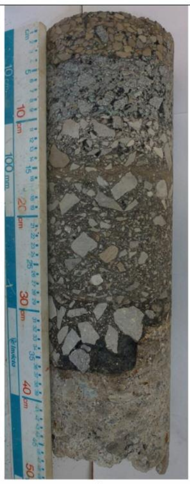
Wokingham.
RG40 3GA.
Tel: 01344 773131

Top of core photo:

Figure E-2: Core133112, A1(M) Shincliffe

CORE LOG



Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	44	44	TS	14	GS	Sound	Intact	Y	-VE
2	44	104	60	DBM	20	GNT	Sound	Intact	Y	-VE
3	104	173	69	DBM	32	LST	Sound	Intact	Y	-VE
4	173	291	118	DBM	32	LST	Sound	Intact	Y	-VE
5	291	362	71	DBM	32	LST	Big voids at base	Intact	Y	-VE
6	362	411	49	CBM	40	G	Sound	-	Y	-VE
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7
Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150		
Project Code:	11112687 1		
Client:		**Coring Date:**	N/K
Project:	A1(M)	**TRL LMS Ref:**	133113 1
Location:		**Core Ref:**	3
		Logged by:	PH
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**	
Checked by:			

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RG40 3GA.
Tel: 01344 773131

Top of core photo:

Figure E-3: Core133113, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	52	52	TS	14	GS	Sound	Intact	N	-VE
2	52	109	57	DBM	20	GNT	Sound	Intact	Y	-VE
3	109	220	111	DBM	32	LSt	Sound	Intact	N	-VE
4	220	287	67	DBM	20	LST	Sound	De-Bonded	Y	-VE
5	287	371	84	DBM	32	LST	Sound	Intact	N	-VE
6	371	495	124	CBM	40	G	Sound	-	N	-VE
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7
Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150		
Project Code:	11112687 1		
Client:		**Coring Date:**	N/K
Project:	A1(M)	**TRL LMS Ref:**	133114 1
Location:		**Core Ref:**	4
		Logged by:	PH
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**	
Checked by:			

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Nine Mile Ride,
Wokingham.
RG40 3GA.
Tel: 01344 773131

Top of core photo:

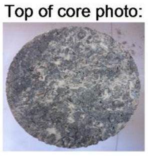

Figure E-4: Core133114, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	42	42	TS	14	GS	Sound	Intact	N	-VE
2	42	99	57	DBM	20	GNT	Very Voided	Intact	Y	-VE
3	99	187	88	DBM	32	LST	Very Voided	Intact	Y	-VE
4	187	289	102	DBM	32	LST	Very Voided	Intact	Y	-VE
5	289	330	41	HRA	32	SLAG	Very Voided	-	Y	-VE
6										
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7

Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150				
Project Code:	11112687 1				
Client:				**Coring Date:**	N/K
Project:	A1(M)			**TRL LMS Ref:**	133115 1
Location:				**Core Ref:**	5
				Logged by:	PH
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**		**Checked by:**	

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Tel: 01344 773131

Top of core photo:

Figure E-5: Core133115, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	51	51	TS	14	GS	Sound	Intact	N	-VE
2	51	108	57	DBM	20	GNT	Sound	Intact	Y	-VE
3	108	194	86	DBM	32	LST	Sound	Intact	Y	-VE
4	194	283	89	DBM	32	LST	Sound	Intact	Y	-VE
5	283	341	58	HRA	32	SLAG	Sound	-	Y	-VE
6										
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7

Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150				
Project Code:	11112687 1				
Client:				**Coring Date:**	N/K
Project:	A1(M)			**TRL LMS Ref:**	133116 1
Location:				**Core Ref:**	6
				Logged by:	PH
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**		**Checked by:**	

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Tel: 01344 773131

Top of core photo:

Figure E-6: Core133116, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	37	37	TS	14	GS	Sound	Intact	Y	-VE
2	37	103	66	DBM	20	GNT	Very Voided	Intact	Y	-VE
3	103	197	94	DBM	32	LST	Very Voided	Intact	Y	-VE
4	197	290	93	DBM	32	LST	Very Voided	Intact	Y	-VE
5	290	319	29	HRA	32	SLAG	Sound	Intact	Y	-VE
6										
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7
Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150	**Project Code:**	11112687 1
Client:		**Coring Date:**	N/K
Project:	A1(M)	**TRL LMS Ref:**	133117 1
Location:		**Core Ref:**	7
		Logged by:	PH
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**	
Checked by:			

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Top of core photo:

Figure E-7: Core133117, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	38	38	TS	14	GS	Sound	Intact	Y	-VE
2	38	96	58	DBM	20	GNT	Sound	Intact	Y	-VE
3	96	200	104	DBM	32	LST	Sound	Intact	Y	-VE
4	200	284	84	DBM	32	LST	Very Voided	Intact	Y	-VE
5	281	325	44	HRA	32	SLAG	Sound	-	Y	-VE
6										
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7
Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150	**Project Code:**	11112687 1
Client:		**Coring Date:**	N/K
Project:	A1(M)	**TRL LMS Ref:**	133118 1
Location:		**Core Ref:**	8
		Logged by:	PH
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**	
Checked by:			

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Top of core photo:

Figure E-8: Core133118, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	39	39	TS	14	GS	Sound	Intact	Y	-VE
2	39	101	62	DBM	20	GNT	Sound	Intact	Y	-VE
3	101	179	78	DBM	32	LST	Sound	Intact	Y	-VE
4	179	289	110	DBM	32	LST	Sound	Intact	Y	-VE
5	289	341	52	HRA	32	SLAG	Sound	Intact	Y	-VE
6										
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7
Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150				
Project Code:	11112687 1				
Client:			**Coring Date:**	N/K	
Project:	A1(M)		**TRL LMS Ref:**	133119	1
Location:			**Core Ref:**	9	
			Logged by:	PH	
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**	**Checked by:**		

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Top of core photo:

Figure E-9: Core133119, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	37	37	TS	14	GS	Sound	Intact	Y	-VE
2	37	89	52	DBM	20	GNT	Sound	Intact	Y	-VE
3	89	195	106	DBM	32	LST	Sound	Intact	Y	-VE
4	195	277	82	DBM	32	LST	Sound	Intact	Y	-VE
5	277	335	58	HRA	32	SLAG	Sound	De-Bonded	Y	-VE
6	335	700	365	CBM	40	G	Sound	-	Y	-VE
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7
Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150				
Project Code:	11112687 1				
Client:			**Coring Date:**	N/K	
Project:	A1(M)		**TRL LMS Ref:**	133120	1
Location:			**Core Ref:**	10	
			Logged by:	PH	
Grid Ref: Eastings (X)		**Grid Ref: Northings (Y):**	**Checked by:**		

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Top of core photo:

Figure E-10: Core133120, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	35	35	TS	14	GS	Sound	Intact	Y	-VE
2	35	93	58	DBM	20	GNT	Sound	Intact	Y	-VE
3	93	195	102	DBM	32	LST	Sound	Intact	Y	-VE
4	195	277	82	DBM	32	LST	Sound	Intact	Y	-VE
5	277	320	43	HRA	32	SLAG	Sound	De-Bonded	Y	-VE
6	320	670	350	CBM	40	G	Sound	-	Y	-VE
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7
Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150		Project Code:	11112687 1	
Client:			Coring Date:	N/K	
Project:	A1(M)		TRL LMS Ref:	133121	1
Location:			Core Ref:	11	
			Logged by:	PH	
Grid Ref: Eastings (X)		Grid Ref: Northings (Y):	Checked by:		

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Top of core photo:

Figure E-11: Core133121, A1(M) Shincliffe

CORE LOG

Layers					Aggregate		General Remarks			PAK Test for tar +VE/-VE
No.	Top mm	Btm mm	Thick mm	Material	Max Size mm	Type	Condition	Bond	Voids Y/N	
1	0	35	35	TS	14	GS	Sound	Intact	Y	-VE
2	35	82	47	DBM	20	GNT	Sound	Intact	Y	-VE
3	82	180	98	DBM	32	LST	Sound	Intact	Y	-VE
4	180	269	89	DBM	32	LST	Sound	Intact	Y	-VE
5	269	325	56	HRA	32	GNT/SLAG	Sound	-	Y	-VE
6										
7										
8										
9										

Sampling Method: BS EN 12697- 27 Clause 4.7
Abbreviations: TS=Thin Surfacing; HRA=Hot Rolled Asphalt; DBM =Dense Bituminous Macadam; HBM=Hydraulically Bound Material; GS=Gritstone; GNT=Granite; LST=Limestone; G=Gravel.

Core Dia (mm):	150		Project Code:	11112687 1	
Client:			Coring Date:	N/K	
Project:	A1(M)		TRL LMS Ref:	133122	1
Location:			Core Ref:	12	
			Logged by:	PH	
Grid Ref: Eastings (X)		Grid Ref: Northings (Y):	Checked by:		

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Top of core photo:

Figure E-12: Core133122, A1(M) Shincliffe

E.2 Air voids content from A1(M) Shincliffe

Table E-1: Air voids content results from cores

Core No.	Binder course				Base			
	Density (Mg/m³)		Air voids content (%)		Density (Mg/m³)		Air voids content (%)	
	Bulk	Max.	Direct	Mean max.	Bulk	Max.	Direct	Mean max.
133111	2.426	2.650	8.5	9.1	2.310	–	–	9.1
133112	2.432	–	–	8.9	2.268	–	–	10.8
133113	2.410	–	–	9.7	2.341	–	–	7.9
133114	2.248	2.689	16.4	15.8	2.393	–	–	5.9
133115	2.238	–	–	16.2	2.209	2.544	13.2	13.1
133116	2.422	–	–	9.3	2.297	–	–	9.6
133117	2.384	–	–	10.7	2.287	–	–	10.0
133118	2.486	–	–	6.9	2.422	2.540	4.6	4.7
133119	2.350	–	–	12.0	2.337	–	–	8.1
133120	2.416	–	–	9.5	2.371	–	–	6.7
133121	2.352	–	–	11.9	2.367	–	–	6.9
133122	2.463	–	–	7.7	2.451	–	–	3.6
Mean	2.386	2.670	12.4	10.6	2.338	2.542	8.9	8.0
Maximum	2.486	–	–	16.2	2.451	–	–	13.1
Minimum	2.238	–	–	6.9	2.209	–	–	3.6
Range	0.248	–	–	9.3	0.242	–	–	9.5
Std. dev.	0.077	–	–	2.9	0.068	–	–	2.7

E.3 Stiffness results from A1(M) Shincliffe

Table E-2: Stiffness modulus and bulk density results from cores

Core No.	Stiffness (IT-CY) (GPa)		Bulk density (Mg/m³)	
	Binder course	Base	Binder course	Base
133111	3.429	4.892	2.426	2.31
133112	3.229	6.297	2.432	2.268
133113	3.014	4.934	2.410	2.341
133114	1.986	5.897	2.248	2.393
133115	2.148	4.384	2.238	2.209
133116	4.156	7.824	2.422	2.297
133117	3.209	6.082	2.384	2.287
133118	3.426	7.200	2.486	2.422
133119	3.473	4.611	2.350	2.337
133120	3.156	6.057	2.416	2.371
133121	3.453	5.254	2.352	2.367
133122	4.081	7.687	2.463	2.451
Mean	3.230	5.927	2.386	2.338
Maximum	4.156	7.824	2.486	2.451
Minimum	1.986	4.384	2.238	2.209
Range	2.170	3.440	0.248	0.242
St'd Dev.	0.642	1.172	0.077	0.068

Appendix F NCHRP project summaries

This Appendix contains NCHRP project summaries extracted from the internet in August 2013.

F.1 NCHRP 09-43, Mix design practices for warm mix asphalt

F.1.1 Project data

Funds:	$522,501
Research Agency:	Advanced Asphalt Technologies, LLC
Principal Investigator:	Dr Ramon Bonaquist
Effective Date:	3/22/2007
Completion Date:	1/31/2011
Comments:	The project final report is available as NCHRP Reports 691 and 714.

F.1.2 Background

The objective of this project was to develop a mix design method for warm mix asphalt (WMA) in the form of a draft AASHTO-recommended practice for use by engineers and technicians in the public and private sectors. This method was to (1) be based on Superpave mix design methodology, (2) include a suite of performance tests to assess whether a WMA mix design will provide satisfactory field service, and (3) be applicable to any WMA technology used to lower mixing and compaction temperatures.

The key product of this research project is a draft recommended appendix to AASHTO R 35, Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA), titled Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA). This recommended appendix was developed and validated by the results of an extensive program of laboratory and field testing on a wide range of WMA technologies. In addition to this practice, the contractor produced (1) a chapter on WMA mix design for inclusion in the mix design manual produced in NCHRP Project 9-33, A Mix Design Manual for Hot Mix Asphalt, and (2) materials and media for a 1-day training course on WMA mix design.

The project final report is available as NCHRP Report 691, Mix Design Practices for Warm Mix Asphalt. The print and PDF versions of the report include three appendixes:

- Appendix A: Draft Appendix to AASHTO R 35: Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA);
- Appendix B: Commentary to the Draft Appendix to AASHTO R 35; and
- Appendix D: Proposed Standard Practice for Measuring Properties of Warm Mix Asphalt (WMA) for Performance Analysis Using the Mechanistic-Empirical Pavement Design Guide Software.

The remaining two appendixes are only available online:

- Appendix C: Training Materials for the Draft Appendix to AASHTO R 35; and
- Appendix E: NCHRP Project 09-43 Experimental Plans, Results, and Analyses.

A supplement to NCHRP Report 673, *A Manual for Design of Hot Mix Asphalt with Commentary*, based on Appendix A of NCHRP Report 691 is available as NCHRP Report 714, Special Mixture Design Considerations and Methods for Warm Mix Asphalt: A Supplement to NCHRP Report 673: A Manual for Design of Hot Mix Asphalt with Commentary.

Information on a core set of WMA specimen conditioning procedures and test methods proposed for common use, insofar as possible, in all present and future WMA studies are presented in NCHRP Research Results Digest 370, Guidelines for Project Selection and Materials Sampling, Conditioning, and Testing in WMA Research Studies.

F.2 NCHRP 09-47, Engineering properties, emissions, and field performance of warm mix asphalt technologies

F.2.1 Project data

Funds:	$79,000
Research Agency:	Asphalt Institute
Principal Investigator:	Michael Anderson
Effective Date:	3/31/2008
Completion Date:	1/8/2009
Comments:	Phase II of this project will be accomplished as NCHRP Project 9-47A.

F.2.2 Background

Hot mix asphalt (HMA) is produced at temperatures between 140 °C and 160 °C. These temperatures ensure that the aggregate is dry, the bitumen coats the aggregate, and the HMA mix has a suitable workability. HMA needs to be workable so it can be transferred into storage silos, transported, placed, and compacted. Even higher temperatures are used for HMA mixtures containing polymer-modified bitumen and crumb rubber bitumen.

Technology is now available to decrease HMA production temperature by between 15 °C and 55 °C. These relatively new processes and products use various physicochemical means to reduce the shear resistance of the HMA at construction temperatures while reportedly maintaining or improving pavement performance.

While the current state of the practice for producing HMA has been shown to comply with existing environmental, health and safety standards, reducing HMA production and placement temperatures will provide several benefits, including reduced emissions, fumes, and odours, and a cooler work environment. An energy savings from lower production temperatures is evident with the use of warm mix asphalt (WMA) technology.

The quality of the HMA construction and performance may also be improved when production temperatures are lower. Workability improvements may result in higher in-place density. This decrease in in-place air voids decreases the permeability of the HMA and the long-term or in-service hardening of the bitumen as well as reducing water damage that can occur in the HMA.

Workability improvements also have the potential to extend the construction season and the time available for placement of the asphalt mixture during a given day. Due to enhanced workability of the HMA, it may be placed under cooler weather conditions.

A significant amount of bitumen ageing occurs during the mixing and placing of HMA. Lower production temperatures for asphalt paving mixtures will decrease the ageing of the bitumen during production. This decrease in ageing can improve thermal and fatigue cracking resistance.

The use of WMA technology has some potential engineering challenges. Since the bitumens may not harden as much at the lower production temperatures, a softer binder will likely be in the HMA mixtures when the pavement is opened to traffic and the mixture may have a greater potential for rutting. In addition, traffic may not be allowed on the pavement at the conclusion of the compaction process until the mixture cools beyond what is normally required for conventional HMA. Because binders may be softer and some WMA technologies use water as a workability aid, WMA may be more susceptible to moisture damage. The relationship among engineering properties of such mixes and field performance needs to be investigated to facilitate the implementation of this technology.

F.2.3 Objectives

The objectives of this project were to:

(1) establish relationships among engineering properties of WMA binders and mixes and the field performance of pavements constructed with WMA technologies,

(2) determine relative measures of performance between WMA and conventional HMA pavements,

(3) compare production and laydown practices and costs between WMA and HMA pavements, and

(4) provide relative emissions measurement of WMA technologies as compared to conventional HMA technologies.

Project deliverables shall include:

(1) recommended modifications to the preliminary WMA mix design and analysis procedure under development in NCHRP Project 9-43,

(2) a protocol for laboratory evaluation of WMA performance,

(3) guidelines for WMA production and construction, and

(4) an updated emissions measurement protocol.

F.2.4 Product availability

The Phase I interim report is available for loan upon request to NCHRP.

F.3 NCHRP 09-47A, Properties and performance of warm mix asphalt technologies

F.3.1 Project data

Funds:	$1,121,000
Staff Responsibility:	Edward T Harrigan
Research Agency:	National Center for Asphalt Technology--Auburn University
Principal Investigator:	Randy West
Effective Date:	7/13/2009
Completion Date:	6/30/2013

F.3.2 Background

The use of warm mix asphalt (WMA) technology presents some potential engineering challenges. Because the bitumens may not harden as much at the lower production temperatures, a softer binder is likely to be present in the WMA mixtures when the pavement is opened to traffic and the mixture may have a greater potential for rutting. In addition, traffic may not be allowed on the pavement at the conclusion of the compaction process until the mixture cools beyond what is normally required for conventional HMA. Because binders may be softer and some WMA technologies use water as a workability aid, WMA may be more susceptible to moisture damage. The relationships among engineering properties of such mixes and field performance need to be investigated to facilitate the implementation of this technology.

F.3.3 Objectives

The objectives of this project are to:

(1) establish relationships among engineering properties of WMA binders and mixes and the field performance of pavements constructed with WMA technologies,

(2) determine relative measures of performance between WMA and conventional HMA pavements,

(3) compare production and laydown practices and costs between WMA and HMA pavements (including necessary plant adjustments to optimize plant operations when producing WMA), and

(4) provide relative emissions measurement of WMA technologies as compared to conventional HMA technologies.

Project deliverables shall include:

(1) recommended modifications to the preliminary WMA mix design and analysis procedure under development in NCHRP Project 9-43,

(2) a protocol for laboratory evaluation of WMA performance,

(3) guidelines for WMA production and construction,

(4) an updated emissions measurement protocol, and

(5) a project database on CD-ROM.

