TRIAL OF WARM MIX ASPHALT IN BINDER AND SURFACE COURSES

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ABSTRACT

The increased emphasis on reducing the energy needed and CO_2 emissions of products of all types has encouraged, amongst other things, a move towards asphalts that can be mixed and compacted successfully at lower temperatures. Advera® WMA is designed to produce a sustained, time-release foaming of the bitumen at a warm mix asphalt production temperature of 120 °C rather than around 160 °C. The product was trialled during the surfacing of a quarry access road, which was monitored. The monitoring included the construction, the resulting material properties, the carbon dioxide equivalent emissions and the temperature changes with time after compaction. The findings show that, whilst the modified asphalt at lower temperatures was not identical to the control mixture, a successful mixture could be laid at significantly lower temperature and with lower CO_2 emissions. The lower mixing and compaction temperatures possible by the inclusion of Advera reduces the carbon footprint of asphalt significantly. The use of Advera to reduce the laying temperature by 20 °C will also allow opening to traffic between 20 min and 40 min earlier. However, the model for time to opening to traffic will allow estimates to be made, but needs validation from other sites to refine it.

Keywords: Warm asphalt mixture, Embodied carbon, Stiffness, Permanent deformation, Durability

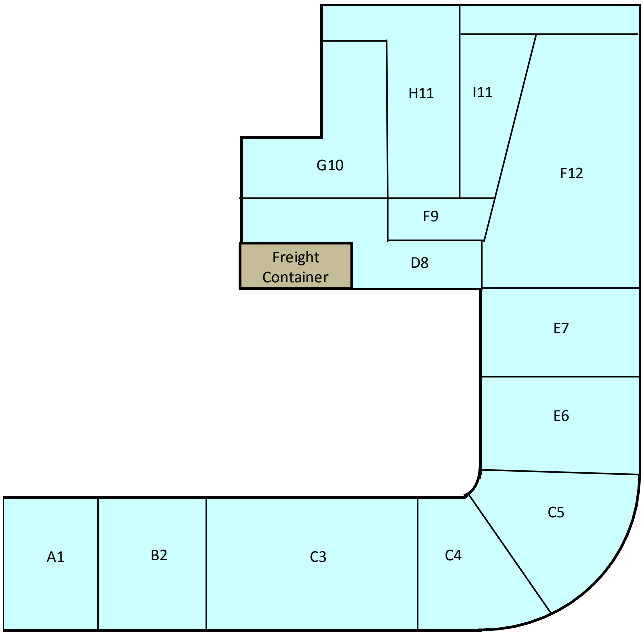
1 INTRODUCTION

PQ Corporation was founded in 1831 in Philadelphia and has become a leading producer of silicate, zeolite and other performance materials serving the detergent, pulp and paper, chemical, petroleum, catalyst, water treatment, construction and beverage markets. It is a global enterprise, operating in 19 countries on five continents. Among their recent products is an asphalt additive based on zeolite, Advera® WMA Aluminosilicate (hereafter referred to as Advera), which allows the asphalt to be mixed and laid at lower temperatures than is traditional.
The additive was designed to produce a sustained, time-release foaming of the bitumen at a warm mix asphalt production temperature of 120 °C. It contains 20 % moisture which is structurally and chemically bound in the zeolite. The zeolite releases its moisture over a sustained period of time causing lasting micro-foaming, with the foam being retained in the mixing process. Lower production and compaction temperatures are claimed to be realised compared to other foamed systems. When the additive is added to an asphalt mixture design, it will allow the asphalt to be produced and placed at temperatures which are claimed to be 30 °C to 40 °C below conventional hot mix asphalt temperatures. If any residual moisture remains in the asphalt, it should be re-absorbed by the additive and bound in place. Once in place, the additive is claimed to behave as a mineral filler.
A pilot-scale trial was set up and monitored on a newly constructed access road to the car park of Aggregate Industries' (AI) quarry at Haughmond Hill in Shropshire. The objectives of the trial were:

- Mixing temperature reduction – the level of temperature reduction achievable in the mixing process.
- Mixing capabilities – the ability of a standard asphalt plant to mix at low temperatures.
- The time/temperature curve for the asphalt laying cycle – the temperature/time progression as the product moves through the various stages of the laying process.
- Reduced time before traffic can return to the road – the time taken after the material has been laid before traffic can return to the road.
- Carbon lifecycle analysis – collect the data required to calculate the effect of reducing the temperature of the mixture on the overall carbon footprint of asphalt.

2 PILOT-SCALE TRIAL

The trial was laid on Wednesday, 12 and Thursday, 13 June 2010 with AC 20 binder course being laid on the first day and SMA 10 surface course being laid on the second day. On both days, the initial mixture was the control with no Advera after having been mixed at the conventional target mixing temperature for that mixture type. The asphalt for subsequent sections was mixed at reducing target mixing temperatures and contained the additive, usually at 0.3 %. The additive was added manually, whereas it is expected that a mechanical delivery system will be installed for regular use. The method of delivery may have an impact on the dispersion of the zeolite and, hence, its efficacy and the overall consistency.
Most batches were delivered straight to site, but some loads were travelled for some time to replicate the common situation where the site is distant from the plant. The final sections were laid with a control mixture without any additive that was mixed at a reduced temperature. The layout of the different sections is shown schematically in Figure 1. The sections are shown as if they were identical for both days but the joints between them did not sit over each other and were, in some cases, several metres apart.



Not to scale.
Figure 1: Schematic of site for trial sections laid at Haughmond Quarry

The asphalt mixture used for the control binder course was AC 20 Dense Bin 40/60 in accordance with clause B.3.4.8 of PD 6691 [1]. The weather on Wednesday, 12 June 2010 was generally overcast but dry and still. The first load was mixed at around 13:00 and the laying of the last load finished at around 20:00. The ambient temperature was measured at c.10 °C at around 18:00 cooling to c.7.5 °C by 20:00, which is relatively chilly for June, but no values were obtained for earlier in the day.
The additive content and the temperatures measured at the plant, at the screw as it was being laid, behind the screed after it had been laid and after compaction are set out in Table 1. The temperatures behind the screed and at the screw were measured by infra-red and, therefore, are of limited accuracy. The aggregate in one mixture was found not to be full coated, so was discarded without being laid. The batch time was then increased from 30 s to 45 s for subsequent mixtures.

Most of the material was taken straight from the plant to the site, but for two loads, only half of the load was laid initially with the remainder being sent off to be driven around before returning to be laid in a separate Section in order to simulate the typical situation.
The control section was laid without anything abnormal occurring, as was the case with Section 2 when the temperature had been dropped 8 °C below the conventional but still 12 °C more than targeted. After Section 2, the screed temperature was dropped to 125 °C in order to be comparable with the mixing temperatures.

Table 1: AC 20 mixtures and temperatures produced on Day 1

Section Number	Mixture Number	Advera content (%)	Mixing time (s)	Temperature (°C)			
				At plant	At screw	Behind screed	Compacted
1	M1-1	0	30	166.5	147	132	104
2	M1-2	0.3	30	152	135	131	98
3	M1-3	0.3	30	136	120	117	74
4	M1-4	0.3	30	117	100	95	69
5*	M1-2*	0.3	30	152	116	113	73
6	M1-6	0.3	45	125	116	110	76
7	M1-7	0.3	45	118	112	110	72
8	M1-8	0.3	45	117.5	104	102	65
9	M1-9	0.25	45	118	–	101	72
10*	M1-4*	0.3	30	119	108	104.5	75
11	M1-10	0	45	124	112	104	69

* Part of load transported around before being laid

The asphalt mixture used for the control surface course was SMA 10 Surf 40/60 in accordance with Annex D of PD 6691 [1]. The weather on Thursday, 13 June 2010 was similar to the previous day except there was some very light rain briefly during the day. The first load was again mixed at around 13:00 but the laying of the last section finished at around 19:00. The ambient temperature averaged c.16 °C during laying operations, much more what would be expected for June than those of the previous day.
The additive content and the temperatures measured at the plant, at the screw as it was being laid, behind the screed after it had been laid and after compaction are set out in Table 2. The temperatures behind the screed and at the screw were again measured by infra-red and, therefore, are of limited accuracy. Two loads were driven around for some time before returning to be laid in order to simulate the typical situation. During the laying of Section C, one wagon failed to connect with the paver hopper and asphalt was deposited on the ground that had to be scraped up to allow the paver to continue. Apart from the delay, there were no other observed resulting adverse effects.
Tearing was evident on Section G at one point. Apart from this, however, the paving went without any unusual problems. The operators found handling the colder mixtures less easy than normal because of the increased stiffness, but not impossible to hand lay when needed.

Table 2: SMA 10 mixtures and temperatures produced on Day 2

Section Number	Mixture Number	Advera content (%)	Mixing time (s)	Temperature (°C)				Time after laying (min)
				At plant	At screw	Screed	Compacted	
A	M2-1	0	40	168	149.8	142	40†	30
B	M2-2	0.3	40	158	142.5	137.3	110	10
C	M2-3	0.3	40	144.5	135.5	129.5	114	2 & 8
D	M2-4*	0.3	40	128	111.5	110	96	5
E	M2-5	0.3	40	118	106	105	90	–
F	M2-6	0.3	55	120	98	97	91	–
G	M2-7	0.3	55	121	94	97	82	–
H	M2-9	0	55	132.5	115	110	96	5
I	M2-8*	0.25	55	128	108	115	103	–

* Load transported around before being laid.
† Temperature unexpectedly low even allowing for 30 min delay.

3 MATERIAL PROPERTIES

3.1 Core thicknesses

A number of cores were taken from the trial sections on Fri day, 14 June 2010 to allow measurement of the material properties of the mixtures. The thicknesses of the two layers of each were recorded in cores and their statistics are given in Table 3. There was considerable variation, particularly in the binder course, but this is to be expected because of the need for regulation on this type of surface.