F.3.4 Product availability

The Phase I interim report is available for loan on request to NCHRP.

A three-part compilation of the critical reviews of the literature on warm mix asphalt technologies conducted in NCHRP Projects 9-47, 9-47A, 9-49, 9-49A, and 9-53 is available here: Part I; Part II; and Part III.

Information on a core set of WMA specimen conditioning procedures and test methods proposed for common use, insofar as possible, in all present and future WMA studies are presented in NCHRP Research Results Digest 370, Guidelines for Project Selection and Materials Sampling, Conditioning, and Testing in WMA Research Studies.

F.4 NCHRP 09-49, Performance of WMA technologies: Stage I – Moisture susceptibility

F.4.1 Project data

Funds: $450,000
Staff Responsibility: Edward T Harrigan
Research Agency: Texas Transportation Institute
Principal Investigator: Amy Epps Martin
Effective Date: 7/26/2010
Completion Date: 9/30/2013
Comments: The draft final report is under review by NCHRP.

F.4.2 Background

Recently, interest in warm mix asphalt (WMA) has dramatically increased. WMA is now seen as an alternative to hot mix asphalt (HMA) offering the potential to lower energy demand during production and construction, reduce emissions at the plant and the paver, and increase allowable haul distances. However, there are still questions about the long-term performance and durability of WMA pavements. One key issue is the moisture susceptibility of WMA pavements. Concerns about WMA moisture susceptibility include the possibility that aggregates will be inadequately dried at lower production temperatures and the fact that several WMA technologies introduce additional moisture in the production process. The moisture susceptibility of HMA is evaluated by a variety of standard laboratory tests. The results of these tests on WMA indicate that WMA may be more susceptible to moisture damage than HMA. However, more limited data suggest that the resistance of WMA to moisture damage improves with time and may ultimately be equivalent to that of HMA. In some situations, anti-strip agents are added to WMA to address the issue of moisture susceptibility. However, as is the case with HMA, anti-strip agents may not always be compatible or work effectively with WMA.

The objectives of this research were to (1) assess whether WMA technologies adversely affect the moisture susceptibility of flexible pavements and (2) develop guidelines for identifying and limiting moisture susceptibility in WMA pavements.

F.4.3 Status

A three-part compilation of the critical reviews of the literature on warm mix asphalt technologies conducted in NCHRP Projects 9-47, 9-47A, 9-49, 9-49A, and 9-53 is available here: Part I; Part II; and Part III.

Information on a core set of WMA specimen conditioning procedures and test methods proposed for common use, insofar as possible, in all present and future WMA studies are presented in NCHRP Research Results Digest 370, Guidelines for Project Selection and Materials Sampling, Conditioning, and Testing in WMA Research Studies.

The draft final report is under review by NCHRP.

F.5 NCHRP 09-49A, Performance of WMA technologies: Stage II – Long-term field performance

F.5.1 Project data

Funds:	$922,425
Staff Responsibility:	Edward T Harrigan
Research Agency:	Washington State University
Principal Investigator:	Haifang Wen
Effective Date:	4/29/2011
Completion Date:	7/28/2016
Comments:	Work is underway on Phase II.

F.5.2 Background

The use of warm mix asphalt (WMA) technology offers significant benefits, notably, lower energy demand during production and construction, reduced emissions at the plant and the paver, and increased allowable haul distances. However, it also presents potential engineering challenges. Lower WMA production temperatures and the water injection used with some WMA technologies have raised concerns about possible rutting and moisture susceptibility of WMA pavements. Thus, facilitating the implementation of WMA technologies in the United States requires the collection and analysis of definitive information on the material and engineering properties and long-term performance of WMA pavements constructed with the wide range of WMA technologies now available.

F.5.3 Objectives

The objectives of this research are to (1) identify the material and engineering properties of WMA pavements that are significant determinants of their long-term field performance and (2) propose best practices for the use of WMA technologies. In this research, the phrase "long-term" is defined as a minimum of 4 years after construction. The performance of 17 WMA pavements (with one to three WMA technologies) and their HMA control sections in the following states are being monitored over the life of Project 9-49A:

- New pavements constructed in 2011 and 2012: Iowa, Louisiana, Montana, Tennessee, and Texas.
- Existing pavements, constructed from 2005 to 2010: Colorado, Maryland, Minnesota, Missouri (2), Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, and Washington (2).

F.5.4 Status

Work is underway on Phase II.

Information on a core set of WMA specimen conditioning procedures and test methods proposed for common use, insofar as possible, in all present and future WMA studies are presented in NCHRP Research Results Digest 370, Guidelines for Project Selection and Materials Sampling, Conditioning, and Testing in WMA Research Studies.

A three-part compilation of the critical reviews of the literature on warm mix asphalt technologies conducted in NCHRP Projects 9-47, 9-47A, 9-49, 9-49A, and 9-53 is available here: Part I; Part II; and Part III.

F.6 NCHRP 09-52, Short-term laboratory conditioning of asphalt mixtures

F.6.1 Project data

Funds: $800,000
Staff Responsibility: Edward T Harrigan
Research Agency: Texas A&M Research Foundation
Principal Investigator: David Newcomb
Effective Date: 6/1/2012
Completion Date: 11/30/2014
Comments: Work is underway on Phase II.

F.6.2 Objective

The objective of this research is to develop procedures and associated criteria for short-term laboratory conditioning of asphalt mixtures for mix design and performance testing to simulate the effects of (1) plant mixing and processing to the point of loading in the transport truck and (2) the initial period of field performance. These procedures and criteria shall be representative of the asphalt production facilities and production temperatures (approximately 115 °C to 170 °C) currently found for asphalt mixtures.

Accomplishment of the project objective will require at least the following tasks.

F.6.3 Tasks

F.6.3.1 Phase 1

Task 1: Prepare a critical review of current and emerging asphalt production plant types, technologies, and operating parameters.

Task 2: Develop a detailed work plan for a coordinated experiment to determine the effects of (1) plant mixing and processing to the point of loading into the transport truck (Phase I: Construction) and (2) an initial period of performance in the field (Phase II: Post Construction) on binder absorption by the aggregate and asphalt mixture characteristics related to stiffness, permanent deformation, and cracking. The work plan shall first establish base line data for HMA production and then expand to the full range of WMA and HMA production temperatures. The work plan shall stress the determination of the point in service where WMA ageing becomes equivalent to that of HMA and consider the following factors, at a minimum:

a. Mix production temperatures between approximately 115 °C to 170 °C.
b. A range of aggregates from low to high binder absorption.
c. Dense-graded asphalt mixtures from 9.5-mm to 25-mm NMAS.
d. Modified and unmodified binder grades.
e. A range of current asphalt plant categories and operating characteristics, e.g., moisture content of the aggregate, plant type (e.g., batch plant, parallel- and counter-flow drum mixers, etc.), and production rate.

Task 3: Identify test sites and projects necessary to satisfy the requirements of the Task 2 work plan and secure the cooperation of the responsible agencies in a timely manner.

Task 4: Conduct the sampling and testing required to satisfy the experiment design for the Phase I work plan.

Task 5: Analyse the data collected in Task 4 to determine (a) the effects of production temperature, binder absorption by the aggregate, plant type and operating parameters, and other pertinent factors on mixture properties and (b) verification of the WMA mix design method developed in NCHRP Project 9-43 for aggregates with a bitumen absorption greater than 1 %. Based on the findings, prepare (1) a procedure and associated criteria in AASHTO standard format for laboratory conditioning of asphalt mixtures for mix design to simulate the binder and mixture ageing that occur during plant mixing and processing and (2) a field procedure in the format of an AASHTO recommended practice to measure the effects of asphalt plant mixing and processing on binder absorption by aggregate and asphalt mixture characteristics.

Task 6: Prepare a final report for Phase I that documents results, summarizes findings, draws conclusions, and presents the proposed procedure and practice in AASHTO standard format.

F.6.3.2 Phase II

Task 7: Conduct the sampling and testing required to satisfy the experiment design for the Phase II work plan.

Task 8: Analyse the data collected in Task 7 to determine (1) the binder and mixture ageing that occur during an initial period of performance in the field and (2) the point in service where WMA ageing becomes equivalent to that of HMA. Based on these results, prepare a procedure and associated criteria in AASHTO standard format for short-term laboratory conditioning of asphalt mixtures to simulate their ageing in an initial period of performance in the field.

Task 9: Prepare a final report for Phase II that documents results, summarizes findings, draws conclusions, and presents the proposed procedure in AASHTO standard format.

F.6.3.3 Phase III

Task 10: Submit a project final report based on the Tasks 6 and 9 reports that documents results, summarise findings, draws conclusions, and presents the proposed procedures and practice in AASHTO standard format. An appendix to the report shall include electronic files of all test data and results collected and measured in Phases I and II on appropriate media.

F.7 NCHRP 09-53, Properties of foamed asphalt for warm mix asphalt applications

F.7.1 Project data

Funds:	$700,000
Staff Responsibility:	Edward T Harrigan
Research Agency:	Texas A&M Research Foundation
Principal Investigator:	David Newcomb
Effective Date:	6/1/2012
Completion Date:	8/31/2014
Comments:	Work is underway on Phase 2.

F.7.2 Objectives

The objectives of this research are to (1) determine the key properties of foamed bitumens that significantly influence the performance of asphalt mixtures and (2) develop laboratory protocols for foaming of bitumens and laboratory mixing procedures.

F.7.3 Status

Work is underway on Phase 2.

A three-part compilation of the critical reviews of the literature on warm mix asphalt technologies conducted in NCHRP Projects 9-47, 9-47A, 9-49, 9-49A, and 9-53 is available here: Part I; Part II; and Part III.

F.8 NCHRP 09-54, Long-term ageing of asphalt mixtures for performance testing and prediction

F.8.1 Project data

Funds:	$800,000
Staff Responsibility:	Edward T Harrigan
Research Agency:	North Carolina State University
Principal Investigator:	Y Richard Kim
Effective Date:	5/21/2013
Completion Date:	5/21/2016

F.8.2 Background

The characterization of asphalt pavement materials is increasingly important as mechanistic-empirical pavement design and performance prediction methods are implemented. Materials characterization for ageing is a requirement for such mechanistic analysis and research is warranted to improve current practice. Current pavement performance prediction models have different levels of sophistication for numerically simulating the increased stiffness from ageing (e.g., the Global Ageing System in Pavement ME Design) and the competing phenomena of accumulated damage and deterioration manifesting as a reduction in modulus (e.g., CalME). A prominent shortcoming in the materials technology supporting the use of these models is using an accelerated laboratory procedure to accurately characterize the long-term field condition of asphalt pavements due to oxidative ageing. The long-term procedure in AASHTO R 30, Mixture Conditioning of Hot Mix Asphalt (HMA), prescribes ageing compacted mixtures at 85°C for 5 days, a time and temperature combination that the original Strategic Highway Research Program (SHRP) research estimated – based on limited field calibration – to reflect a critical duration of field exposure as little as 5 or 7 years or as much as 10 years. This single time-temperature combination may not be applicable for all the different climates found throughout the United States. To address this issue, research is needed to develop a calibrated and validated procedure to simulate long-term ageing of asphalt mixtures for performance testing and prediction.

F.8.3 Objective

The objective of this research is to develop a procedure calibrated and validated with field data to simulate long-term ageing of asphalt mixtures for performance testing and prediction.

This research will provide a basis for future development of a methodology for integrating the effects of long-term ageing in Pavement ME Design and other mechanistic design and analysis systems and using the methodology to enable consideration of long-term ageing in full-scale and accelerated pavement testing (APT) results.

The research shall be limited to bitumen-aggregate mixture ageing procedures because these will inherently take air voids (permeability) and bitumen-aggregate chemical interaction into account.

During the development of this procedure, consideration shall be given to (1) different types of cracking distress which originate towards the top or bottom of the asphalt pavement layers and are impacted by ageing and (2) the potential differential ageing within an asphalt pavement layer.

Accomplishment of the project objective will require at least the following tasks.

F.8.4 Tasks

F.8.4.1 Phase I Develop a calibrated, validated procedure to simulate long-term ageing of asphalt mixtures for performance testing and prediction

Task 1: Prepare a critical review of the literature to fully understand and appreciate the following topics, at a minimum:

- Mechanisms governing the long-term ageing of asphalt mixtures in in-service pavements
- Material properties that are representative of and sensitive to different levels of ageing in in-service pavements
- Types and effects of in situ variables that affect the governing mechanisms during long-term ageing
- Laboratory ageing equipment and procedures with emphasis on their rationales, efficiency, costs, and validation
- Comparison of the different ageing behaviour between hot mix asphalt and warm mix asphalt and between virgin and reclaimed asphalt pavement mixes
- Diffusion and heat transfer models appropriate to asphalt mixtures in in-service pavements
- Algorithms to capture the effects of binder oxidation and its effects on mixture behaviour for implementation in performance prediction programs such as DARWin-ME

Task 2: Prepare a detailed work plan for a coordinated laboratory and field experiment to (1) identify key ageing index properties of asphalt mixtures, (2) use these index properties to define a reliable long-term ageing procedure that mimics field ageing conditions, and (3) provide a basis for future development of a methodology for incorporating the effects of long-term ageing in analyses made with DARWin-ME and other mechanistic design and analysis systems.

Candidate ageing index properties include carbonyl absorbance, carbonyl plus sulfoxide absorbance, dynamic shear crossover modulus, and viscosity. In addition, the work plan will consider potential variables such as project climate and service life, mixture density (air voids), and test specimen geometry, as well as the type and location of cracking distresses of interest.

Submit the work plan and the Task 1 critical literature review in an interim report to NCHRP. Meet with NCHRP approximately 1 month later to review the work plan and receive approval to proceed with Task 3.

Task 3: Conduct the approved Task 2 work plan in the following sequence of subtasks:
- Acquire the necessary original materials (bitumens and aggregate) and field cores.
- Evaluate various ageing procedures identified in Task 1 and select candidate procedures for further testing and development.
- Determine requisite ageing index properties from original materials and cores from in-service pavements.
- Conduct a preliminary assessment and sensitivity analysis of promising ageing procedures.
- Develop a final long-term ageing protocol and conduct a field calibration.
- Evaluate the effects of ageing on cracking in asphalt pavements and develop a future research plan to implement the long-term ageing procedure and associated models in Pavement ME Design.
- Prepare a proposed AASHTO standard procedure for long-term ageing of asphalt mixtures for performance testing and prediction.
- Conduct an analysis of the cost and benefit associated with the replacement the long-term ageing procedure in AASHTO R 30 with the proposed procedure from this research.

F.8.4.2 Phase II Reporting

Task 4: Submit a final report that documents results, summarizes findings, draws conclusions, and presents (1) the proposed procedure to simulate long-term ageing of asphalt mixtures for performance testing and prediction in AASHTO standard format, (2) the proposed plan for future research; and (3) the cost and benefit analysis. An appendix to the report shall include electronic files of all test data and results collected and measured in Phase I on appropriate media.

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F.9 NCHRP 09-55, Recycled asphalt shingles in asphalt mixtures with warm mix asphalt technologies

F.9.1 Project data

Funds:	$600,000
Staff Responsibility:	Edward T Harrigan
Research Agency:	National Center for Asphalt Technology--Auburn University
Principal Investigator:	J Richard Willis
Effective Date:	6/10/2013
Completion Date:	9/10/2016

F.9.2 Objective

The objective of this research is to develop a design and evaluation procedure that provides acceptable performance of asphalt mixtures incorporating WMA technologies and RAS, with and without RA, for project-specific service conditions.

This research is expected to address the following issues, at a minimum:
1. Minimizing the risk of designing and producing mixes containing WMA technologies and RAS with poor constructability and durability.
2. Minimizing the risk of designing and producing mixes containing WMA technologies and RAS that are susceptible to premature failure.
3. Evaluating type, source, quality, and characteristics of RAS, with and without RA.
4. Binder design and selection, including evaluation of the composite binder.
5. The current range of asphalt mix production temperatures.

F.10 NCHRP 20-07/Task 311, Development of a warm mix asphalt technology evaluation program

F.10.1 Project data

Funds:	$49,920
Research Agency:	Myers McCarthy Consulting Engineers, LLC
Principal Investigator:	Leslie Myers McCarthy
Effective Date:	3/3/2011
Completion Date:	8/31/2012

F.10.2 Objective

The objective of this research was to develop a standardized evaluation program for WMA technologies that is compatible with AASHTO NTPEP's centralized system of testing, evaluation, and data reporting of engineering materials for the state DOTs.

The project final report will be summarized in an NCHRP Research Results Digest planned for publication in mid-2012. A draft of a proposed AASHTO NTPEP Work Plan for Material Additives and Processes for Warm Mix Asphalt is available here for download.

Appendix G NCHRP Project Case Studies

These projects case studies were assembled by TRL in 2013.

G.1 NCHRP Project 9-47, Engineering properties, emissions and field performance of warm mix asphalt technologies

G.1.1 NCAT test track

(Vol I, pp 31)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Warmer than UK.

In November 2005, two WMA test sections using Evotherm™ ET were constructed at the NCAT test track. These test sections used a PG 67-22 bitumen, with and without the addition of 3 % latex. The test sections were compared to an HMA control section using a PG 67-22 bitumen. After 500,000 ESALs, the reported rut depths for the Evotherm™ ET test sections were the same as for the HMA control section. It should be noted that the measured rut depths were practically non-existent – less than 1.5 mm for all sections.

G.1.2 Summary of comparison - WMA and HMA

(Vol I, pp 35-36)

WMA and HMA mixtures were compared to evaluate similarities and differences in three main areas:

- Materials and production costs;
- Emissions; and
- Lab and field performance.

A comparison of the materials and production costs indicates that while WMA mixtures offer savings from reduced fuel consumption, it may not be enough to immediately offset the cost of the initial investment (in the case of the water-based process technologies) or the additives (in the case of the remaining WMA additives). This is a somewhat tricky conclusion, however, as other benefits such as increased production or late-season paving may provide additional economic incentives for WMA mixtures.

A comparison of emissions indicates unequivocally that WMA mixtures will result in lower stack emissions. The magnitude of the reduction in CO, CO_2, SO_2 and NO_x is a function of the temperature used in the production of WMA, but should be expected to be at least 10 % and perhaps much higher. Data from laydown emissions is very limited in the literature, but suggests that even HMA emissions at construction are low, often below detection and well-controlled.

A comparison of field and lab performance indicates that in many cases WMA should be comparable to HMA. Field densities appear to be similar, with slighter ease of compaction noted for WMA mixtures. Performance testing indicates that lack of plant ageing may cause the WMA mixture to be initially more susceptible to rutting, but can be alleviated somewhat with proper bitumen grade selection (and use of RA). The same lack of plant ageing may allow WMA mixtures to have improved cracking resistance initially compared to HMA mixtures. Moisture susceptibility testing has been conducted with mixed results. The greatest concern is the effect of residual internal aggregate moisture in WMA mixtures on stripping resistance. No major concerns have been raised in regards to in-place performance of the road when using WMA mixtures.