Table 3: Statistics of core thicknesses

Statistic	Surface course (mm)	Binder course (mm)	Total (mm)
Mean	42.6	79.3	121.9
Standard deviation	6.9	13.2	17.6
Minimum	28	58	90
Maximum	60	104	152

3.2 Voids at refusal density

AI compacted specimens to refusal in accordance with BS EN 12697-9 [2] of each mixture produced for the trial at the plant. These samples were measured for bulk density in accordance with BS EN 12697-6 [3] and maximum density in accordance with BS EN 12697-5 [4], from which the air voids content at refusal were calculated in accordance with BS EN 12697-8 [5]. These results are given in Table 4.
The air voids content at refusal are effectively those air voids that cannot be filled, so it is not surprising that all the results for each mixture are close, roughly in line with the expected testing variation.

Table 4: Maximum and refusal densities

Mixture number	Refusal density (kg/m^3)	Maximum density (kg/m^3)	Air voids content (%)
M1-1	2516	2582	2.6
M1-2	2522	2605	3.2
M1-3	2519	2605	3.3
M1-4	2529	2605	2.9
M1-6	–	–	–
M1-7	2527	2605	3.0
M1-8	2534	2605	2.7
M1-9	2533	2583	1.9
M1-10	2539	2582	1.7
Mean	2597	2527	2.7

Mixture number	Refusal density (kg/m^3)	Maximum density (kg/m^3)	Air voids content (%)
M2-1	2412	2525	4.5
M2-2	2420	2515	3.8
M2-3	2440	2515	3.0
M2-4	2414	2515	4.0
M2-5	2415	2515	4.0
M2-6	2420	2515	3.8
M2-7	–	–	–
M2-8	2413	2523	4.4
M2-9	2424	2525	4.0
Mean	2519	2420	3.9

3.3 Air voids content

The cores extracted for mechanical testing were measured for bulk density in accordance with BS EN 12697-6 [3] before undergoing the mechanical tests. Some were also measured for maximum density in accordance with BS EN 12697-5 [4] after the testing. Assuming that the reference density was consistent for the control and trial mixtures, the air voids content of the layers were calculated in accordance with BS EN 12697-8 [5]. These results are plotted separately for the two mixtures against the temperatures at which they were mixed at the plant, at the screw as it was being laid and behind the screed after it had been laid in Figures 2 to 7. The temperatures after compaction were not used because of the variable time after compaction that the measurements were made. The points with the normal mixing time have solid fill while those with the extended mixing time have white centres. Linear trend lines were applied separately to both main sets of data (Advera and control).
As would be expected, the air void contents for the control mixtures in both layers increased with reduced temperature as measured at all stages, although the shape of increase cannot be judged because only two temperatures were used. There is a general increase in air voids content as the temperature reduces for the modified mixtures but at less than half the rate than for the control mixture. This increase is shown by the linear trend lines that have been plotted in Figures 2 to 7. However, the range of values at mixing temperatures below 120 °C becomes very wide, with the higher air voids contents (above 8 %) being from Sections 8 and 9, when the ambient temperature had dropped. The two linear trend lines cross at the standard mixing temperature for that mixture type.
For the temperatures at the screw and behind the screed for the AC 20 binder course mixture with the additive, the trend line shown in Figure 6 is similar to the trend line for the mixing temperatures. However, the points appear to be on a line parallel to the control line apart from two points, one either side. Ignoring these two points as outliers, the parallel trend would indicate an increase of about 0.25 % in air voids contents with each 1 °C drop in temperature for both mixture types. The two apparent outliers are Section 2, which is nearer to the control line, and Section 4, which had a lower air voids content than expected from the trend line but which was laid early in the afternoon when the ambient temperature was still relatively warm (around 15 °C).

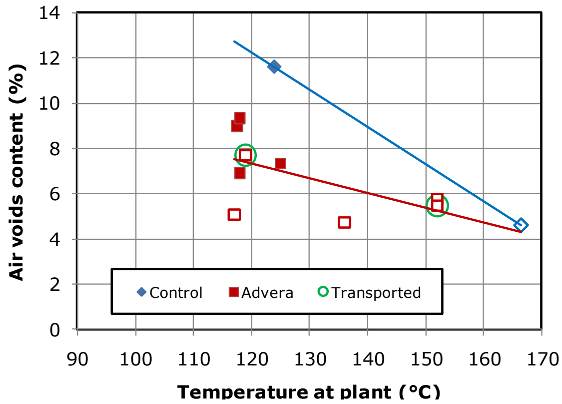


Figure 2: Change in air voids content with temperature mixed at plant for binder course AC

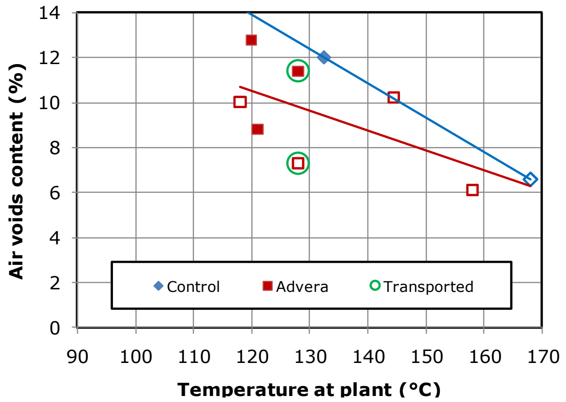


Figure 3: Change in air voids content with temperature mixed at plant for surface course SMA

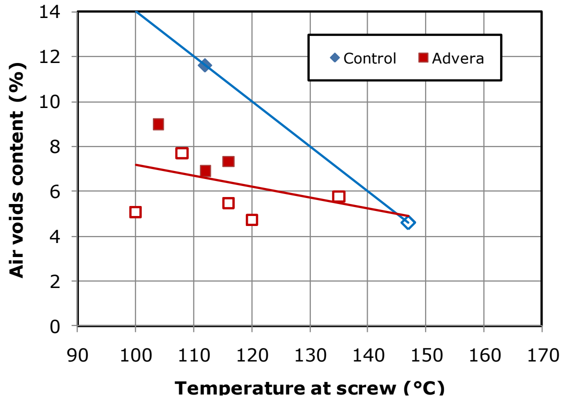


Figure 4: Change in air voids content with temperature at screw for binder course AC

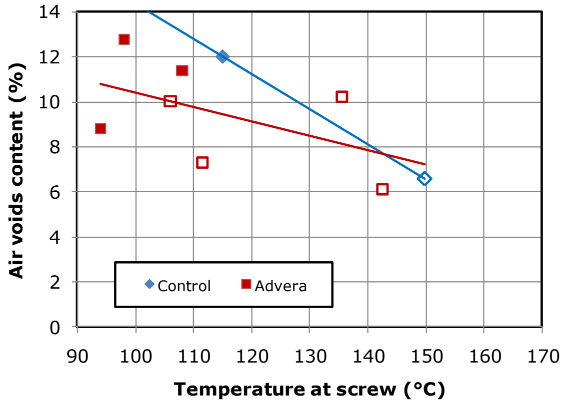


Figure 5: Change in air voids content with temperature at screw for surface course SMA

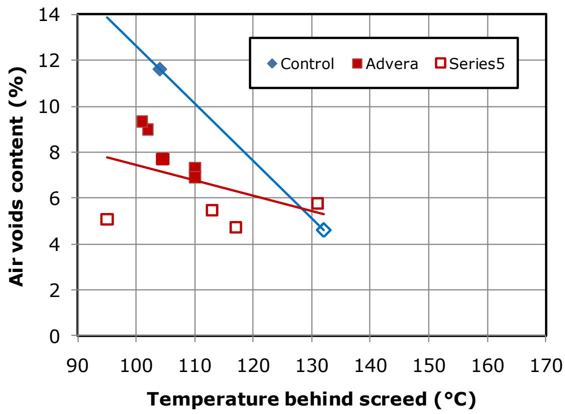


Figure 6: Change in air voids content with temperature behind screed for binder course AC

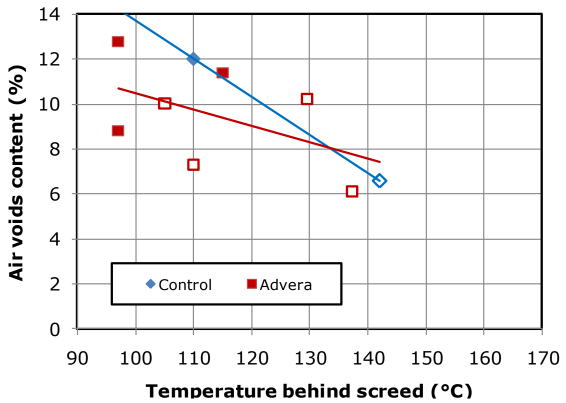


Figure 7: Change in air voids content with temperature behind screed for surface course SMA

With the addition of the additive to the SMA 10 surface course mixture, the air voids content again increased with reduced temperature to a lesser extent than the control mixture. However, the reduction was less than for the binder course mixture and more variable, with Section C actually having higher voids than would the control mixture at the same temperatures from its trend line.
Overall, the results indicate that the additive does "work" in terms of improving the effect of compaction for mixtures that are laid colder than traditionally.

3.4 Stiffness

150 mm diameter cores taken from the AC 20 binder course were tested for indirect tensile stiffness modulus in accordance with Annex C of BS EN 12697-26 [6]. The mean values for each Section are plotted against the temperatures at which they were mixed at the plant, at the screw whilst it was being laid and behind the screed after it had been laid in Figure 8 to 10. Again, the temperatures after compaction were not used because of the variable time after compaction that the measurements were made. The points with the normal mixing time have solid fill while those

with the extended mixing time have white centres. Linear trend lines were applied separately to both main sets of data (Advera and control).

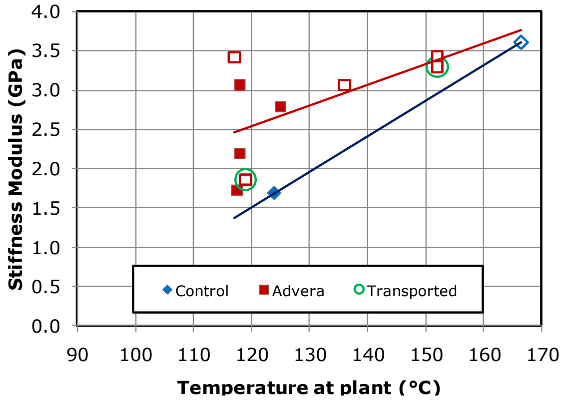


Figure 8: Change in stiffness modulus with temperature mixed at plant for binder course AC