G.2 NCHRP Project 9-47A, Engineering properties, emissions and field performance of warm mix asphalt technologies (Vol I, pp 39 – Vol II, pp 144)

G.2.1 *Initial performance of foam WMA mixes in Western Canada*

(Reyes *et al*., 2009) (Vol I, pp 152 - Vol II, pp 4)

Relevance to UK	
Type of asphalt:	Asphalt concrete designed using Marshall method.
LTA system:	Available in UK.
Climate:	Colder than UK.

Four WMA asphalt mixtures were constructed in September 2007 in order to evaluate the performance of the Astec DBG system in Western Canada. The mixtures incorporated various proportions of recycled asphalt pavement (RA) and recycled asphalt shingles (RAS) in order to determine the potential influence of recycled materials on mixtures produced with this process. The mixtures were 75-blow Marshall mixtures containing an 80/100A bitumen. The mixtures were all produced between 130 ºC and 135 ºC. Approximately, 250 tonnes of each mixture were produced. Table G-1 presents information regarding each of the four mixtures. It should also be noted that the virgin mixture was used as a base course, where the other mixtures were all surface mixtures.

Table G-1: WMA mixture characteristics

Date	Mixture (Astec DBG)	RA (%)	RAS (%)	Project Locations
8 Sept. 2007	Virgin	0	0	North Burnaby Ready Mix Plant
8 Sept. 2007	15 % RA	I5	0	
15 Sept. 2007	15 % RA & 5 % RAS	15	5	Coquitlam Sand & Gravel Pit
15 Sept. 2007	50 % RA	50	0	

A visual condition index (VCI) in accordance with the *Pavement Surface Rating Manual of the Ministry of Transportation and Highways – Province of British Columbia* was used as an indicator of the pavement surface condition after two years. Based on a scale of one to ten, the VCI combines surface distress data into an overall distress related index. As a combination of several different calculated factors, the VCI ultimately considers the following distresses: alligator cracking, bock cracking, edge cracking, longitudinal and transverse cracking, bleeding, distortion, rutting, shoving, ravelling and potholes. Table G-2 presents a summary of the visual condition index evaluations. In the first column of the table there are several abbreviations. The abbreviation for distress value is DV and that was measured as either high or low. TDV is the sum of all distresses. END is the equivalent number of distresses and ADV is the adjusted distress value. Only the three surface mixtures were evaluated during the VCI determination.

Table G-2: Astec DBG summary of visual condition index

	Distress		
	Astec DBG 15 % RA	DBG 15 % RA - 5 % RAS	DBG 50 % RA
DV-Low	10	21	28
DV-Medium	17	0	4
DV-High	0	0	0
TDV	11	27	32
END	1.3	1.8	2.7
ADV	25	18	21
VCI	7.5	8.2	7.9

Laboratory testing was conducted on six inch cores that were taken after two years of trafficking. Testing included air void determination, tensile strength ratio, resilient modulus and rut testing. Binder tests were also conducted on recovered binders from the cores. From the testing performed on the cores, it was found that the WMA mixtures were all performing along typical behavioural patterns historically seen in conventional HMA. It was also observed that the addition of recycled materials enhanced the performance of the WMA over the virgin WMA mix. This can be seen, for instance, in the tensile strength ratio results (Table G-3). The inclusion of recycled material allowed the WMA to meet the TSR minimum requirement of 80 %.

Table G-3: Astec DBG tensile strength ratio test results

Mixture Type	Average air voids content dry (%)	Dry indirect tensile strength (kPa)	Average air voids content conditioned (%)	Conditioned indirect tensile strength (kPa)	Tensile strength ratio (%)
Astec DBG Virgin	7.64	729.9	7.70	510.4	69.9
Astec DBG 15 % RA	6.63	1194.2	6.83	1005.9	84.2
Astec DBG 15 % RA & 5 % RAS	5.87	1199.2	5.87	1036.5	86.4
Astec DBG 50 % RA	7.33	860.8	7.30	703.1	81.7

Bitumen testing was performed for all four WMAs to evaluate the effect of the inclusion of recycled materials on bitumen stiffness. The results of the bitumen testing on a conventional HMA mixture and the extracted four Astec DBG process WMA mixtures are shown in Table G-4. The results indicate that less age hardening of the bitumen occurred over time. The authors believe this is due to the light ends contained in the bitumen are not being driven off during the production of WMA. They also reference recent research, which indicates that the light ends not evaporated during the mixture production are driven off during the first two years of road service.

In order to evaluate the rutting behaviour of the extracted bitumens at high temperature, values of G*/sin(δ) were plotted at different temperatures. Results are shown in Figure G-1. Notice the increase in G*/sin(δ) with the higher contents of recycled materials. This also suggests that the inclusion of a higher proportion of recycled materials (Astec DBG l5 % RA & 5 % RAS and Astec DBG 50 % RA) significantly change the bitumen properties at high and low temperatures.

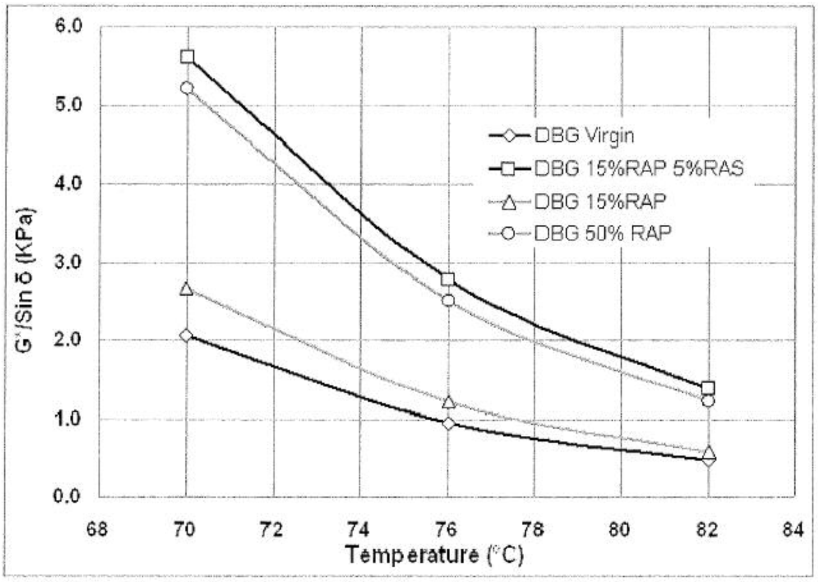

Figure G-1: Recovered bitumen G*/sin(δ) at different temperatures

Table G-4: Astec Double Barrel Green recovered bitumen characteristics

Tests on recovered bitumen		Binders extracted from core samples				
		HMA 80/100A bitumen virgin – RTFOT	Astec DBG virgin	Astec DBG 15 % RA	Astec DBG 15 % RA/ 5 % RAS	Astec DBG 50 % RA
Dynamic shear rheometer						
G*/sin(δ) kPa ≥2.2kPa	@64ºC	3.872	–	–	–	–
	@70ºC	1.775	2.076	2.676	5.615	5.209
	@76ºC	–	0.959	1.213	2.773	2.510
	@82ºC	–	0.470	0.581	1.388	1.229
Predicted failure temperature (ºC)		68.40	69.00	71.03	78.01	77.11

Table G-4: Astec Double Barrel Green recovered bitumen characteristics (cont.)

Tests on recovered bitumen		Binders extracted from core samples				
		HMA 80/100A bitumen virgin – RTFOT	Astec DBG virgin	Astec DBG 15 % RA	Astec DBG 15 % RA/ 5 % RAS	Astec DBG 50 % RA
Pressure ageing vessel residue (AASHTO R28)						
Dynamic shear rheometer						
G*/sin(δ) kPa ≤5000 kPa	@28ºC	–	–	–	4050	2388
	@25ºC	4079	4881	4157	5584	3238
	@22ºC	5658	6737	5773	–	–
Predicted failure temperature (ºC)		23.13	24.78	23.31	26.03	20.72
Bending beam rheometer						
Creep stiffness, MPa ≤300 MPa	@ -6ºC	–	–	–	76	90.7
	@ -12ºC	156	161	163	163	143
	@ -18ºC	287	323	316	–	–
Slope, m - value, MPa ≥0.300	@ -6ºC	–	–	–	0.330	0.316
	@ -12ºC	0.302	0.311	0.316	0.293	0.301
	@ -18ºC	0.259	0.270	0.270	–	–
Predicted failure temperature (ºC)		-22.30	-23.61	-24.09	-20.86	-22.40
Performance grade (PG)		PG 64-22	PG 64-22	PG 70-22	PG 76-16	PG 76-22
Initial performance grade (PG) construction stage		PG 64-22	PG 70-22	PG 70-22	PG 76-16	PG 72-16

G.2.2 Review of warm mix asphalt

(Chowdhury and Button, 2008) (Vol II, pp 45)

Chowdhury and Button reported that as of the writing of their report in 2008, nearly seventy field test sections had been constructed in the United States using WMA. The authors stated that no negative performance had been reported on as of their writing and that overall the sections are performing well. However, most of the sections that have been reported on have been in service for less than five years (Chowdhury and Button, 2008).

G.2.3 *Field performance of warm mix asphalt*

(Hurley and Prowell, 2006) (Vol II, pp 45-47)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Systems available in UK.
Climate:	Missouri is warmer than UK but Wisconsin is similar.

Field trials were constructed in St Louis, Missouri and Milwaukee, Wisconsin using the warm mix technologies Aspha-min®, Evotherm™ ET and Sasobit®. Data were obtained from the test sections in each location to determine the air voids immediately after construction and 6 months after construction. The results from the Milwaukee field trial are shown in Figure G-2 and the results from the St Louis field trial are shown in Figure G-3. No data were collected for the control section after 6 months in Milwaukee and for the control section immediately after construction in St Louis.

Immediately after construction in the Milwaukee trial, the WMA sections and the control all had similar air voids. For the St Louis trial, the warm mixture sections had lower in-place air voids than that of the control section. After the St Louis sections had been trafficked for four summer months (May through October), field rut depth measurements were taken. For all sections, the maximum rut depth was 1.1 mm. In Milwaukee, the average rut depths for the WMA sections were below 1 mm. Therefore, at the time of the report, the field performance indicates that the sections are rut resistant.

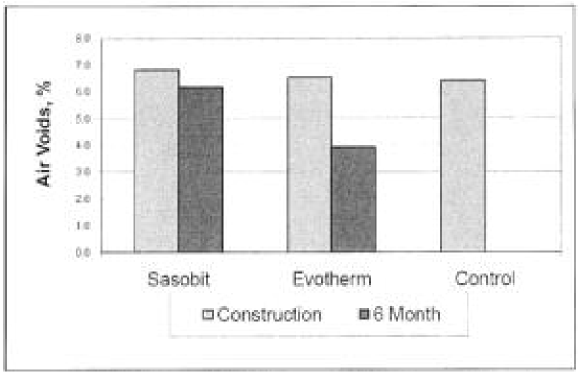

Figure G-2: In-place air voids contents, Milwaukee trial

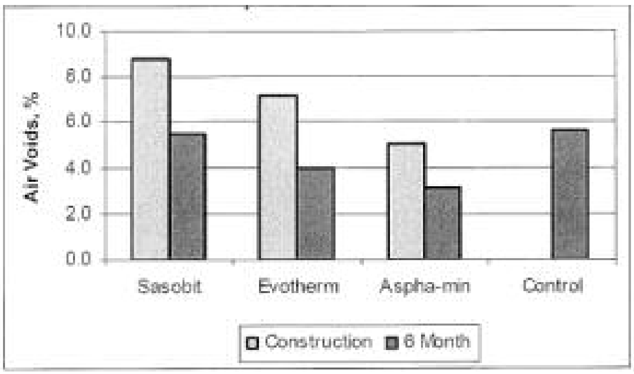

Figure G-3: In-place air voids contents, SL Louis trial

G.2.4 *Warm mix asphalt: European practice*

(D'Angleo *et al*., 2008) (Vol II, pp 47-48)

Many field demonstrations have been constructed in Europe over the last decade. In 2007, a scan team from the United States went to Europe to evaluate their progress with warm mixtures. The scan tour visited Belgium, France, Germany and Norway. The representatives in each country implied that WMA should perform the same if not better than HMA. The European representatives all stressed the importance of removing the moisture from the coarse aggregates to mitigate moisture problems. The European restrictions on moisture were more stringent than the United States: only aggregates with water absorptions of less than 2 % are allowed and the United States typically allows aggregates with up to 5 % absorption.

In France, a number of trials have been constructed. A toll road southwest of Paris was constructed in 2003 using Aspha-min® and the performance (as of time of the scan tour) was comparable to that of HMA. Six technologies have been trialled on small projects in Paris, including a bus lane. Projects built with the technologies are monitored for three years prior to approving the technology. Projects were built in Eure-et-Loir with Aspha-min® and ECOMAC. No performance data was presented on the latter projects.

In Germany, seven field test sections constructed between 1998 and 2001 were visited. Six of the mixtures were stone matrix asphalts (SMA) and the other was a dense-graded mixture. Four warm mix technologies were used for the construction of these sections, including Sasobit®, Asphaltan® B (not used in the United States), Aspha-min® and Sübit® (bitumen modified with Licomont® BS 100). Each test section constructed was accompanied by a companion HMA section for performance comparisons. Each section visited exhibited the same or better performance than the HMA sections.

In Norway, 28 sections were analysed that ranged in age from two to eight years. All the WMA sections used WAM-Foam. Some sections showed considerable deterioration, but the authors attributed this to damage from studded tyres. It was noted that similar damage was observed in HMA sections.

From their visit, the scan team observed the following key features about European methods for warm mix asphalt design, production and construction:

- Differences were noted in the design, production and placement of WMA between the European agencies visited. The European methods also had several differences from the methods used in the United States.
- In general, the aggregates used to produce WMA in the European countries visited had absorptions of less than 2 %. The maximum absorption for aggregates in France was 1 %. In the United States, this number can typically be as high as 5 %.
- All agencies visited stressed the need to ensure that the coarse aggregates are completely dried. In the United States, this may be more difficult due to the higher absorption proportion.
- European contractors blend and modify binders on a routine basis. In the United States, the performance grading system (with required supplier certification) hinders this possibility.
- While in the United States it is important to know if the warm mix additive changes the grade of the binder, European countries focus more on performance test results.
- Placement of HMA and WMA were the same in the countries visited. The only difference was the lower placement temperatures of the WMA.
- When compared to US contractors, European contractors are better equipped to research and develop new WMA technologies.

G.2.5 Warm mix asphalt technology: An overview of the process in Canada

(Davidson, 2008) (Vol II, pp 50-51)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Systems other than Aspha-min® available in UK, Aspha-min® from Germany.
Climate:	Similar but cooler than UK.

According to Davidson (2008), there are five warm mix processes that are currently being evaluated in Canada. Three of the processes are relatively new to Canada and have plans for field trials include Sasobit®, WAM Foam and foamed bitumen using the Astec Double Barrel Green system. The other two technologies, Aspha-min® and Evotherm™ ET and DAT, are more common in Canada and have had multiple field trials constructed (six for Aspha-min® and eleven for Evotherm™ ET as of this writing).

Three of the Aspha-min® trials were placed on roads in the city of Montreal in 2005. Two different binder grades were used to create the mixtures, including a PG 64-28 and a PG 70-28. No additional mixture information was provided. Hot mix sections were also placed in the trials for comparison. The HMA was mixed at 160 ºC and the WMA was mixed at approximately 135 ºC. The laydown temperature for the HMA was between 140 ºC and 150 ºC and between 110 ºC to 125 ºC for the Aspha-min® mixtures. After one year the sections were revisited and no distresses were present in any of the sections.

The other three Aspha-min® trials were completed in 2006. Two of the trials were placed in November during cold weather. The contractor responsible for the construction of the sections stated that the warm mixture was easier to compact than conventional hot mix and that there were no issues with construction.

From 2005 to 2006, four Evotherm™ ET trials were conducted in Canada. A PG 58-28 binder was used for all four mixtures. One of the trials used mixtures that contained 15 % RA. Additional mixture information was not provided in this paper, but further details can be found in other references by Davidson (56, 57 and 58). The mixtures were produced at temperatures around 25 ºC to 30 ºC lower than HMA. The production temperature of the HMA was not provided. The WMA compaction temperatures ranged from 85 ºC to 95 ºC. Recovered binder penetration values were analysed for one of the field trials to quantify the reduced ageing of the binder when using warm mix technologies. The WMA binder averaged a penetration of 80 while the HMA averaged 48. PG binder gradings were also performed.

In 2007, Evotherm™ DAT was used for two WMA paving demonstrations. One of the demonstrations was conducted in December 2007 because the road could not be paved with conventional hot mix during such cold weather. Because no asphalt plants were open near the paving site, the mixture was produced and hauled 460 km (eight hours) to the jobsite. The ambient temperature was -10 ºC and the mixture arrived at the jobsite at temperatures ranging from 90 ºC to 130 ºC. No additional mixture information was provided. At the time the article was written, the warm mix was performing well, with no distresses. In an Evotherm™ ET trial, samples of loose mixture and cores were obtained and tested to determine the resilient and dynamic moduli. Statistical testing showed that there was no significant difference between the HMA and WMA for both values.

Davidson stated that thus far, no issues have been encountered while paving with warm mixtures in Canada. Many of the trial sections were three years old and all were still performing well.

G.2.6 Investigation of foamed asphalt (warm mix asphalt) with high RA content for sustainment und rehabilitation of asphalt pavement

(Hodo *et al*., 2009) (Vol II, pp 52)

Relevance to UK	
Type of asphalt:	No reference to type used.
LTA system:	Available in UK.
Climate:	Warmer than UK.

A pavement built with Astec's DBG foaming WMA technology was constructed in Chattanooga, Tennessee in June of 2007. The WMA test section was constructed the day prior to mainline paving. Cores were extracted from the test section for laboratory testing. The in-place density of both mixtures from the test section was approximately 2 % lower than desired. The authors stated that this could have been prevented with more passes of the roller. There were no issues during the production of the warm mixture at the plant and the mixture had good workability except when the placement temperature dropped below 110 ºC. The authors recommended keeping the mixture above this temperature to ensure proper handling and compaction. After compaction, the sections had appearances similar to that of HMA and had no signs of distress after one year in service.

G.2.7 Incorporating high percentages of RA and WMA technology into thin hot mix asphalt overlays to be utilized as a pavement preservation strategy

(Mogawer *et al*., 2009) (Vol II, pp 52)

Relevance to UK	
Type of asphalt:	Asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Similar to UK.