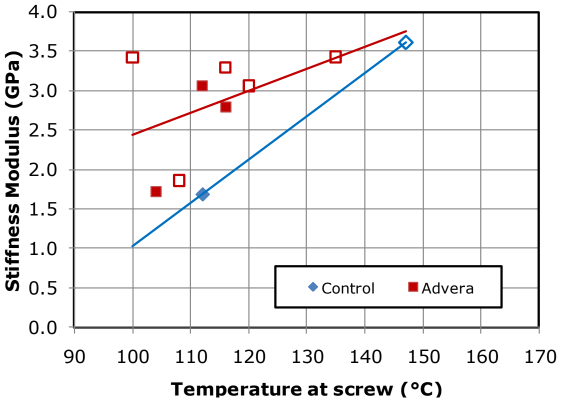


Figure 9: Change in stiffness modulus with temperature at screw for binder course AC

The stiffness modulus results are consistent with those for air voids content. The control mixtures had a lower stiffness modulus at the lower temperature whilst the mixture with the additive also reduced but at a slower rate. The stiffness range at mixing temperatures below 120 °C was wide, with the lowest values (below 2.5 GPa) being for Sections 8, 9 and 10, when the ambient temperature had dropped. In particular, Figure 10 seems to show that the stiffness is not adversely affected for temperatures behind the screed of more than 110 °C; below that figure, the results are more variable.

Overall, the results indicate that the additive does appear to reduce the loss of stiffness for mixtures that are laid colder than traditionally, at least down to temperatures of 120 °C.

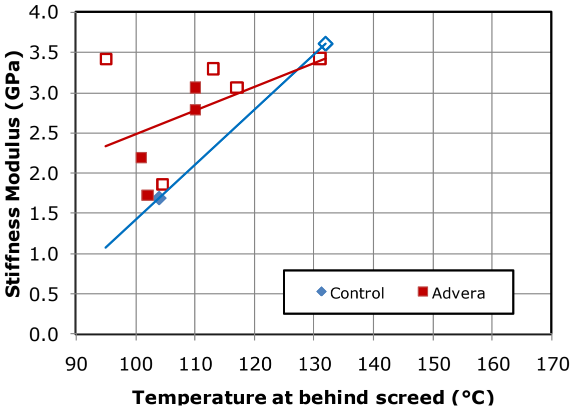


Figure 10: Change in stiffness modulus with temperature behind screed for binder course AC

3.5 Water sensitivity

The cores tested for stiffness were then tested for sensitivity to water in accordance with the guidelines for the assessment of thin surfacing systems [7]. The cores are conditioned and the change of stiffness modulus measured. The conditioning should be repeated three times, where each condition cycle consists of:

- In distilled water at 20 ° and partial vacuum of 510 mm Hg for 20 min;
- In water at 60 °C for 6 h; and
- In water at 5 °C for 2 h.

The cores were only conditioned for two cycles because of the damage that occurred to some of them. The inability to complete the test may be partly due to using cores with cut faces, allowing easy access for the water to get between the binder film and aggregate surface, rather than the usual moulded specimens. The stiffness ratios after both one and two conditioning cycles are plotted against the temperatures at which they were mixed at the plant, at the screw as it was being laid and behind the screed after it had been laid in Figures 11 to 16. Again, the temperatures after compaction were not used because of the variable time after compaction that the measurements were made. The points with the normal mixing time have solid fill while those with the extended mixing time have white centres. Linear trend lines were applied separately to both main sets of data (Advera and control).

The control mixture at the standard mixing temperature had a stiffness ratio of about 1.4 after both the first and second conditioning cycle, indicating that the curing effect was greater than the damage induced during the first cycle and that the second cycle did no further damage. It is assumed that these cores would have completed the test successfully if put through the third conditioning cycle. The control mixture at the reduced mixing temperature of 118 °C, however, had a stiffness ratio less than 0.8, the acceptable level after the complete test, after the first conditioning cycle and less than 0.2 after two conditioning cycles, indicating that, when mixed at that temperature, the mixture was highly sensitive to water damage.

The mixture with the additive also attained stiffness ratios of around 1.4 after the first conditioning cycles except when mixed below 120 °C, when the ratio varied but was generally significantly lower. The stiffness ratios for those mixtures mixed below 120 °C were from, in increasing order, Sections 8, 9, 10, 7 and 4, with Section 4 being at an acceptable level. All the other Sections were laid late in the afternoon when the ambient temperature had dropped. The relationships with the temperatures were similar but less clearly defined. In particular, Figures 11, 13 and 15 suggest that the stiffness ratio is not significantly affected by mixing temperatures above 120 °C; temperatures at the screw above 115 °C; and temperatures at the screed above 110 °C, respectively.

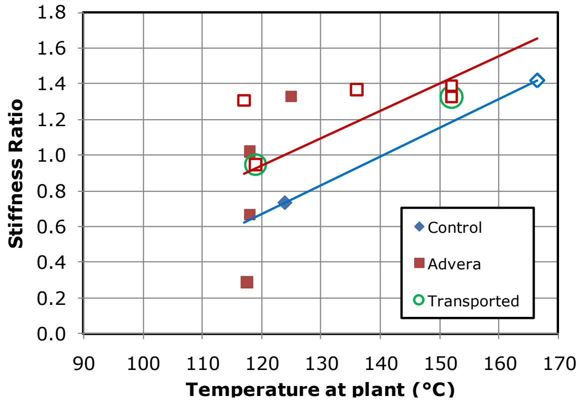


Figure 11: Change in stiffness ratio with temperature mixed at plant after one conditioning cycle for binder course AC

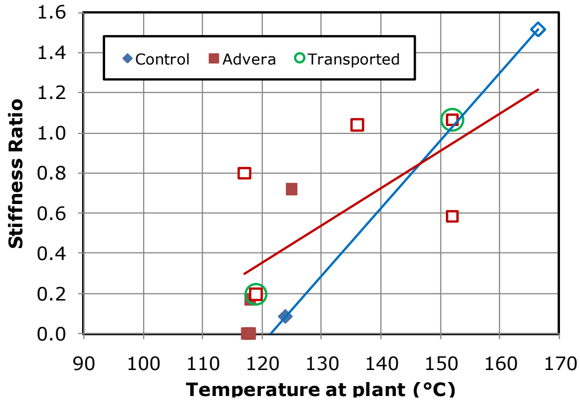


Figure 12: Change in stiffness ratio with temperature mixed at plant after two conditioning cycles for binder course AC

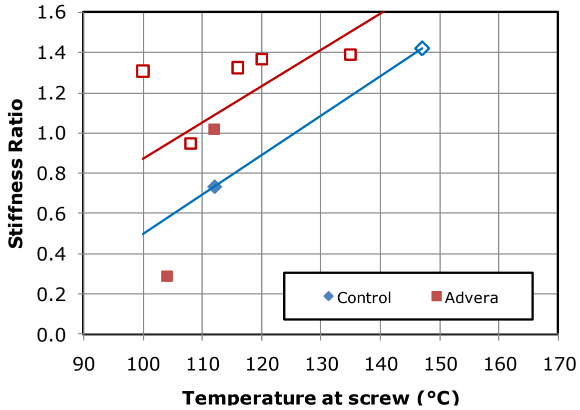


Figure 13: Change in stiffness ratio with temperature at screw after one conditioning cycle for binder course AC

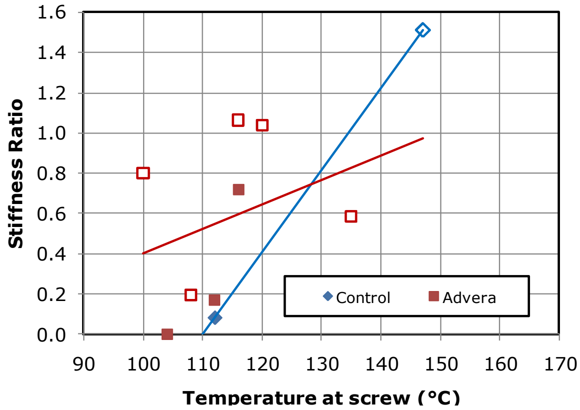


Figure 14: Change in stiffness ratio with temperature at screw after two conditioning cycles for binder course AC

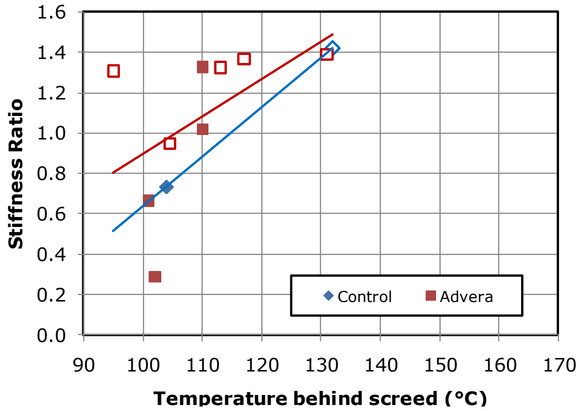


Figure 15: Change in stiffness ratio with temperature behind screed after one conditioning cycle for binder course AC

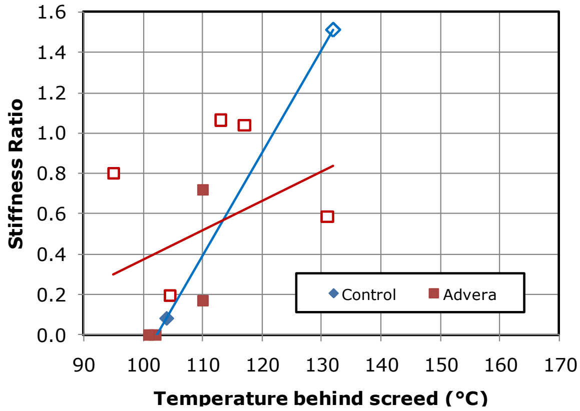


Figure 16: Change in stiffness ratio with temperature behind screed after two conditioning cycles for binder course AC

After the second conditioning cycle, the stiffness ratio was generally no better than unity even with mixing temperatures above 120 °C. The same relationship with the mixing temperature appears to apply as after the first temperature except for Section 2, which had a surprisingly low stiffness ratio given that it was mixed at a high temperature in the early afternoon when the ambient temperature was warm. The reason for this anomaly is not clear, although the test as undertaken on cut specimens is particularly severe.