A WMA field trial was constructed in October 2007 in Massachusetts using Sasobit® at a dosage of 1.5 % by weight of binder. A Superpave 4.75 mm NMAS mixture with a PG 52-33 binder with 30 % fractionated RA was used. The extracted binder from the RA graded as a PG 94-4. The aggregates were a blend of crushed stone (unknown type), manufactured sand and natural sand. Latex was also added to the mixture at a dosage rate of 1.5 % by weight of virgin binder to protect against cracking. The WMA was placed on a road that serves as the entrance to a recycling centre and heavy traffic loads were anticipated for the section. There were no issues with laydown, compaction or workability of the mixture. The authors stated that after almost a year of trafficking, there were no visible distresses on the warm mixture section.

G.2.8 Laboratory and field evaluations of foamed warm mix asphalt projects

(Wielinski *et al*., 2009) (Vol II, pp 53)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using Hveem rather than UK methods.
LTA system:	Available in UK.
Climate:	Warmer and drier than UK.

Two WMA paving demonstrations were performed in Indio, California in 2008. Both projects were paved using foamed bitumen produced using the Astec Double Barrel Green system. Both demonstrations consisted of a Hveem half inch mixture with a target stability of 39, bitumen content of 5.5 % and air voids of 4.4 %. No anti-stripping agent was used. A PG 70-10 binder was used for the mixture as well as 15 % RA. The authors did not specify what aggregate type was used. HMA control mixtures were constructed for each demonstration. The target plant discharge temperatures for the WMA and HMA were 135 ºC and 166 ºC.

The first demonstration placed in February 2008 was the entrance to a Granite Construction plant and used both HMA and WMA sections for comparison. The location of the demonstration was chosen because of the steep grades present and the heavy traffic (1.3 million tons of materials hauled annually).

The second demonstration was placed on Avenue 40 in March 2008. Approximately 1,050 tons of warm mixture were placed for this project. The bitumen contents for both the WMA and the control were consistent and ranged from 5.3 % to 5.5 %. The moisture contents of both the WMA and HMA ranged from 0.02 % to 0.08 % and there was not a significant difference between the two. The authors did not explain how they measured the moisture content values. Aggregate samples were obtained during production and the moisture contents ranged from 1.1 % to 1.7 %. On the second and third days of production, there was a considerable increase in sand equivalency (from an average of 55 to an average of about 70). This was not anticipated because the P_{200} value (air voids) ranged from 5.9 % to 6.3 % throughout the project.

For the first demonstration, field cores were extracted and tested for density. The WMA was compacted to about 93 % of G_{mm} and the HMA was about 92 % of G_{mm} (max.

density). These results indicate that warm mixture has better density than HMA using the same compactive effort. However, in the second demonstration the HMA had a higher in-place density (94 % of G_{mm}) than the WMA (93 % of G_{mm}). After a year of trafficking, the authors stated that both sections were performing well and that no visible distresses were present.

G.2.9 Weather-mix asphalt: Warm approach works in California, where climates of all kinds play

(Barros and Dmytrow, 2009) (Vol II, pp 54-56)

Relevance to UK	
Type of asphalt:	Mostly porous asphalt with some DBM.
LTA system:	Available in UK.
Climate:	Warmer and drier than UK.

At the time of the writing of the report, seven warm mix asphalt projects had been conducted in the state of California and were being evaluated by CalTrans. Four of the seven were open graded friction course mixtures with polymer-modified binders, two included rubberized asphalt concrete (RAC) and one was a standard dense-graded material. Additional warm mix projects are planned for 2009 and 2010 using open-graded rubberized asphalt concrete.

In 2006, a gap-graded RAC WMA trial section was conducted using Sasobit®. [No mixture information was provided.] The WMA trial is located on a shoulder of Highway 152 near Gilroy, California. After over two years, the section is still performing well.

In 2007, CalTrans began performing accelerated testing on WMA mixtures using a heavy vehicle simulator at the University of California Pavement Research Center. The manufacturers of three warm mix technologies participated in the study: the PQ Corporation (Advera®), MeadWestvaco (Evotherm™ DAT) and Sasol Wax (Sasobit®). [The mixture information and dosage rates of the warm mix additives were not provided.] The first phase of testing began in October 2007 and was completed in June 2008. Based on the results, it appears that WMAs can perform the same as conventional hot mix. The second phase of testing to evaluate moisture susceptibility is still underway.

A temporary detour was constructed using Evotherm™ DAT warm mix technology while State Route 70 was being realigned. The mixture was a dense-graded material made with a PG 64-16 binder. [The aggregate type was not specified.] The section had high truck traffic (15 %) and was located on an incline. After four months, the section was performing well with no signs of distress when it was removed.

A warm mix demonstration project was conducted on Highway I near Morro Bay using an OGFC with a PG 58-34 polymer-modified binder in May 2008. Three warm mix technologies were used, including Advera®, Evotherm™ DAT and Sasobit®. The aggregate type was not specified. A control HMA section was constructed as well. The haul time for the mixtures was one hour. After nine months in service, all sections were performing well and will be re-evaluated after the winter.

In Point Arena, California a warm mix section was constructed using Evotherm™. [The authors did not specify the Evotherm™ technology used, or any mixture information.] The warm mixture was hauled between three to four hours to the jobsite, yet still was produced at temperatures 11 ºC to 17 ºC lower than conventional hot mix. In general, the OGFC warm mixture had an improved appearance and was easy to compact.

Another warm mix technology was tested in California on the shoulder of I-5 also in May 2008. The Astec DBG system was used to produce the WMA. [No further mixture information was provided.] The production and placement temperatures were lowered by 14 ºC to 19 ºC. Two weeks later, another warm mix asphalt was constructed and the Astec DBG system was used in conjunction with Evotherm™ DAT. The production and placement temperatures were lowered by an additional 17 ºC by using both technologies together.

G.2.10 Field testing of warm mix asphalt

(West, 2009) (Vol II, pp 59-65)

The findings for several WMA field projects monitored by NCAT were presented at the WMA & Recycling Symposium in June 2009. The findings included data from 13 projects. These projects occurred from October 2005 to October 2008 and included demonstrations in Opelika and Birmingham, Alabama; St Louis, Missouri; San Antonio, Graham and Bridgeport, Texas; Iron Mountain, Michigan; Milwaukee, Wisconsin; Daytona, Florida; Nashville, Tennessee; Kimbolton, Ohio; Rock Hill, South Carolina and Royal, Nebraska. Mixture information, lift thicknesses, WMA technology, dosage rates, weather, production temperatures, tonnage, production rates and paving rate data were collected for each project, but were not provided in the presentation. This presentation represented an initial attempt to synthesize data from several of the projects previously presented individually in this literature review.

For one project, the rate of cooling of WMA and HMA were recorded over time using a temperature gun. The HMA appeared to cool at a faster rate than WMA due to its larger difference from ambient temperatures.

Mixture testing was conducted on plant-produced, laboratory-compacted materials, generally both with- and without reheating. The mixture testing included tensile strength, Hamburg wheel tracking device and APA rutting results, IDT creep compliance, dynamic modulus and flow number testing.

Tensile strength ratios (TSRs) were determined in accordance with AASHTO T 283 at 25 ºC. The TSR values for both HMA and WMA from the NCAT field project are shown in Figure G-4. As seen in the figure, WMA consistently had lower TSR values than HMA at compaction temperatures below 116 ºC. However, for temperatures greater than 118 ºC, there was no consistent trend between TSRs of HMA and WMA. A paired t-test showed that for temperatures less than 116 ºC, the TSR values of the WMA were significantly less than the HMA. At temperatures greater than 118 ºC, the TSR values of the HMA and WMA were not statistically different.

Hamburg wheel tracking device testing was performed on the samples in accordance with AASHTO T 324 at 50 ºC. The stripping inflection point results are shown in Figure G-5 with the red line indicating a stripping inflection criterion of 5,000 cycles. Statistical testing showed that the stripping inflection points for HMA and WMA were not significantly different for either of the same temperature groupings mentioned previously (less than 116 ºC and greater than 118 ºC). The rut depths from the Hamburg test are shown in Figure G-6. Again, statistical testing showed that the rut depths for HMA and WMA were not significantly different for either of the temperature groupings. However, the rut depths for the WMA are slightly higher when compared to the HMA. Rutting rates were also compared for HMA and WMA and the differences between them were not significant.

APA testing was performed on the samples in accordance with AASHTO TP 63 at the climatic base PG high temperature. Rut depth measurements for HMA and WMA are shown in Figure G-7. The results were divided into the same compaction temperature groups as before and tested with a paired t-test. The results showed that for temperatures less than 116 ºC, the WMA rut depths were significantly greater than the HMA rut depths. At temperatures above 118 ºC, there was no significant difference between the rut depths of the HMA and WMA. As for overall results, most WMA mixtures met the maximum 5.5 mm rut depth criterion, but typically did have higher rut depths than HMA.

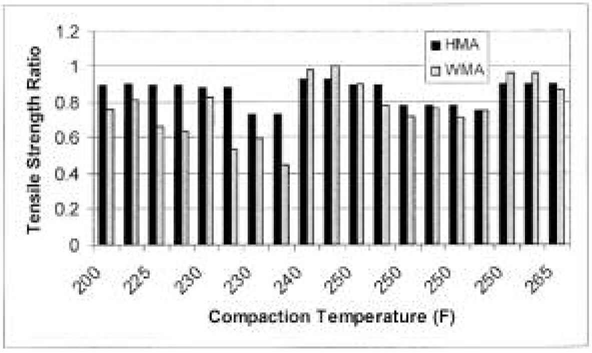

Figure G-4: TSR results for HMA and WMA

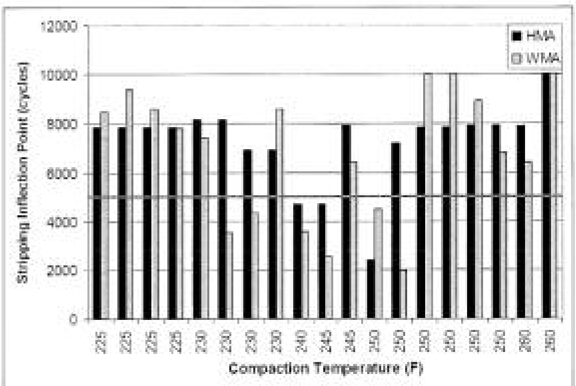

Figure G-5: Hamburg stripping inflection points for HMA and WMA

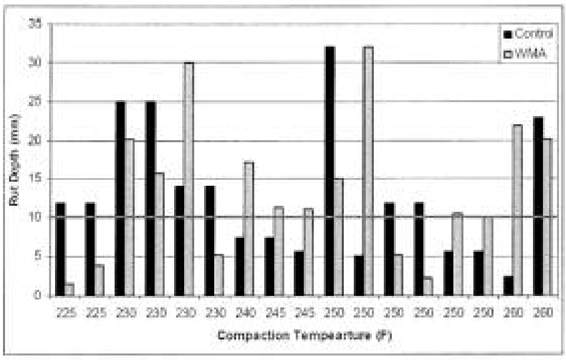

Figure G-6: Hamburg rut depths for HMA and WMA

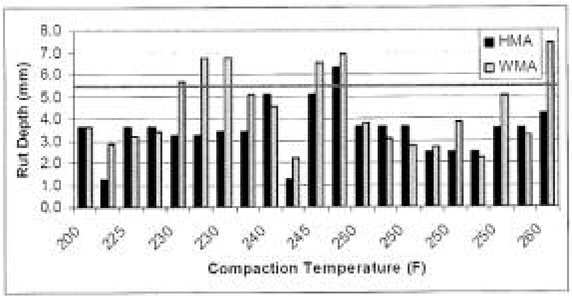

Figure G-7: APA rut depths for HMA and WMA

Solvent extractions and recoveries were performed to determine the continuous grades of the HMA and WMA after production. The high and low continuous grades of the HMA and WMA binders are shown in Figures G-8 and G-9, respectively. The original binder grades were not provided. From these results, it is apparent that the WMA mixtures did not age and harden as much as the HMA. However, in some cases the difference was not substantial.

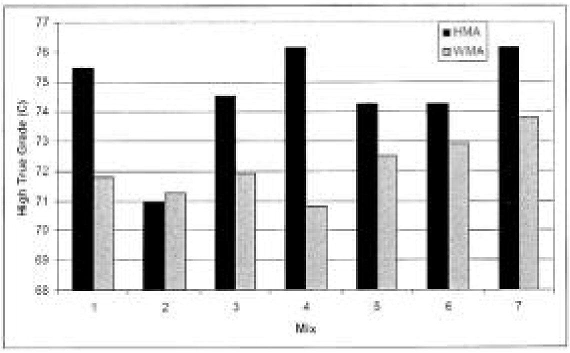

Figure G-8: High continuous grades for HMA and WMA

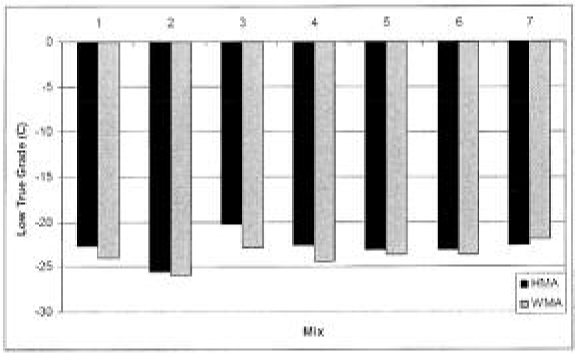

Figure G-9: Low continuous grades for HMA and WMA

Cores were obtained from three of the field demonstration locations and tested for indirect tensile strength. The oldest site where cores were extracted was approximately two-years old. The tensile strength results showed that the WMA strengths improved over time as the binders oxidized and some degree of curing occurred. After two years in service, the WMA and HMA had similar tensile strength values. Additionally, core analysis showed that the majority of densification of WMA occurs in the first six months in service.

From simple visual inspection of the paving sites, it appeared that HMA and WMA had the same amount of rutting and that the crack resistance of the WMA is at least equal to (and in some cases better) than HMA. Most importantly, none of the field trials had shown any signs of moisture damage thus far.

G.2.11 Michigan field trial of warm mix asphalt technologies: Construction summary

(Hurley *et al*., 2009a) (Vol II, pp 74-75)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Similar to UK.

Sasobit® was evaluated as part of a WMA demonstration in Michigan on M95. The condition of the pavement was assessed after two years of trafficking. Visual inspections were conducted to evaluate cracking and no cracking was observed. String line measurements were taken to determine the extent of rutting. Rutting was non-existent to minimal. Cores were obtained from both the WMA and HMA sections. The air voids in the Sasobit mixture reduced marginally after 2 years' service whilst the control material showed a significant reduction in air voids. The indirect tensile strength increased for both mixtures from the time of construction to after 2 years trafficking.

G.2.12 Missouri field trial of warm mix asphalt technologies: Construction summary

(Hurley *et al*., 2010a) (Vol II, pp 76-77)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Systems other than Aspha-min® available in UK, Aspha-min® from Germany.
Climate:	Warmer than UK.

A WMA demonstration was conducted in St Louis, Milwaukee on Hall Street in May 2006. The demonstration evaluated three WMA technologies; Evotherm™ ET, Sasobit® and Aspha-min®. A control HMA section was also constructed. The mixture design used for all four mixtures was a 12.5 mm NMAS surface Superpave mixture that contained 10 % RA. The base binder was a polymer PG 70-22. An anti-stripping agent, ARR MAZ Ad-here HP Plus, was added to the virgin binder.

Construction occurred at night over a ten day period. The control mixture was produced at 160 ºC and compacted at around 149 ºC. The WMA target compaction temperatures ranged between 93 ºC and 121 ºC. The mixtures were hauled approximately 25 minutes from the plant to the paving site. Paving and compacting operations were the same for all four mixtures.

The performance of the sections was monitored through two years of trafficking. String line rut measurements were obtained to quantify the extent of rutting. The average rutting ranged from 0.5 to 1.1 mm. Small reflective cracks were observed in the sections. Field cores were obtained and the air void content and indirect tensile strength (ITS) of each core was determined. The average air void content after two years was similar for the Aspha-min®, control, Evotherm™ ET and Sasobit® mixtures. Overall, the WMA had lower ITS values at the time of construction compared to the control mix, but gained strength within the first two years to be comparable to the control mix. The ITS for two technologies, Aspha-min® and Evotherm™ ET, decreased between 6-months and two-years. This could be testing variability or an indication of the beginning of moisture damage.

G.2.13 Preliminary evaluation of warm mix asphalt field demonstration: Franklin, Tennessee

(Kvasnak *et al*., 2009) (Vol II, pp 78-79)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Warmer than UK.

In October 2007, a WMA demonstration was conducted in Franklin, Tennessee on SR 46. Four WMA technologies were evaluated. The four WMA technologies were Astec DBG, Evotherm™ DAT, Sasobit® and Advera® WMA. Three plants were used to produce the WMA mixtures and so three Marshall mixture designs were used. All three of the designs were 12.5 mm nominal maximum aggregate size 75 blow Marshall mixtures. An SBS modified PG 70-22 bitumen used in all of the mixtures.

The Astec DBG was produced at 126 ºC. The Advera® WMA and Sasobit® were produced at 121 ºC. The Evotherm™ DAT was produced at 115 ºC. There were equipment issues on the job that were not related to the mixture that slowed down paving (i.e. rollers breaking down). There were no observed issues with paving any of the sections. Field cores were obtained from the WMA sections. Figure G-10 illustrates the density results of the field cores. The first set of field cores obtained for all of the WMA sections failed to meet the density requirements. A second set of field cores were obtained for each section and those average densities did meet the field density requirements.

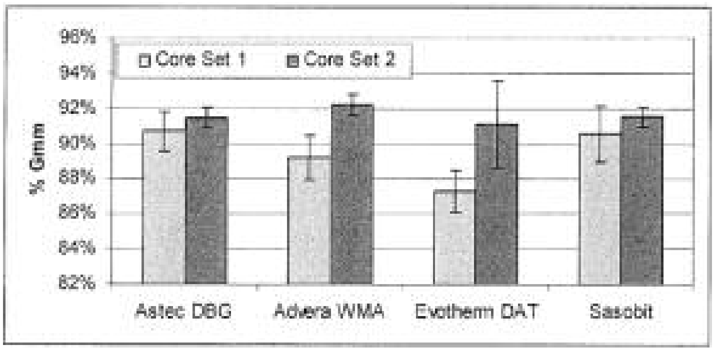

Figure G-10: Field densities after construction

The condition of the pavement was assessed after one year of trafficking. There were some spots in the control and Advera® WMA sections where bitumen was pooling on the surface of the pavement. The pools were about a half-dollar size. There was some ravelling exhibited in all of the sections. Cores were obtained from each section. Figures G-11 and G-12 illustrate the densities and ITS for each section. WP stands for cores taken from in the wheel-path while BW stands for cores taken from between the wheel-paths. From these figures, it can be seen that the core densities have a substantial impact on the tensile strengths.