Although the results do not follow a clear-cut pattern, the modified mixtures did generally perform better in this test than the control mixture at the same temperature but not better than the control mixture at the conventional temperature.

3.6 Wheel-tracking

200 mm diameter cores taken from the SMA 10 surface course were tested for wheel-tracking in accordance with BS EN 12697-22 [8] using the small device with Procedure B. The initial result for Section F was significantly different from those for the other sections. Therefore, further cores were taken from that section and the tests repeated, this time with results that are consistent with the others. Therefore, the results from the initial set of Section F cores are taken as outliers.

The results for both rut depth and wheel-tracking rate, excluding the outlier results, are plotted against the temperatures at which they were mixed at the plant, at the screw whilst it was being laid and behind the screed after it had been laid in Figures 17 to 22. Again, the temperatures after compaction were not used because of the variable time after compaction that the measurements were made. The points with the normal mixing time have solid fill while those with the extended mixing time have white centres. Linear trend lines were applied separately to both main sets of data (Advera and control).

The rut depth and tracking rate increase with reduced temperature for the control mixture, as would be expected. The results for the modified mixture appear to reduce slightly with the initial drop in temperature before rising below a temperature of about 120 °C behind the screed. However, the increase in both parameters was less than for the control mixture except for wheel-tracking rate on Section I, which was a transported material that was laid at the end of the day. Again, although the results do not follow a clear-cut pattern, the modified mixtures did generally perform better in this test than the control mixture at the same temperature.

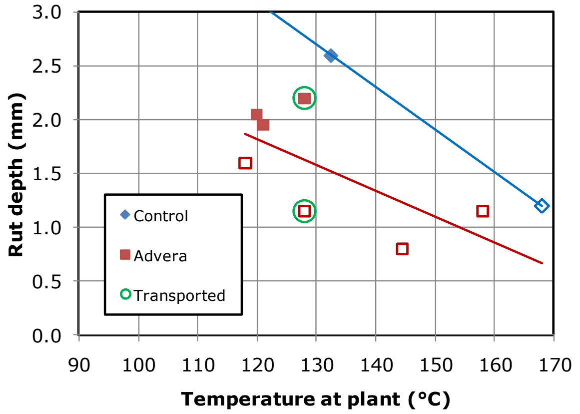


Figure 17: Change in rut depth with temperature mixed at plant for surface course SMA

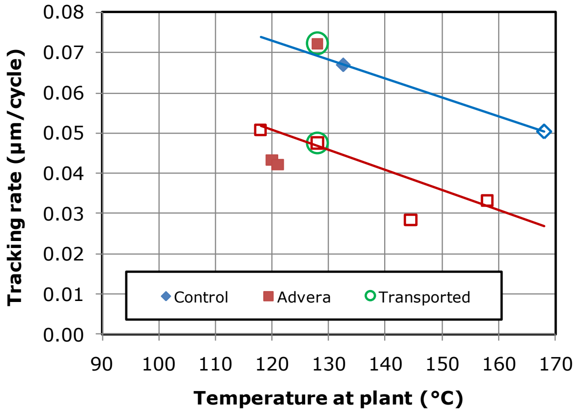


Figure 18: Change in tracking rate with temperature mixed at plant for surface course SMA

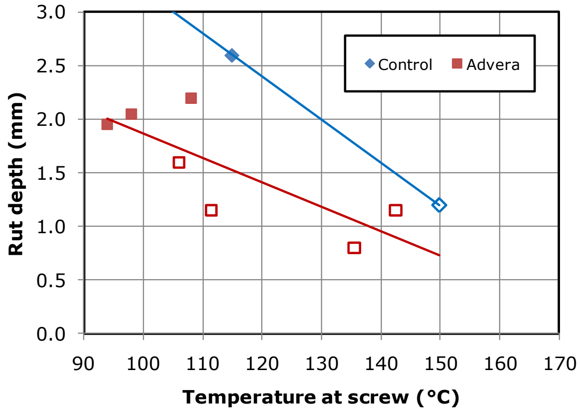


Figure 19: Change in rut depth with temperature at screw for surface course SMA

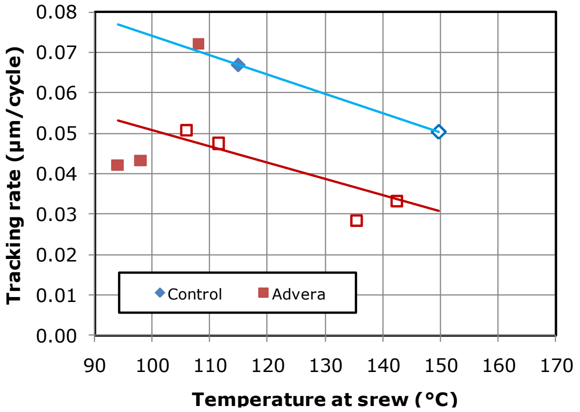


Figure 20: Change in tracking rate with temperature at screw for surface course SMA