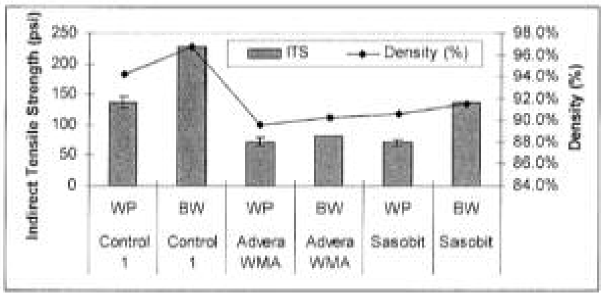

Figure G-11: Indirect tensile strength of cores for Franklin plant mixtures

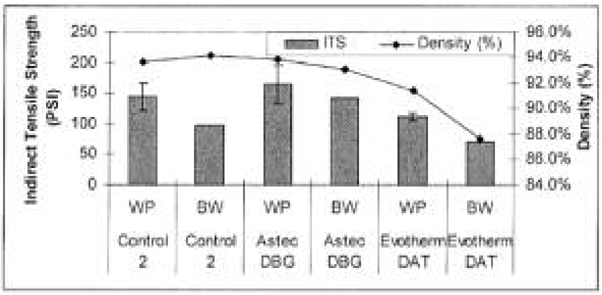

Figure G-12: Indirect tensile strength of cores for Danley and Murfeesboro plant mixtures

G.2.14 Preliminary results from the California warm-mix asphalt study

(Jones, 2009) (Vol II, pp 80-85)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using Hveem rather than UK methods.
LTA system:	Available in UK.
Climate:	Warmer and drier than UK.

The Phase I test sections were located at a quarry and commercial asphalt plant near Aromas, California. Each section included two 60 mm lifts of asphalt concrete. A standard Hveem mixture design was used and no adjustments were made to accommodate the WMA additives. Target production temperature for the Control mixture was set at 155 ºC and 120 ºC for the WMAs. The test sections were constructed in September 2007, using a drum plant at the quarry. Table G-5 summarises the quality control data for the mixtures.

Table G-5: Quality control of mixture after production

Parameter	Target	Range	Control	Advera	Evotherm	Sasobit
AC Binder Content (%)[1]	5.2	5.1 - 5.4	5.29	5.14	5.23	4.48
Moisture (before plant) (%)	–	–	0.24	0.41	0.37	0.31
Moisture (after silo) (%)	<1.0	–	0.09	0.25	0.32	0.25

[1] AASHTO T-308

The moisture contents of all four aggregate runs prior to entering the drum were lower than the Caltrans end-of-drum moisture content specification of 1.0 %.

Modifications to the asphalt plant to accommodate the warm-mix additives were overseen by the warm-mix technology providers. The Advera® and Evotherm™ were added to the mixture through pipes placed immediately below and above the bitumen supply line respectively, while the Sasobit® was blended with the bitumen in a tank prior to mixture production. The following observations from the mixture production were made:

- No problems were noted with producing the asphalt mixtures at the lower temperatures. The target mixture production temperatures (i.e., 155 ºC and 120 ºC) were achieved.
- The aggregate gradations of the four mixtures were similar, generally met the targets and were within the required ranges.
- Although a PG 64-16 bitumen was specified in the work plan, subsequent tests by the Federal Highway Administration indicated that the binder graded as PG 64-22. After blending, the Sasobit® binder graded as a PG 70-22.
- The binder contents of the Control and Advera® and Evotherm™ mixtures were similar and all close to the target. The binder content of the Sasobit® mixture was 0.72 % below the target and 0.62 % below the lowest permissible content. This discrepancy was considered likely to influence behaviour of the mix. The problem was attributed to a binder feed rate problem from the tanker during mixture production.
- Moisture contents of the mixture samples collected at the silos showed a more interesting trend. The moisture content of the Control mixture was just 0.09 %, considerably lower than those of the mixtures with additives, which had moisture contents of 0.25 % (Advera® and Sasobit® mixtures) and 0.32 % (Evotherm™). Although moisture contents in all mixtures were well below the minimum specified limit, the higher moisture contents of the WMA mixtures indicates that less moisture evaporates from the aggregate at the lower production temperatures.

The test sections were constructed using conventional equipment and followed conventional procedures. Some haze/smoke was evident on the Control mixture during transfer of the mixture from the truck to the paver. No haze or smoke was observed on the mixtures with additives. Construction procedures and final pavement quality did not appear to be influenced by the lower construction temperatures. The Advera® mixture showed no evidence of tenderness and acceptable compaction was achieved. Some tenderness was noted on the Evotherm™ DAT and Sasobit® mixture sections resulting in shearing under the rollers at various stages of breakdown and/or rubber-tired rolling, indicating that the compaction temperatures were still higher than optimal. No problems were observed after final rolling at lower temperatures. Tenderness on the Evotherm™ and Sasobit® mixture sections was not considered as being significantly different from that experienced with conventional mixtures during normal construction activities.

Average air-void contents on the Control and Advera® mixture sections were 5.6 % and 5.4 % respectively. Air void contents for the Evotherm™ and Sasobit® mixture sections, which both showed signs of tenderness during rolling, were approximately 7.0 %, with the caveat that the Sasobit® mixture binder content was lower than the target while that for the Evotherm™ mixture section was not. Based on these observations, it was concluded that adequate compaction could be achieved on warm-mixtures at the lower temperatures. Optimal compaction temperatures are likely to differ between the different WMA technologies.

The Heavy Vehicle Simulator (HVS) test section layout, test setup, trafficking and measurements followed standard University of California Pavement Research Center (UCPRC) protocols for the first and second phases of testing. An average maximum rut of 12.5 mm over the full monitored HVS test section was set as the failure criteria for the experiments.

The pavement temperature at 50 mm was maintained at (50±4) ºC in both phases to assess rutting potential under typical pavement conditions. Infrared heaters inside a temperature control chamber were used to maintain the pavement temperature. The pavement surface received no direct rainfall as it was protected by the temperature control chamber.

During Phase 1, the sections were tested predominantly during the wet season (October through March); however, it is unlikely that any water entered the pavement structure due to the confinement on both sides of the test sections. During Phase 2, each section was pre-soaked with water for a period of 14 days prior to testing, A 150 mm high dam was constructed around each test section and a row of 25 mm diameter holes was drilled to the bottom of the upper lift of asphalt away from the section and 254 mm apart. During testing, a constant flow of preheated water (50 ºC) was maintained across the section at a rate of 15 L/hour to try to induce moisture damage.

The HVS loading program for each section is summarized in Table G-6 All trafficking was carried out with a dual-wheel configuration, using radial truck tyres (1 1R22.5- steel belt radial) inflated to a pressure of 720 kPa, in a channelized, unidirectional loading mode. Load was checked with a portable weigh-in-motion pad at the beginning of each test and after each load change.

Rutting was measured with a laser profilometer and pavement temperatures were monitored using thermocouples imbedded in the pavement. A dedicated nearby weather station monitored ambient temperature, rainfall, relative humidity, wind speed and direction and solar radiation. The duration of the tests on the four sections varied from 170,000 load repetitions (Evotherm™) to 285,000 load repetitions (Sasobit®). A range of daily average temperatures was therefore experienced; however, the pavement temperatures remained constant throughout HVS trafficking.

Rutting behaviour (average maximum rut and average deformation) for the four sections was compared. The duration of the embedment phases on Section B (Advera®) and Section C (Evotherm™) were similar to that of the Control; however, the depth of the ruts at the end of the embedment phases on these two sections was slightly higher than the Control. In both instances, this was attributed to less oxidation of the binder during mixture production because of the lower plant temperatures and is unlikely to relate to early rutting on in-service pavements with typical highway traffic volumes. Additional binder testing to study effects of the additives on binder properties was beyond the scope of this phase of the study. The slightly greater moisture contents of these mixtures may also have had an influence. Rutting behaviour on the WMA sections followed trends similar to that of the Control in terms of rut rate (rutting per load repetition) after the embedment phase.

Although the Sasobit® performance cannot be directly compared against the Control due to the lower bitumen content of the Sasobit® section, it was concluded that the three WMA additives tested in this experiment will not significantly influence the rutting performance of the mix.

Table G-6: Summary of HVS loading programme

Phase	Section	Wheel Load (kN)	Repetitions	ESALs*	Cumulative ESAL on Section
1	Control	40	185,000	185,000	185,000
		60	10,000	54,900	239,900
	Advera®	40	170,000	170,000	170,000
	Evotherm™	40	185,000	185,000	185,000
	Sasobit® ‡	40	185,000	185,000	185,000
		60	100,000	549,014	734,014
	Sub-Total		835,000	1,328,914	–
2	Control	40	185,000	185,000	424,900
		60	80,000	439,200	864,100
		90	106,000	3,195,000	4,059,100
	Advera® ‡	40	157,000	157,000	327,000
		60	32,000	175,700	502,700
		90	431,500	13,006,100	13,508,800
	Evotherm™	40	166,000	166,000	351,000
		60	118,000	647,800	998,800
		90	68,000	2,049,600	3,048,400
	Sasobit® ‡	40	152,000	152,000	886,014
		60	137,000	752,000	1,638,014
		90	175,500	5,289,900	6,927,914
	Sub-Total		1,807,500	26,200,400	–

* ESAL = Equivalent Standard Axle Load

‡ Testing terminated before failure criteria was reached

The Phase 2 testing on the four sections was started in the summer of 2008 and ended in the spring of 2009. The duration of the tests on the four sections varied from 352,000 load repetitions (Evotherm™) to 620,000 load repetitions (Advera®).

Embedment phases were noted at each load change on all sections. There was a distinct difference in performance of the Advera® and Sasobit® sections compared to the Control and Evotherm™ sections, in that the latter two sections rutted at a notably faster rate than the former two sections. The Control and Evotherm™ sections were shaded by an adjacent shed for much of the day, while the Advera® and Sasobit® sections had sun for most of the day. Binder testing is underway to determine if different ageing played a role in this behaviour. Trafficking was terminated on the Advera® and Sasobit® sections before the failure criterion was met in the interests of completing the study. None of the sections showed any indication of moisture damage on completion of testing.

Top-down cracking was observed in all four sections, with no significant difference in the crack patterns, crack length, or crack density between the sections. Cracks did not appear to penetrate below the top lift of asphalt on any of the sections.

A forensic investigation, consisting of core and test pit assessments provided no indication of moisture damage in any of the sections. Rutting on all four sections was confined to the top lift of asphalt only. Debonding of the top and bottom lifts of asphalt was observed on the Control section only. Determining the reason for this was beyond the scope of this phase of the study, but may be investigated at a later stage. A tack coat was used between lifts.

Although the lower bitumen content of the Sasobit® section confounded its comparison to the control HMA, this phase of testing further reinforced findings from the first phase that the three warm-mix asphalt additives do not negatively influence the rutting performance of the mix. The results also indicate that the three warm-mix additives did not increase the moisture sensitivity of the mixtures compared to the Control. Binder ageing of the warm and hot mixtures and its effect on performance over time deserves further investigation.

G.2.15 Summary of field performance

(Vol II, pp 87)

The construction and field performance of several WMA pavements has been documented and compared to HMA pavements. The construction conclusions have indicated that with the exception of plant modifications for introducing a WMA technology the production and placement equipment for WMA is the same as those used for HMA. Several reports on construction did indicate that the rate of production was reduced when a WMA technology was produced. It was also emphasized in some of the reports from contractors that the flighting in a drum plant was adjusted to increase the aggregate dwell time in the drum.

Most studies reported that WMA was placed without any issues. In a few cases there were issues with material sticking to truck beds and compaction. Comparisons of in place WMA to HMA have indicated that despite concerns about moisture damage and rutting, the WMA pavements are performing similar to that of the HMA. Field cores of WMA pavements at the time of construction through two years indicate that WMA pavements rapidly increase in tensile strength and often result in similar ITS values to that of HMA after two years. The results of the literature review suggest that WMA is performing at least as well as the HMA.

G.3 NCHRP Project 9-49, Performance of WMA technologies: Stage I – Moisture susceptibility

(Vol II, pp 145 – Vol III, pp 45)

G.3.1 WMA Technologies

(Vol II, pp 147-148)

WMA technologies allow for the production and placement of asphalt concrete paving materials at temperatures approximately 28 ºC cooler than the temperatures typically used in the production of HMA. There are a number of technologies that satisfy this definition through different mechanisms and provide economic, environmental, and engineering benefits in terms of reduced viscosity of the binder and/or mix to allow for complete coating of the aggregate by the binder, sufficient adhesion between the aggregate and binder, and mixture compactibility at lower temperatures (Diefenderfer *et al*., 2007). Table G-7 presents a summary of the results of laboratory studies on four different WMA technologies.

WMA technologies as described in this section can be classified by process type as those where water is introduced (foaming) or those where water is typically not utilized (additive). Reductions in viscosity at lower temperatures are realized with the foaming technologies through the expansion of water as it turns to steam. The additive technologies rely on surfactants, rheology modifiers, and/or other organic material or waxes alone or combined with each other. More detailed information on each of the WMA technologies, including necessary plant modifications and experience/usage in the United States can be found elsewhere (NAPA, 2008; Prowell et al., 2011). The majority of large volume field sections in the United States utilise Double Barrel® Green, Evotherm™, Sasobit®, and Advera® WMA, because these were the first available WMA technologies (Prowell et al., 2011).

Table G-7: Studies of the laboratory performance of different WMA technologies

WMA technology	Test method	Reference	Conclusions
Advera®	HWTT	Austerman *et al.*, 2009	Based on SIP: Mixtures are more moisture susceptible More moisture susceptible vs. Sasobit®
Aspha-min®	Adhesive Bond Strength	Wasiuddin et al., 2008	No significant effect on SFE No significant improvement in wettability Increased adhesion for PG 70-28; no effect for PG 64-22
	HWTT	Hurley and Prowell, 2006	Less rutting resistance vs. HMA control Hydrated lime improves rutting resistance
Aspha-min® (Cont.)	ITS/ITSR	Hurley and Prowell, 2006	Lower ITS at reduced ageing and compaction temperatures Improved ITS and TSR at higher short-term ageing temperature Lower TSR values vs. HMA control TSR values <80 % Hydrated lime reduced moisture susceptibility
Sasobit®	Adhesive Bond Strength	Wasiuddin *et al.*, 2008 and Wasiuddin *et al.*, 2011	Increased wettability Decrease in dry cohesive strength by -25 % Decrease in binder-aggregate adhesive bond by -30 % Reduced total SFE of the binder
	HWTT	Austerman *et al.*, 2009	Based on SIP: Mixtures are more moisture susceptible Less moisture susceptible vs. Advera®
		Hearon & Diefenderfer, 2008	Based on rut depth at20,000 cycles: No difference in rutting of WMA vs. HMA
		Hurley & Prowell, 2006	Improved rutting resistance with limestone but not with granite aggregate Anti-stripping additive improves rutting resistance
		Mohammad *et al.*, 2008	No difference in rutting vs. control
	ITS/TSR	Hearon & Diefenderfer, 2008	Improved TSR after long-term ageing of the mixtures TSR improved with higher mixing temp. TSR > 80 % in all cases where anti stripping additives were used
		Hurley & Prowell, 2006	Lower ITS values vs. HMA control TSR values < 80 % - Improved TSR with use of anti-stripping additive
		Mohammad *et al.*, 2008	Lower ITS values vs. HMA control Statistical significant differences in ITS vs. HMA control for aged specimens No significant differences for TSR

Table G-8: Laboratory tests for characterizing moisture susceptibility

Category	Tests & standards	Moisture conditioning	Output
Uncompacted loose mixtures or component	Boiling Water Test ASTM D3652 Ultrasonic	Boiling water, 10 min	Level of stripping by visual rating
	Accelerated Moisture Conditioning (UAMC)	Ultrasonic conditioning in 60 ºC water bath, 5h	Mass loss
	Net Adsorption Test (NAT)	Wet condition (presence of water)	Amount of bitumen remaining on the aggregate surface after desorption
	Surface Free Energy (SFE)	Wet condition (calculated)	Conditioned to unconditioned adhesive bond strength ratio
	Bitumen Bond Strength (BBS)	Wet condition (presence of water) or conditioned specimens	Maximum pull-out tensile force
Comparison of conditioned mixtures and unconditioned	Modified Lottman Test AASHTO T283	Partial vacuum saturation, 1 optional F/T cycle, and 60ºC water bath	Conditioned Indirect Tensile Strength (ITS), unconditioned ITS, conditioned to unconditioned tensile strength ratio (TSR)
	Immersion-Compression Test AASHTO T165	60ºC water bath	Conditioned and unconditioned compressive strength ratio
	Energy Ratio (ER)	Vacuum saturation and cyclic pore pressure with hot water	Dissipated creep strain energy – DCSE
	E*/ECS AASHTO TP 62 AASHTO TP 34	Environmental Conditioning System (ECS)	Conditioned to unconditioned E* stiffness ratio (ESR)
	Resilient Modulus ASTM D4123	Partial vacuum saturation, optional F/T cycle, and hot water bath	Conditioned M_R, unconditioned M_R, conditioned to unconditioned M_R ratio
	Dynamic Mechanical Analyser (DMA)	Partial vacuum saturation, 1 h	Conditioned to unconditioned crack growth index ratio at 10,000 cycles
Repetitive loading in the presence of water	Hamburg Wheel-Tracking Test (HWTT) AASHTO T324	50 ºC water bath	Rut depth at 20,000 load cycles and Stripping Inflection Point (SIP)
	Asphalt Pavement Analyzer (APA) AASHTO TP 63	Partial vacuum saturation, 1 F/T cycle, 60 ºC depth ratio water bath and testing water bath at PG high temperature	Conditioned to unconditioned rut
	Model Mobile Load Simulator 3 (MMLS3)	60 ºC water bath	Visual stripping evaluation, conditioned to unconditioned rut depth ratio, and conditioned to unconditioned TSR
Repetitive loading in the presence of water (Cont.)	Moisture Induced Stress Tester (MIST)	Unsaturated specimen with water at 60ºC under compressed air and vacuum cycles	Visual stripping evaluation, change in bulk specific gravity, and conditioned to unconditioned TSR

G.3.2 Laboratory Characterisation

(Vol III, pp 4-6)

To evaluate the moisture susceptibility of specific binder-aggregate combinations and the effectiveness of minimization strategies including the use of anti-stripping agents and good construction practices, laboratory testing is utilized in the mix design stage on LMLC specimens or as a forensic tool on PMFC cores. As part of these laboratory testing methods, laboratory moisture-conditioning protocols are followed before testing mixtures in a wet or conditioned state. In some cases, the measured properties are compared with corresponding properties measured in a dry or unconditioned state. An ideal laboratory moisture-conditioning protocol should accelerate the penetration of moisture through the binder film and, at the same time, minimize complicating effects such as damaging the structure of the mixture.

The laboratory approaches shown in Table G-8 with their corresponding test methods include boiling the mixture in a loose state or utilizing Ultrasonic Accelerated Moisture Conditioning (UAMC), vacuum saturation of the compacted mixture, soaking the compacted mixture in a hot water bath, freezing the mixture, and cycling pore water pressure to more closely simulate field conditions. Other approaches apply repetitive loading in the presence of moisture. These conditioning protocols and associated laboratory tests for assessing mixture susceptibility to moisture damage are described in this section based on categorization of the representative tests as shown in Table G-8 as:

(1) tests on loose uncompacted mixtures or component materials,
(2) tests that mechanically measure stiffness or tensile strength of laboratory-compacted specimens or field cores before and after moisture conditioning to simulate field conditions, and
(3) tests that utilise repetitive loading of compacted mixtures in the presence of water.

The relationship with field performance is the ultimate test of laboratory characterisation methods for identifying moisture-susceptible asphalt concrete paving mixtures and the effectiveness of materials (binder-aggregate compatibility and/or anti-stripping agents) and methods (increased density) to combat the deteriorative effects of moisture. Table G-8 is not exhaustive, but the representative list captures the commonly used and currently available tests that were adopted as national standards and recently developed and promising methods. Solaimanian *et al*. (2003) and Santucci (2010) provide a more extensive list that includes less commonly used and older test methods.

G.3.3 WMA field experience

(Vol III, pp 29-31)

Many different contractors across the United States and Canada have used WMA in demonstration or trial projects. Selected examples of contractors' experiences as reported by NAPA and by the Canadian Technical Asphalt Association are listed in Table G-9 (Aurilio and Michael, 2008; Forfylow and Middleton, 2008; Hughes et a1.,2009; Johnston *et al*. 2008; Manolis *et al*., 2008 ,2009; NAPA, 2008). The concerns and/or objectives of the trial pavements and the lessons learned from the studies are summarised. These examples demonstrate that WMA is an effective and environmentally friendly material with tangible benefits and overall appropriate performance.

The majority of the agencies that have evaluated field performance of trial or routine WMA pavements indicate that they are in good condition and showing no signs of moisture damage (Brown, 2008; Diefenderfer and Hearon, 2010; Estakhri *et al*.,2010; Kim *et al*.,2010; Prowell *et al*., 2007; Prowell *et al*., 2011). Exceptions are one project located in Franklin, Tennessee (wet, no freeze climate) and another located in Kimbolton, Ohio (wet, freeze climate), where the occurrence of ravelling has been reported.

The project in Ohio is located on SR-541 and was built in 2006 using Evotherm™, Sasobit® and Aspha-min®, along with a control HMA section. Each section was approximately 10 miles long. The materials used in the mixture included a PG 70-22 modified binder with 15 % RA and limestone aggregate. The compaction temperatures of the WMA ranged from 110 ºC to 127 ºC. After periodic monitoring of the pavement, the Ohio DOT reported that the WMA sections were showing signs of ravelling (i.e., loss of aggregate from the pavement surface). From the visual observations, the Evotherm™ section had the smallest degree of distress while the Sasobit® showed the greatest. Factors contributing to the ravelling were attributed to poor construction practices (i.e. mixture dragging under the screed and poor handwork) as well as the lower placement temperatures, especially for Sasobit® (Hurley *et al*., 2009).

The project in Tennessee is located on SR-46 and was built in 2007 using Advera® WMA, Astec DBG®, Evotherm™ DAT, and Sasobit® plus two control HMA sections. The WMA pavements were produced between 115 ºC and 127 ºC and placed at 110 ºC.

Table G-9: Documented trial WMA pavements

Contractor	Location	Date	Tech-nologies	Production temp.	Compaction temp.	Concerns/objectives	Lessons learned
Boggs Paving, Inc.	York Co., SC	Oct 2007	Astec DBG®	132 ºC	88 ºC	– Use high contents of RA in WMA	– Up to 50 % RA was incorporated – Appropriate densification was achieved – Rutting performance adequate
Graniterock	Northern California: San Benito Co., Hwy 152, Santa Clara Co.	Spring 2006	Aspha-min®, Evotherm™, Sasobit®	127 ºC	121 ºC	– Effective production of WMA – Changes in the paving process – Service life of the WMA – Long-term benefits of WMA – Differences between WMA technologies – Use of rubberized bitumen in WMA	– WMA improved workability of rubberized bitumen – Technologies have their limits – Proper technology selection should be done depending on the characteristics of the job
Hubbard Construction Co.	Florida State Rd., 417 and Orlando, FL	Feb 2006 and 2007	Aspha-min®, Astec DBG®	121-143 ºC	107-127 ºC	– Use of WMA with open graded friction course – Drain-down potential	– Compaction window was extended – Workability was improved – Less measured drain-down with WMA – No shoving was observed soon after opening to traffic – Starting paving at a higher temperature and gradually reduce it to find optimum
Lehman-Roberts Co.	Memphis, TN	Dec 2007, April 2008	Terex®	127 ºC	118 ºC	– Volumetrics of the WMA – Use of RA in WMA	– Comparable volumetrics to HMA – Tender compaction zone was avoided

Table G-9: Documented trial WMA pavements (cont.)

Contractor	Location	Date	Tech-nologies	Production temp.	Compaction temp.	Concerns/objectives	Lessons learned
LoJac Enterprises, Inc.	State Rd 46, Williamson County, TN	2007	Astec DBG®	127 ºC	110 ºC	– Workability – Rutting – Internal moisture – Freeze/thaw damage – Moisture susceptibility and stripping problems – Applicability of HMA mix design to WMA	– Harder to achieve target compaction at very low temperatures – Starting construction at a higher temperature and gradually reducing it worked best
Shelley & Sands, Inc.	Ohio State Route 541	Sep 2006	Aspha-min®, Evotherm™, Sasobit®		110-127 ºC	– Reduced bitumen fumes at the plant and paving site – Reduce energy consumption – Extend the paving season – Increase haul distance – Use of RA in WMA	– Reduction in emissions as high as 77 % – Promising technology with no apparent performance trade-off
Suit-Kote Corp.	State Rt. 11, Cortland, NY	Jul 2006	Low-Energy Asphalt – LEA	93 ºC	82-96 ºC	– Resistance to heavy traffic soon after construction	– Good in-place and less variable density achieved – WMA exhibited less cracking vs. HMA – Energy consumption reduced by 47 % – Good performance of WMA after 1-vr in-service
Bitumar, Inc.	Victoria St, Ottawa	Oct 2007	Sasobit®	129 ºC	110 ºC	– Evaluate the performance of WMA using Sasobit® – Change in paving and compaction procedures – Costs	– No problems encountered during production, paving, or compaction of WMA – Fuel savings of up to 30 % vs. HMA

Table G-9: Documented trial WMA pavements (cont.)

Contractor	Location	Date	Tech-nologies	Production temp.	Compaction temp.	Concerns/objectives	Lessons learned
Coco Asphalt Engineering	Ramps on Hwy 401, Hamilton, Ontario	Oct 2008	HyperTherm ™	124 ºC	93 ºC	– Compare performance properties of WMA vs. HMA – Evaluate use of polymer-modified binder in WMA.	– Both WMA and HMA had acceptable moisture susceptibility characteristics – WMA had marginally larger rutting levels – WMA had better fatigue characteristics vs. HMA
LaFarge Inc.	Taradale, Calgary, Alberta	Aug 2005	Warm-Foam	102 ºC	N/A	– Calibration and coordination of the soft binder, water for foaming, and hard binder – Moisture susceptibility potential	– Similar volumetric characteristics of WMA vs. HMA – Fatigue performance of WMA better vs. HMA
LaFarge, Inc.	Katimavik Rd and Oxford Rd 4, Ottawa	Oct-Dec 2007	HyperTherm ™	121 ºC	113 ºC	– Extend the paving season by placing WMA during cold weather	– WMA can be placed in extreme cold temperatures – WMA provides increased workability
LaFarge, Inc.	Vancouver, British Columbia	Sept 2007	Astec DBG®	129 ºC	N/A	– Evaluate economic, environmental and performance factors to assess the sustainability of WMA – Evaluate introduction of RA and RAS	– At a mixing temperature of 121 ºC with 50 % RA non-uniform coating occurred – Compaction of WMA with RA and RAS was enhanced and workability improved – Moisture susceptibility is not affected negatively by the DBG® process – Energy savings of 24 % and emissions reductions of 10 % – Visual evaluation after two years showed good performance

Table G-9: Documented trial WMA pavements (cont.)

Contractor	Location	Date	Tech-nologies	Production temp.	Compaction temp.	Concerns/objectives	Lessons learned
McAsphalt Industries	Hwy 111, Saint John, New Brunswick	2007	Evotherm™	129 ºC	93 ºC	– Physical properties and performance comparison of WMA vs. HMA	– Significant decrease in fumes – Safer and more pleasant work environment – WMA more workable – Easier to achieve required density – Less segregation observed in the WMA – Tighter longitudinal joints achieved with WMA – Good performance after 1 year in service
	Rt. 106, Allison, New Brunswick	2008	Evotherm™ 3G	129 ºC	118 ºC		
	Rt. 135, Burnsville, New Brunswick	2008	Evotherm™ 3G				

Visual inspections were conducted after 1 year in service. During the assessment, it was noted that the control HMA pavements exhibited ravelling as well as the Astec DBG® and the Evotherm™ DAT along the centreline of the pavement. The Sasobit® was less affected by ravelling. Ravelling in the Advera® WMA pavement was more severe, especially in areas shaded by trees. Tests performed on extracted cores from the pavements indicate that the HMA control had the highest ITS values, while the Advera® WMA and the Sasobit® exhibited significantly lower ITS values (Kvasnak *et al*., 2070). Despite the occurrence of ravelling in these two pavements, the distress was neither severe nor extensive and the reports did not indicate that the functionality or ride quality of the pavement was impacted.

G.4 NCHRP Project 9-49A, Performance of WMA technologies: Stage II – long-term field performance

(Vol III, pp 46-70)

G.4.1 San Antonio Loop 368, Texas

(Estakhri. *et al*. 2010; Button *et al*., 2007) (Vol III, pp. 48-49)

Relevance to UK	
Type of asphalt:	Unstated asphalt type.
LTA system:	Available in UK.
Climate:	Hotter and drier than UK.

Texas Department of Transportation (TxDOT) placed their first warm mix asphalt trial using the Evotherm™ ET technology on Loop 368 of the San Antonio District in 2006. The existing pavement (prior to placement of the warm mix and control) consisted of a cold-milled asphalt surface that had been seal coated with AC-15P and a Grade 4 pre-coated aggregate. The thickness of the WMA overlay is 51 mm. Plant-produced loose WMA and HMA mixtures were reheated in the laboratory to prepare gyratory samples. The compaction temperatures for WMA and HMA mixtures were 115 ºC and 149 ºC, respectively. These samples were used to conduct laboratory tests including Hamburg Wheel Tracking test (HWTT), overlay test, and density test using X-ray CT images.

Both WMA and HMA pavements were evaluated one month, one year, and three years after pavement construction based on field performance evaluation and laboratory testing on field cores (HWTT, overlay test, resilient modulus test, and air void distribution using X-ray CT). As indicated from one-year cores, HMA samples had clear bitumen absorption while no bitumen absorption was found in the WMA samples (Figure G-13). The WMA and HMA samples obtained one year after construction behaved similarly in the HWTT and overlay tests. After three years, some cracking started to develop in both the WMA and HMA sections, as shown in Figure G-14. However, there is no evidence of any rutting in either WMA or HMA sections.

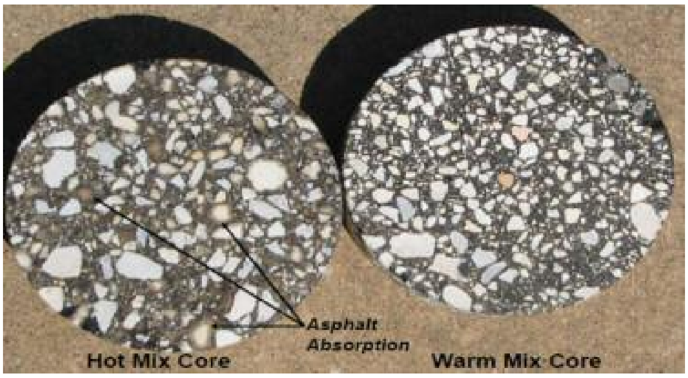

Figure G-13: Photos of Loop 368 one-year cores

Figure G-14: Evidence of cracking in both WMA and HMA sections

G.4.2 Austin SH 71, Texas

(Estakhri *et al*., 2010) (Vol II, pp 50)

Relevance to UK	
Type of asphalt:	Unstated asphalt type.
LTA system:	Available in UK.
Climate:	Hotter and drier than UK.

The Austin SH 71 project was constructed in 2008 using Evotherm™ DAT technology along with an HMA control section. The production temperatures were 165 ºC for HMA and 115 ºC for WMA. The design mixture was a Type C dense-graded mixture for both WMA and HMA. The thickness of the overlay is 51 mm.

Soon after construction, both WMA and HMA cores were taken and tested using HWTT rutting test and indirect tensile strength test. HWTT results indicated that the rutting resistance of HMA is better than that of Evotherm™ DAT technology. Indirect tensile strength test results showed that the HMA is stronger than WMA. Based on the results of ground penetration radar (GPR), the WMA pavement had similar in-place density and uniformity as the HMA control section.

After one year of service, field cores were taken from both WMA and HMA pavements to conduct laboratory tests. Tests on these cores included air voids, indirect tensile strength, overlay test, and HWT test. Visual survey indicated that the pavements performed well after one year's service and there were no signs of distress in either HMA or WMA pavement sections.

G.4.3 Lufkin FM 324, Texas

(Estakhri *et al*., 2010) (Vol II, pp 50)

Relevance to UK	
Type of asphalt:	Type D asphalt concrete, similar to DBM.
LTA system:	Available in UK.
Climate:	Hotter and drier than UK.

In 2008, the Lufkin district placed WMA pavement field trials with four different WMA technologies, Sasobit®, Evotherm™ DAT®, Akzo Nobel Rediset® and Advera®. HMA pavement was also constructed as a control. A Type D dense-graded mixture was used for both HMA and WMA, with a production temperature of 165 ºC for HMA and 115 ºC for WMA. The thickness of WMA layer is 38 mm.

During construction, TTI's Pave-IR System was used to evaluate the thermal characteristics of the WMA and HMA materials. Pave-IR thermal images indicated that the temperature of HMA material is higher than that of WMA material. The WMA pavement also had a more uniform temperature distribution. Plant-mixed mixtures were cured for 2 hours at 121 ºC for the HMA and 104 ºC for all of the WMA, followed by on-site compaction. These samples were sent to laboratory for HWTT testing and overlay testing. HWTT results indicated that only the Sasobit® and HMA mixtures passed the HWTT criteria. Overlay test results showed that compared with the HMA, the Advera® and Evotherm™ improved dramatically in cracking resistance.

Visual inspection indicated that all four WMA pavement sections and the HMA control sections performed well in the first year of service. No evidence of rutting or cracking has been observed. Field cores were also taken for conducting air voids testing, indirect tensile strength testing, overlay testing, and HWT rut depth testing.

G.4.4 Fort Worth BU 287 Project, Texas

(Estakhri *et al*. 2010) (Vol III, pp 50-51)

Relevance to UK	
Type of asphalt:	Type B and Type D asphalt concretes, similar to DBM.
LTA system:	Available in UK.
Climate:	Hotter and drier than UK.

In 2008, the Fort Worth project was constructed on BU 287 north of Saginaw using Evotherm™ DAT, but with no HMA control section. A similar pavement, SH114 in the Fort Worth district was used for comparison. The average daily traffic of the road was 24,100 vehicles per day. The existing pavement structure varies throughout the project. Much of the cross-section consists of several inches asphalt concrete pavement over 203 mm of crushed stone flexible base. A portion of the project is CRCP with an existing 89 mm overlay which was milled and replaced; and another portion consists of jointed concrete pavement. The WMA project consists of two portions, 254 mm Type-B WMA shoulder rehabilitation and 89 mm of type-D WMA resurfacing on the entire project. The mixture production temperatures at load-out were 115 ºC for Type-B WMA mixture and 135 ºC for Type-D WMA mixture.

Cores were taken at the time of construction and then after one year's service. HWTT, indirect tensile strength test and air void measurements were conducted for both Type-B and Type-D WMA mixture.

The pavement was evaluated for the field performance. The GPR data revealed that the almost 355 mm thick WMA shoulder on BU 287 was uniformly compacted throughout the depth with no signs of any defects. Two months after construction, falling weight deflectometer (FWD) tests were performed on the WMA section and a similar HMA section. Based on testing data, there was no significant difference in structural strength characteristics of the two pavements. After one year service, the WMA section performed well with no evidence of rutting or cracking distress.

G.4.5 SR-79, Alabama

(Kvasnak *et al*., 2010) (Vol III, pp 51-52)

Relevance to UK	
Type of asphalt:	Unspecified.
LTA system:	Available in UK.
Climate:	Hotter than UK.

This project was constructed in the northwest of Tarrant City, Alabama on SR-79 in 2007. The majority of the project was a two-lane highway, and the WMA and the associated HMA control mixtures were placed in the southbound lane. The project used Evotherm™ DAT as the WMA additive. RA and recycled asphalt shingles (RAS) were included in both WMA and HMA mixtures. The production temperature ranged from 107 ºC to 124 ºC for WMA mixture and 146 ºC to 180 ºC for HMA mixture.

Loose mixtures were sampled to determine bitumen content, bitumen properties, and aggregate gradations. Plant-produced mixtures were compacted in the field and tested using HWTT, indirect tensile strength test and asphalt pavement analyzer (APA) test for evaluating moisture susceptibility, rutting resistance and cracking potential of the mixture. Additional specimens were reheated and compacted in the laboratory for conducting dynamic modulus and flow number testing. TSR test results showed that the HMA specimens exhibited higher tensile strengths and tensile strength ratios (TSR) than the WMA. The results from the APA, HWTT, flow number and dynamic modulus test consistently indicate that the WMA mixture was less stiff and slightly more rutting-susceptible than the HMA control mixture. Indirect tensile strength tests showed that compared with other mixtures placed, the WMA is less resistant to load-induced damage (e.g. fatigue cracking). The Hamburg wheel tracking results indicated that the WMA may be more susceptible to stripping damage than the HMA although all mixtures passed the Hamburg stripping inflection criterion of a minimum of 5,000 cycles.

Three site revisits were conducted. The first and the second site revisits included visual inspection. On the third revisit, both visual inspection and evaluation on field cores were conducted. At the first site revisit, the pavements were found to have segregation issues regardless of mixture type. No cracking and other distress were observed. At the second visit, cracks in the WMA paving sections and patches in the HMA sections were also found. The usage of the WMA additives was found to have no influence on the bond between pavement lifts. During the third site visit, one year after construction, field cores were taken from each section. Asphalt contents, aggregate gradations, air voids, indirect tensile strength and bond strength were determined from field cores. The IDT strength of the WMA field cores was found to be similar to the HMA cored samples one year after construction.

G.4.6 NCAT test sections

(Prowell *et al*., 2007; Chowdhury and Button, 2008) (Vol III, pp 53)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Warmer than UK.

A WMA project (Evotherm™ ET) with a HMA control section was constructed at NCAT test track in early November 2005. Sections N1 and N2 were milled to a depth of 127 mm to complete the structural rehabilitation of those sections. Two lifts of 19.0-mm nominal maximum aggregate size (NMAS) WMA were placed in Sections N1 and N2. The top 25 mm of sections N1 and N2 was Evotherm™ with PG 67-22 binder and HMA control mixture. Section E9 consisted of the original track structure, 500 mm of HMA, 125 mm of asphalt treated drainable base and 150 mm of aggregate, with a 25-mm Evotherm™ overlay at the surface.

The production temperatures for WMA and HMA were 115 ºC and 164 ºC, respectively. Plant-mixed HMA and WMA mixtures were compacted in the laboratory close to test sections. The mixtures were evaluated for volumetrics, rutting resistance (APA test) and moisture susceptibility (AASHTO T283). Manual distress survey was conducted and field cores were taken to conduct moisture susceptibility test. The two WMA sections and HMA section showed excellent field performance in terms of rutting, after an application of little over half a million ESALs within 43 days.

G.4.7 Orlando, Florida demonstration project

(Hurley and Prowell, 2005; Chowdhury and Button, 2008) (Vol III, pp 53-54)

Relevance to UK	
Type of asphalt:	Fine-grained asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available from Germany.
Climate:	Hotter than UK.

In February 2004, a field demonstration project using Aspha-min® zeolite was constructed at Hubbard Construction's equipment yard in Orlando, Florida. The existing surface was milled and tacked prior to paving. The control mixture was a fine-graded Superpave mixture with 20 % RA, and was designed for a traffic level of 3-10 million ESALs. The production temperatures for Aspha-min® and HMA control mixture were 150 ºC and 170 ºC, respectively.

Plant-mixed loose WMA and HMA mixtures were compacted in laboratory at compaction temperatures of 132 ºC and 150 ºC, respectively. APA tests were conducted to determine the rutting potential of the mixtures and TSR tests were used to evaluate the moisture susceptibility. In the field, the WMA mixture was reported to be more workable than the control mixture. Based on an analysis of field core samples, the WMA section was found to have comparable density as the control section.

The pavement was revisited in 2005. No signs of distress were evident in either the Aspha-min® warm mixture lanes or the control mixture lanes. Five 150 mm diameter cores were taken from each section to determine ITS and density.

G.4.8 SR-417 project, Florida

(Sholar and Nash, 2009) (Vol III, pp 54)

Relevance to UK	
Type of asphalt:	Porous asphalt.
LTA system:	Available from Germany.
Climate:	Hotter than UK.

This project consisted of a 1.220-km test section of FC-5 open-graded friction course placed in the southbound passing lane of SR-417 utilizing the Aspha-min® WMA technology. Directly to the north of the WMA test section is a 1.648 km control section, consisting of the same FC-5, without the Aspha-min® additive. Both mixtures contain a polymer-modified PG 76-22 bitumen and were constructed in February 2006.

The mixing temperature was 160 ºC for the HMA control mixture and was 132 ºC for the WMA mixture. Samples of each mixture type were obtained and tested for their cracking properties based on the Energy Ratio concept developed at the University of Florida. Pavement condition surveys were performed in May 2006 and July 2009 to evaluate the rutting, cracking and ride rating performance of each section. Results showed that there was no difference in field performance between the HMA and WMA sections.

G.4.9 US-92 (SR-600) project, Florida

(Sholar and Nash, 2009) (Vol III, pp 54)

Relevance to UK	
Type of asphalt:	Asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Hotter than UK.

This project consisted of a 1.872-km test section of SP-12.5 structural mixture placed in the eastbound travel and passing lanes of US-92 in Lakeland utilising the Evotherm™ DAT WMA technology. Directly to the west of the WMA test section is a 1.020-km control section, consisting of the same SP-12.5 mixture but without the Evotherm™ additive. Both mixtures contained a polymer modified PG 76-22 bitumen and were constructed in October 2007. Subsequently, a conventional HMA FC-5 open-graded friction course mixture was placed over the structural mixture. The mixing temperature was 163 ºC for the HMA control mixture and was 121 ºC for the WMA mixture.

Samples of each mixture type were tested to determine the cracking properties of the mixture utilizing the Energy Ratio concept, rutting performance utilizing the Asphalt Pavement Analyzer (APA) and moisture susceptibility utilizing the tensile strength ratio (TSR) approach.

Pavement condition surveys were performed in November 2007 and December 2008 to evaluate the rutting, cracking, and ride rating performance of each section. Results indicated that there were no practical differences between the WMA and HMA control sections.

G.4.10 SR-11, Flagler County, Florida

(Sholar and Nash, 2009; Copeland *et al*., 2010) (Vol III, pp 54-55)

Relevance to UK	
Type of asphalt:	Porous asphalt.
LTA system:	Available in UK.
Climate:	Hotter than UK.

The SR-11 WMA project was located at the south of Bunnell utilizing the Astec Double Barrel Green (DBG) technology with an HMA control section. Both WMA and HMA mixtures contained a RA-800 bitumen and 45 % fractionated RA. The test sections were constructed in December 2007 and January 2008. Subsequently, a conventional HMA FC-12.5 dense-graded friction course mixture was placed over the structural mixtures. The mixing temperatures for the WMA and HMA control mixture were 132 ºC and 154 ºC, respectively.

During construction, PG grading was conducted in accordance with AASHTO M 320 and the binder samples were taken from five sources: virgin binder, coarse fraction of RA, fine fraction of RA, plant-produced control mixture and plant-produced WMA mixture. Both plant mixtures were reheated to 150 ºC before conducting binder extraction and recovery. Additional plant-produced loose mixtures were collected to test dynamic modulus and flow number and these samples were also reheated to 150 ºC before compaction. PG grading test showed that the high RA WMA mixture had a lower PG grade than that of the high RA HMA mixture.

Samples of each mixture type were tested for the cracking properties using the Energy Ratio concept, the rutting performance using the APA and flow number, the moisture susceptibility using the tensile strength ratio (TSR) and the AMPT dynamic modulus. Mixture tests results indicated that both $|E^*|$ values and the Fn values of RA WMA mixture are lower than that of the RA control mixture.

Pavement condition surveys were performed in June 2008 and July 2009 to evaluate the rutting, cracking and ride rating performance of each section. Results showed that there were no practical differences between the HMA and WMA sections.

G.4.11 SR-46, Franklin, Tennessee

(Kvasnak *et al.*, 2010) (Vol III, pp 55-56)

Relevance to UK	
Type of asphalt:	No reference to type used.
LTA system:	Available in UK.
Climate:	Warmer than UK.

The project in Tennessee is located in Franklin on SR-46 and was built in 2007 using Advera® WMA, Astec DBG®, Evotherm™ DAT and Sasobit® plus two control HMA sections. It was also included in the NCHRP 9-474 study. SR-46 is a two-lane road with mostly automobile traffic and the average daily traffic is 10,492. The thickness of the overlay is 32 mm. Prior to overlay, TDOT surveyed the condition of the existing pavements in terms of roughness index (PSI), IRI, rut depth, distress index and pavement quality index (PQI). The existing pavement surface was cracked and crack sealant had been applied in several locations.

The WMA mixtures were produced between 115 ºC and 127 ºC and placed at 110 ºC. Plant-mixed samples were compacted on site to evaluate compactibility, moisture susceptibility (TSR), rutting susceptibility (APA and HWTT), dynamic modulus and low temperature cracking resistance (indirect tensile creep compliance). Field cores were also taken to measure in-place density and indirect tensile strength. Bitumens were extracted and recovered from plant-produced mixture to evaluate the ageing that occurred at the different mixture production temperatures.

Visual inspections were conducted after one year in service. During the assessment, it was noted that the control HMA, the DBG WMA pavement and the Evotherm™ DAT WMA pavement exhibited ravelling along the centreline of the pavement. The Sasobit® was less affected by ravelling. Ravelling in the Advera® WMA pavement was more severe, especially in areas shaded by trees. Tests performed on extracted cores from the pavements indicate that the HMA control had the highest indirect tensile strength, while the Advera® WMA and the Sasobit® exhibited significantly lower indirect tensile strength values (Kvasnak *et al*., 2010). Despite the occurrence of ravelling in these pavements, the distress was neither severe or extensive and the reports did not indicate that the functionality or ride quality of the pavement was impacted.

G.4.12 MD Route 925, Maryland

(Burke, 2006) (Vol III, PP 57)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Similar to UK.

In 2005, the Maryland State Highway Administration (SHA) completed a WMA project in Charles County using Sasobit® technology with 15 % RA. A control mixture was also paved with 15 % RA. The mixture was designed at the 0.3 to 3 million ESALs level using a PG 64-22 bitumen. During construction, the temperature of the control mixture behind the paver was approximately 154 ºC to 176 ºC and the temperature of the WMA mixture was 132 ºC. A thermal camera was also used to track the temperatures during paving, and the results indicated a fairly consistent mat temperature distribution. The WMA section with Sasobit® was reported to be easy to handle and have better compactibility even at a lower temperature.

Visual inspection after one year indicated that the pavements performed well in both HMA and WMA sections with no visible signs of deterioration or distress. It exhibited a smooth texture and a minimal amount of segregation. However, after more than five-years of service life, some areas of segregation and centreline cracking have been observed on both control and WMA sections.

G.4.13 Antelope County, Nebraska, trial sections

(Kim *et al*., 2010) (Vol III, pp 57-58)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Similar to UK but more extreme.

In 2008, Nebraska Department of Roads (NDOR) paved four trial sections, including two WMA sections (Evotherm™ WMA and Advera® zeolite WMA) and their control HMA section, in Antelope County, Nebraska. The trial sections started from Elgin and ended at US Highway 20.

During construction, compaction temperature was around 124 ºC for WMA and around 135 ºC for HMA. Field-mixed loose mixtures were collected and transported to the laboratories for comprehensive evaluations. Tests included PG grading for extracted and recovered bitumen, dynamic modulus test, creep compliance test, uniaxial static creep test, APA test, TSR test and semi-circular bending (SCB) fracture test with moisture conditioning. In general, the WMA additives were found to have no significant impact on the viscoelastic stiffness characteristics of the asphalt mixtures. All WMA mixtures showed better rutting resistance than the HMA control mixture, with the Sasobit® WMA[*] having the highest rut resistance. Based on the results from AASHTO T283 test and the SCB fracture test with moisture conditioning, WMA mixtures showed greater potential to moisture damage than other mixtures.

The pavement sites were visited in 2009 (one year after placement) and in 2010 (two years after placement). Visual evaluations of each section indicated that both the WMA and HMA sections performed well without any major distresses. In addition to the visual evaluation, the performance of WMA pavements was also assessed using pavement performance data (roughness, rut depth, and surface texture) collected by PathRunner. The rut depth and the roughness of WMA and HMA sections were found to be similar.

[*] Not given in list of systems trialled despite reference here.

G.4.14 Iron Mountain M95 project, Michigan

(Hurley *et al*., 2009) (Vol III, pp 58-59)

Relevance to UK	
Type of asphalt:	No reference to type used.
LTA system:	Available in UK.
Climate:	Similar to UK.

The Michigan Iron Mountain M95 project was constructed in 2006 using Sasobit® WMA technology along with an HMA control section. The WMA was used as an overlay for the top 38 mm of the surface course in the passing lane. The control test section was placed in the newly constructed adjacent travel lane of M95. For the control HMA mixture, the mixing temperature was approximately 163 ºC and the compaction temperature was 149 ºC. For the WMA mixture, the mixing and compaction temperatures were 127 ºC and 121 ºC, respectively.

This project was monitored by the NCHRP project team 9-47 A. During construction, loose mixtures were sampled at the plant and compacted on-site. Performance tests were conducted, including Asphalt Pavement Analyzer (APA) test (AASHTO TP 63), tensile strength ratio (TSR) test (AASHTO T 283), Hamburg Wheel Tracking test (AASHTO T 324) and dynamic modulus test (AASHTO TP 62). Additional material was also sampled such that comparisons could be made between on-site compacted samples and samples that were reheated prior to compaction.

The site was revisited two years after construction to compare the field performance of the WMA to that of the HMA based on visual observations, field rut depth measurements and field core analysis. The visual inspections were conducted to identify and classify any distresses in accordance with the LTPP guidelines. Rut depth measurements were taken in both the WMA and HMA sections using a string line. Field cores were obtained to evaluate the pavement densification due to traffic loading and the indirect tensile strength. Based on field test results, minor pop-outs of coarse aggregate particles were observed in the Sasobit® section. Rut depths of 1.5 mm were recorded in the right wheel path of the control section and 3 mm in the left wheel path of the control section. After two years, the in-place density of Sasobit® section was similar to the control HMA section, although the HMA section had lower density than the Sasobit® section right after construction. Hurley *et al*. (2009) explained it could be due to the Sasobit® being in the passing lane and thus not receiving the same amount of traffic as the control section. The indirect tensile strengths of both the Sasobit® WMA and the control HMA increased as expected after two years of in-place ageing. No visual stripping was observed in the field cores from either section.

G.4.15 Hall Street, Missouri

(Hurley *et al*., 2010) (Vol III, pp 59-60)

Relevance to UK	
Type of asphalt:	No reference to type used.
LTA system:	Systems other than Aspha-min® available in UK, Aspha-min® from Germany.
Climate:	Warmer than UK.

The Hall Street WMA project was constructed in 2006 using three WMA technologies, Aspha-min®, Sasobit® and Evotherm™ ET, and one HMA control mixture. Both the WMA and the HMA mixtures contained 10 % RA. The average annual daily traffic (AADT) for Hall Street is approximately 21,000 vehicles per day, with 7 % trucks. The existing pavement structure consisted of a concrete pavement that had been previously overlaid with HMA. The production temperatures for the HMA control section, Sasobit® section, Evotherm™ ET section and Aspha-min® section were 160 ºC, 115 ºC, 107 ºC and 135 ºC, respectively.

This project is monitored by the NCHRP 9-47A team. During construction, loose mixture samples of each asphalt mixture were obtained from the end-dump trucks as they were leaving the asphalt plant and were used to produce test specimens for performance testing. Laboratory tests including mixture volumetric tests, APA rutting test (AASHTO TP 63), TSR (AASHTO T 283) and Hamburg Wheel Tracking moisture test (AASHTO T324) and Dynamic modulus. For the Evotherm™ ET and Sasobit®, all specimens were prepared on site with no reheating except for dynamic modulus (E*) specimens. For the Aspha-min® section, all specimens were prepared back in the laboratory with reheating.

Site revisits were conducted to assess the performance of the WMA and HMA pavements. Visual inspections were conducted to identify distresses such as cracking, ravelling, flushing and polished aggregate. The field performance data as of 2008 indicted that limited number of cracks was identified in each section. These cracks seemed to be reflective in nature and appeared to be tight. Visual observation also indicated that there seemed to be a surface texture difference between the centre turn lane placed in 2005 and the WMA and HMA placed in 2006, with the 2006 pavement having rough macro-texture. In general, the pavements performed well after two years of service life with minimal rutting and cracking in all WMA and HMA sections.

G.4.16 SR 541, Ohio

(Hurley *et al*., 2009; Sargand *et al*., 2009; Nazzal *et al*., 2011) (Vol III, pp 60-61)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Systems other than Aspha-min® available in UK, Aspha-min® from Germany.
Climate:	Warmer than UK.

The project in Kimbolton, Ohio is located on SR-541 and was built in 2006 using Evotherm™, Sasobit® and Aspha-min® along with an HMA control section. Each section was approximately 16 km long. The road was originally constructed in the early 1960s using 31.8 mm asphalt surface, 44.5 mm asphalt intermediate layer, 127 mm of granular base and 102 mm of granular material. An overlay of 38 mm of asphalt was applied to the west end in 1985 and the east end in 1987. Another overlay of 38 mm asphalt was added to the entire segment in 1994. The 2006 51 mm overlay layer included two lifts, a standard 19 mm HMA levelling course plus a 32 mm surface course placed in four sections (one HMA control section and three WMA test sections).

The materials used in the mixture included a PG 70-22 modified binder with 15 % RA and limestone aggregate. The compaction temperatures of the WMA ranged from 110 ºC to 127 ºC. During construction of the test sections, gyratory samples were compacted on site. A number of laboratory tests were conducted including mixture volumetric testing, Asphalt Pavement Analyzer (APA) rut testing, AASHTO T 283 testing, Hamburg testing and dynamic modulus testing. Additional material was also sampled such that comparisons could be determined between on-site compacted samples and samples that were reheated prior to compaction. No testing was conducted to evaluate the effects of WMA additives on bitumen properties.

Field cores were taken 3 months, 12 months, 20 months, 22 months and 46 months after construction to evaluate the air voids distribution and indirect tensile strength (ITS). The WMA mixtures were found to have higher indirect tensile strength than the HMA mixture after three months of service; while the HMA ITS values became the highest after 46 months. After 46 months of service, moisture susceptibility testing (AASHTO T283 test) indicated the WMA and HMA had acceptable resistance to moisture damage.

After periodic monitoring of the pavement based on field cores evaluation, visual distress survey, and roughness measurement, the WMA sections were reported to exhibit low levels of ravelling (defined by ODOT as "disintegration of the pavement from the surface downward due to the loss of aggregate particles"). Based on the visual observations, the Evotherm™ section had the smallest degree of distress while the Sasobit® showed the greatest. Factors contributing to the ravelling were attributed to poor construction practices (i.e. mixture dragging under the screed and poor handwork) as well as the lower placement temperatures, especially for Sasobit® (Hurley *et al*., 2009).

IRI values were taken after 3, 27 and 46 months of construction. ANOVA analysis was conducted to analyse IRI data and the results indicated that IRI values of the WMA sections are similar to that of the HMA sections. Mechanistic Empirical Pavement Design (MEPDG) program was used to predict the pavement life, and the results indicated longer service life for the Aspha-min® section than the HMA control section. Based on MEPDG results, the Evotherm™ and Sasobit® sections will require rehabilitation sooner than the HMA control section. After 46 months of service, no measureable rutting was observed. Visual inspections showed no performance problems in those sections.

G.4.17 Highland County, Rappahannock County and York County, Virginia, test sections

(Diefenderfer, 2010) (Vol III, pp 62)

Relevance to UK	
Type of asphalt:	Not reported.
LTA system:	Available in UK.
Climate:	Warmer than UK.

Three trial sections using two WMA technologies were constructed in Virginia in 2006. Two WMA sections were built using Sasobit® technology and the third section was based on Evotherm™ ET. For the Sasobit® sections (1 and 2), the mixtures contained 20 % and 10 % RA. For the Evotherm™ ET section (3), the mixture contained 20 % RA. The experiences with these trial sections were used in the development of the Virginia Department of Transportation's special provision to allow the use of WMA.

The sections were evaluated over a 2-year period to assess the initial performance of the WMA pavements and compare it with that of the HMA control sections. Coring and visual inspections were performed during the initial construction and at intervals of 3 months, 6 months, 1 year and 2 years. The cores were tested to determine air-void contents and permeability, followed by bitumen extraction and recovery to determine the binder's PG grading. In addition, for the two Sasobit® trial sites, historic data, cores and ground-penetrating radar (GPR) results were collected to compare the results on pavement structure.

Visual surveys indicated no significant distresses in the WMA or the HMA sections during the first 2 years in service. Evaluations of the air voids from field cores indicated that generally the air voids for the WMA and HMA were not significantly different from each other. The air-void contents at different ages were significantly different in a few instances; however, no trends concerning air voids were observed. Permeability measurements did not indicate any trends concerning permeability over time. The PG grading of the recovered binder suggested that the WMA produced using Sasobit® aged at a slightly reduced rate than the HMA, as indicated by decreased stiffening effect. No difference in performance grade was measured between the HMA and WMA sections produced using the Evotherm™ emulsion technology.

G.4.18 Santa Clara project, California

(Cheng *et al*., 2010) (Vol III, pp 63-64)

Relevance to UK	
Type of asphalt:	Not reported.
LTA system:	Available in UK.
Climate:	Warmer and drier than UK.

In 2006 Santa Clara Rte. 152 received a 46 mm overlay on the shoulder using 200 tons of RHMA-G mixture with Sasobit® additive. The Sasobit® was added to the rubber binder and mixed for 45 minutes. There was a recorded drop in the production temperature of 22 ºC (from 160 ºC to 138 ºC). The paving took place at night with a 30 minute haul time. After two years, the shoulder was reported as "looked good".

G.4.19 I-5 District 10, California

(Cheng *et al*., 2010) (Vol III, pp64)

Relevance to UK	
Type of asphalt:	Not reported.
LTA system:	Available in UK.
Climate:	Warmer and drier than UK.

Astec Double Barrel Green (DBG) and Evotherm™ WMA technologies were used in the southbound shoulder of I-5 in District 10 near Santa Nella, CA in 2008. The top lift of WMA layer was 36.5 mm. The pavement condition was evaluated in 2010 and there were no signs of distress after two years of service in the field.

G.4.20 I-70 in Silverthorne, Colorado

(Tim *et al*., 2011) (Vol III, p64-65)

Relevance to UK	
Type of asphalt:	Presumably asphalt concrete designed using SuperPave rather than UK methods.
LTA system:	Available in UK.
Climate:	Warmer and drier than UK.

The Colorado Department of Transportation (CDOT) conducted a WMA study in 2007 to compare the production, constructability, laboratory performance, and field performance of three WMA technologies (Advera®, Sasobit® and Evotherm™ DAT) with a control HMA.

The project was located on I-70 about 110 km west of Denver. This project was also included in the NCHRP 9-474 study for short-term field performance monitoring.

The existing pavement is an asphalt pavement with a thickness between 255 mm and 330 mm. After milling 64 mm, a 64 mm layer of overlay was constructed. The 10-year design ESALs of the pavement is 4.85 million based on an annual average daily traffic of 30,000 with 10 % trucks. The WMA test sections were compacted about 17 ºC to 28 ºC cooler than the HMA control.

During construction, the in-place densities were measured with a nuclear -density gauge. Cores were also taken from the pavement in the second and third years. The top lift of pavement was removed from the rest of the core by sawing. The top lift was tested for indirect tensile strength.

Experimental testing was conducted on plant-produced laboratory-compacted gyratory samples without reheating. The engineering properties evaluated included the volumetric properties of the mixture, the moisture susceptibility (TSR and HWTT), bitumen PG grading, dynamic modulus and flow number. The laboratory performance test results indicated the WMA mixtures were slightly more susceptible to rutting and slightly more susceptible to moisture damage than the HMA control mixture was.

Field-performance evaluations (manual distress survey) were conducted annually for three years after construction. Data regarding rutting, in-place void, cracking, ravelling and weathering were gathered to document the performance. After three years of field evaluations, the performance of the WMA test sections was found to be comparable to the HMA control sections in terms of rutting, cracking and ravelling. The field performance was excellent even though the location typically has a very harsh winter climate.

G.4.21 Summary

(Vol III, pp 65-66)

In summary, there are three NCHRP projects that have been conducted or are under going to evaluate the engineering properties and field performance of warm mix asphalt mixtures and pavements. Field WMA studies in 17 states were summarised in this chapter based on their documented project information and field evaluation results, if any. In addition, the team is continuing to collect WMA field projects that has been studied and documented in the US. This information will provide important historical background for identifying candidate WMA projects to be included into the NCHRP project 9-49A study.

Appendix H Scandinavian reports

H.1 Norway

H.1.1 FAVs project LTA2011, sub-project Asphalt Quality

Association Asphalt and Veiservice (FAV), with financial support from the Norwegian Confederation of Industry (NHO) Working Fund, conducted a large trial with low temperature asphalt (LTA) in 2011 (Anon, 2011). The trial was conducted to try to reduce workers' exposure to asphalt fumes by lowering the production temperature whilst not deteriorating the quality of the asphalt product.

Eleven trial sections were constructed, each with parallel fields with a LTA-mixture and a control mixture. A total of six different techniques were tested, three based on additives and three on the foaming of the binder in the mixture. The asphalt quality was described while the chemical and physical aspects were to be reported by the National Institute of Occupational Health (NIOH) in separate reports.

The LTA mixture and the control mixture had the same compositions except for small amounts of additives. It was expected that, if the lower temperature did not make the LTA harder to compact than the control mixture, the binder cover should be identical and the mixtures would have the same life expectancy. Therefore, monitoring was focused on the deformation achieved (wheel track and initial values for transverse and longitudinal evenness) and adhesion properties.

The initial findings showed that LTA mixtures did not differ from the control mixture with respect to the relevant quality parameters. As such, the LTA mixture should not have a shorter life than the control mixture. The ongoing surface condition was to be monitored by the Public Roads Administration. Meanwhile, any differences in the hardening of the binder over time due to the lower temperature during production of the LTA mixture will be followed by the Norwegian Public Roads Administration "Tangible roads" programme.

However, no durability data appear to have been provided.

H.1.2 Chemical work and mechanical stress during application of HMA and LTA

A survey of chemical work and mechanical stress during application of hot asphalt and low temperature asphalt was undertaken during the asphalt season 2011 (Anon, 2012). The purpose of this study was to compare the chemical exposure during application of hot asphalt and low temperature asphalt and to compare the mechanical load by hand-laying of hot asphalt and low temperature asphalt.

The mapping of the chemical working environment comprised stationary measurements of asphalt fumes/vapour, organic and elemental carbon, amines and polyamines and respirable, thoracic and inhalable dust (aerosol) and personal observations of asphalt fumes/vapour and thoracic dust (aerosol) of 11 trials on the laying of hot asphalt and low temperature asphalt. The results showed a mean (statistically significant) reduction in asphalt fumes of between 58 % and 67 % depending on the measurement method; this was attributable to a reduction in asphalt temperature of 29 °C. A statistically significant change was found for amines in the transition from hot asphalt to low temperature asphalt. The study shows that exposure to asphalt fumes/vapour is lower by laying low temperature asphalt compared with hot asphalt.

The mapping of the mechanical loads included measurements of heart rate (pulse) and power usage measured with a force sensor in an asphalt rake at six attempts with hand-laying of hot asphalt and low temperature asphalt on the test field. The results showed no statistically or physiologically significant difference in heart rate or mechanical loading by hand-laying of hot asphalt and low temperature asphalt. The study shows no difference in the mechanical load by hand laying hot asphalt and low temperature asphalt, but the number of experiments carried out was somewhat limited.

No data on the durability of low temperature asphalt is included.

H.1.3 Foam results from field trials

Relevance to UK	
Type of asphalt:	Not reported.
LTA system:	Available in UK.
Climate:	Cooler than UK.

Veidekke (construction company) started with WAM Foam in 1995 with preliminary laboratory trials using bitumen emulsion and having field trials at Hunndalen in 1996 and Lena in 1997 (Lerfald, undated). The use of foam bitumen started in 1998 with laboratory testing field trials at Hobøl in 1999 and 2000 with production in Norway being about 8000 ton in 2001, 15000 ton in 2002 and 17000 ton in 2003. In 2002, 3500 ton of WAM foam were laid at NCC Sweden on E4, in 2003 the material was laid at Ooms Avenhorn, in the Netherlands and in 2004 at Conglobit, Italy.

The deformation resistance is shown on three sections in Figures H-1 to H-3, which show general equivalence between the WAM Foam and the control HMA.

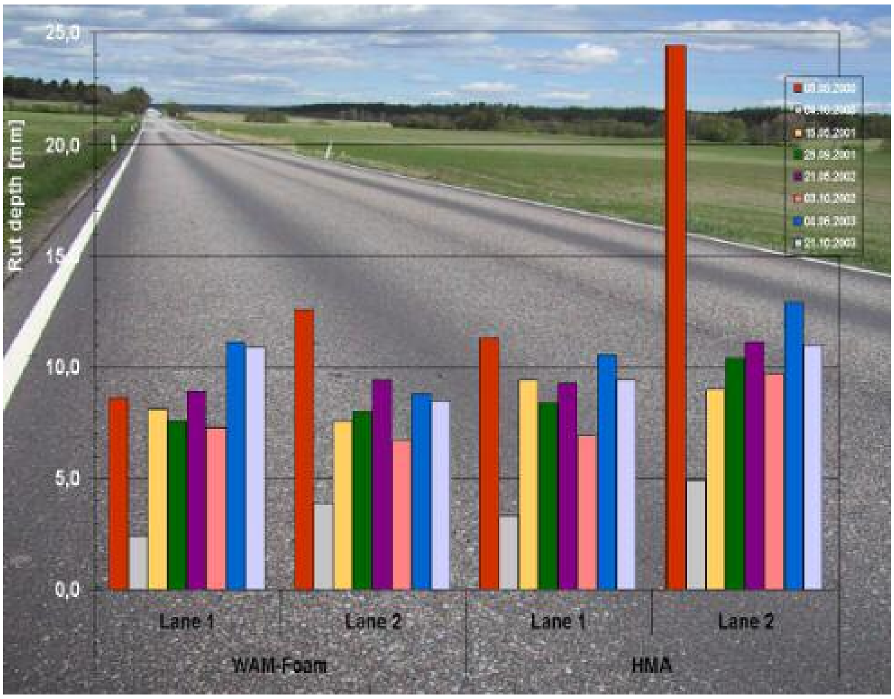

Figure H-1: Rutting 2000 to 2005 on RV120, Hobøl

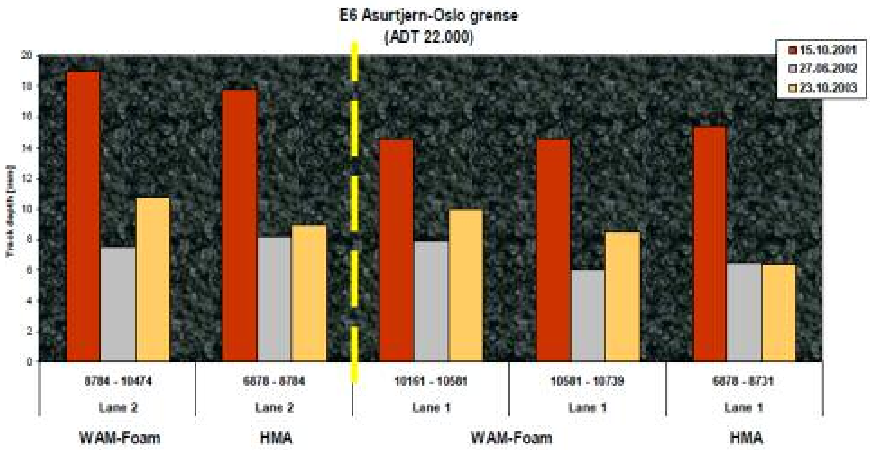

Figure H-2: Rutting on E6 Asurtjern – Oslo

Figure H-3: Rutting on Grandeveien Drøbak

H.2 Sweden

H.2.1 Hudiksvall highway section

Relevance to UK	
Type of asphalt:	Not reported.
LTA system:	Available in Sweden
Climate:	Cooler than UK.

NCC Green Asphalt is a technique based on foam without any additives apart from amine as a fluid adhesion agent to reduce water sensitivity, and its use on 24.5 km stretch of a new dual two-lane highway at Hudiksvall in northern Sweden (Lundberg, undated a). 140 k tons of Green Asphalt were laid as the base, binder course and surface course in

2010 and 2011. Details of the Green Asphalt technology and its advantages are given, but nothing on the in-situ performance of the section.

Another paper (Ulgren et al., 2011) on the Hudiksvall highway section gives more extensive details of the laboratory testing and construction. However, the final section explains that annual measurements of rut depth, evenness (international roughness index, IRI), crossfall, loss of fine material/mastic, characteristics of the recovered binder, water sensitivity (ITSR from cores) and texture (mean profile depth, MPD) will be made for five years. However, no details of measurements already made are given.

A presentation (Lundberg, undated b) starts by discussing the requirement for Sweden to increase the amount of renewable energy and reduce its carbon emissions with particular emphasis on the role of asphalt production. It then goes into the properties of NCC Green Asphalt and its use on the Hudiksvall highway with more extensive details of the laboratory testing and construction. However, it finishes with the extended life expected with NCC roads' Viaco products/Green Asphalt. These estimates appear to be based on laboratory and not site experience because there has not been the time to gain that experience.

The data quoted are reproduced in Table H-1.

Table H-1: Comparative properties claimed

Property	Conventional pavement	Viaco pavement
Pavement	40 mm ABS 16 AN7 50 mm Abb 16 55 mm AG 22 55 mm AG 22	25 mm Viacogrip 16 AN7 PMB 60 mm Viacobind 16 NBS 65 mm Viacobase 22
Depth	200 mm	140 mm
Initial cost	16,661,000	15,583,000
Energy	27 TJ	15.5 TJ
Material	36,021 tonnes	20,245 tonnes
CO_2	1.9 M tonnes	1.06 M tonnes
Functional warranty	5 years	15 years
Annual costs	23 SEK / m² & year	17 SEK / m² & year
Wheel track development Wear SPS Elongation Totally	0.96 mm/year 5.7 g / studded tyre and km 4.5 mm 16.6 mm after 17 years	0.88 mm/year 5.3 g / studded tyre and km 1.6 mm 16.6 mm * after 17 years
Surface course life span Binder course life span Base life span	13 years 20 years 40 years	17 years 40 years 40 years

* Possible transcription given same total deformation clamed despite other deformation parameters improving

It is not known on what basis the extended life spans have been predicted.

H.2.2 Foam technology

Relevance to UK	
Type of asphalt:	Not reported.
LTA system:	Available in UK.
Climate:	Cooler than UK.

LT-Asphalt® principle is based on foam technology from the Netherlands that has been used in Sweden (Landa et al., undated). The moisture in pores of mineral is encapsulated by coating with bitumen (determination: drying at 180 °C for aggregate particles; extraction with toluene for the binder) whilst the vapour pressure improves the workability with the free moisture in voids (determination: pre-extraction with methanol).

Mix design for base and top layer:
- Continuous graded mixtures
- Based on Marshall/Gyratory (EVT temperature)
- Hygroscopic reactive filler (0.5 % to 1.0 %)

Scaling up (20 times) to pilot plant level:
- 25 kg batches
- EVT temperature for B 65
- 90 °C for NyFoam 50 (= B 65)

Testing programme laboratory/pilot plant mixtures:
- ITS + water sensitivity
- Bitumen distribution between coarse and fines

First test trial at the asphalt plant site on 9 September 2002
- Bitumen distribution coarse/fines is different
- Freeze/thaw test has positive result
- Reaction rate hygroscopic filler to high

Study to the reactivity of the hygroscopic filler:
- Five alternatives based on CaO and cement.
- Change of CaO to Portland cement

Study to the reactivity of the hygroscopic filler.

Second and third test trials were laid on 15 November 2002
- Asphalt plant to Breda & Apeldoorn (>100 km)
- Compactibility
- Wet wheel-track test
- Ageing (penetration 65 → 54 for LT-Asphalt but 65 → 27 for hot mix asphalt)

Demonstration track for RWS (Lunteren) on 8&9 April 2003
- Fatigue / Stiffness
- Tri-axial test

Despite the trials being up to 11 years old, there was no information as to their current condition.

A project was undertaken to study the WAM-Foam alternative mixing technique for producing asphalt mixtures (Lundberg, 2001). The method makes it possible to produce at a lower mixing temperature. The main purpose of the project was to clarify two points:

- What is the lowest practical temperature limit of production that can be maintained at a longer continuous production without jeopardising the fibre fabrics in the dust cleaning equipment?
- Is there any moisture left in the aggregate that may have a negative effect on the life of the asphalt pavement?

However, it was the proposal for the project rather than the findings from it.

Another presentation (Lundberg, undated c) gives details of a WAM Project in 2002 on the E4 Antnäs – Gäddvik, a converted dual two-lane road of which only the northbound lanes were treated. The construction consisted of about 3,000 tons of ABT 16 (160/220), 800 tons of WABT 16 (70/100) and about 2,600 tons of WABT 16 (50/70) on different lengths. Details are given on the initial properties of binder penetration after production, Prall test, relative indirect tensile resilient modules, air voids contents, stiffness modulus, workability test and texture depth (sand patch), but no information as to the current condition despite the age of the road.

H.3 References

Anon (2011). FAVs prosjekt LTA2011, Delprosjekt Asfaltkvalitet (FAVs project LTA2011, subproject Asphalt Quality). Presentation.

Anon (2012). Kartlegging av kjemisk arbeidsmiljø og mekanisk belastning ved utlegging av varmasfalt og lavtemperaturasfalt (Mapping of chemical work and mechanical stress during application of hot asphalt and low temperature asphalt). Presentation.

Landa, P, R Lundberg, M Wiklund, U Lillbroända and D Goos (undated). LT-Asphalt®. Presentation.

Lerfald, B O (undated). Short summary WAM Foam (results from field trials)”.

Lundberg, R (2001). WAM-Foam project specification.

Lundberg, R (undated). Sweden’s greener way to paving roads. Public service Review: Transport: Issue 28.

Lundberg, R (undated b). E4 Hudiksvall-Enånger and NCC Green Asphalt. Presentation.

Lundberg, R (undated c). WAM-Foam NCC roads. Presentation.

Ulgren, N, R Lundberg and L Lundqvist (2011). Low temperature asphalt (WMA) in Sweden. 2nd International Warm-mix conference, St- Louis, Missouri, USA, 11-13 October 2011.