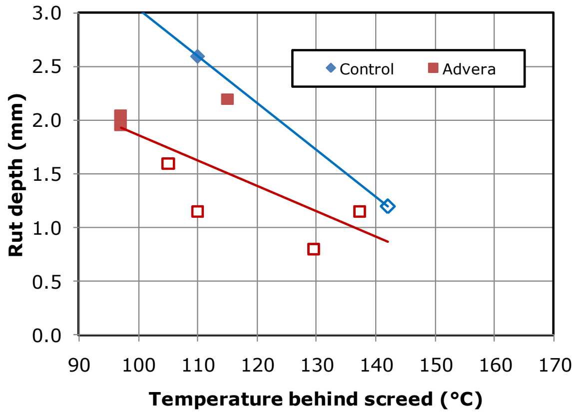


Figure 21: Change in rut depth with temperature behind screed for surface course SMA

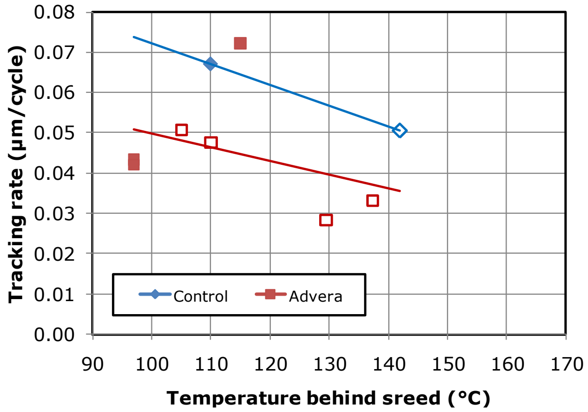


Figure 22: Change in tracking rate with temperature behind screed for surface course SMA

3.7 Durability

The site was re-visited by the lead author on Thursday, 14 July 2011 when the site was 13 months old. The weather was dry and generally sunny, although there were clouds. The visit was in order to undertake a visual inspection of the site in accordance with the TRL Inspection Panel methodology [9] except that the inspection was undertaken by a single individual. The condition of all sections was G (good), irrespective of the temperature at which it was mixed and laid. The higher mark of E (excellent) could not be given because of the variability of the apparent texture within practically all sections. Also, there was a lot of fine material that had accumulated in the texture, presumably from the quarry, which could have obscured some minor potential faults. However, it is not believed that any faults that could have lowered the marking further were missed because of the fine material.
The one-year visual inspection has shown that, with the addition of the additive, there is no disbenefit in reducing the manufacturing temperatures, at least in the early life. Longer monitoring of this and/or other sites will be needed to confirm the longer-term affects. In the absence of such data, the best indicators of potential durability are the air voids contents and the water sensitivity.
The air voids content is a very important property for durability as well as demonstrating the compactibility of a mixture. The reduced rate of increase in the air voids content with a reduction in the mixing and compaction temperatures for the modified mixtures compared to those without is a benefit. However, the ideal would be that, within the temperature that the product was designed, there would be no increase in air voids content.
The water sensitivity results did not follow a clear-cut pattern with the mixtures containing the additive generally performing better than the control mixture at the same temperature but not better than the control mixture at the conventional temperature. However, the loss of water sensitivity could be ameliorated by the inclusion of anti-stripping agents.

4 TEMPERATURE

Thermocouples were inserted into selected sections on both days after compaction was completed. The delay in waiting for compaction lost some early data, but minimised:
- any disruption to the laying process;
- the hazard to the operatives inserting the thermocouples; and
- the likelihood of damage to the leads back to the data logger from the compaction process.

The selected locations were Sections 1, 2 and 6 on Day 1 and Sections A, B and E on Day 2. Two replicate sets of three thermocouples were inserted on each section, the three being near the surface, at mid depth and near the bottom of the asphalt course being laid. In addition, some thermocouples were placed away from the mat in order to record the ambient temperature. All thermocouples were wired back to two data loggers and were left until the temperature had dropped to below 40 °C.
The actual temperatures logged during the trial are shown in Figure 23 for the binder course AC 20 on Day 1 and Figure 24 for the surface course SMA 10 on Day 2.
There seems to have been a problem with the data logger for Section A and B on Day 2 in that there is a gap in recordings for just over an hour between 15:50 and 17:00. However, the curve between these points is consistent with that of the other curves so that it is assumed to be due to non-recording rather than an error in the time recorded.
It can also be seen that there are various anomalies where the temperature appears to increase, which is not logical. Therefore, these data are treated as outliers and removed and the data without these outliers has been used for the analysis.
A model was developed for determining the time that can be saved before the surfacing can be trafficked was required [11]. The model was based on an existing model for determining the time available for compaction [10] updated using the data collected from this trial. Using the model, the minimum time required can be estimated from the (expected)

wind speed at 2 m height, air temperature, initial laying temperature, maximum trafficking temperature that is allowed, the (nominal) compacted layer thickness, the asphalt mixture type and, if required, the accumulated solar reflection.
If the calculated time before trafficking can be permitted is sufficiently long that the weather changed/is expected to change significantly, the calculation has to be calculated in stages by calculating the time between one or more intermediate temperatures. The expected minimum time before trafficking can be permitted will then be the sum of all the steps.

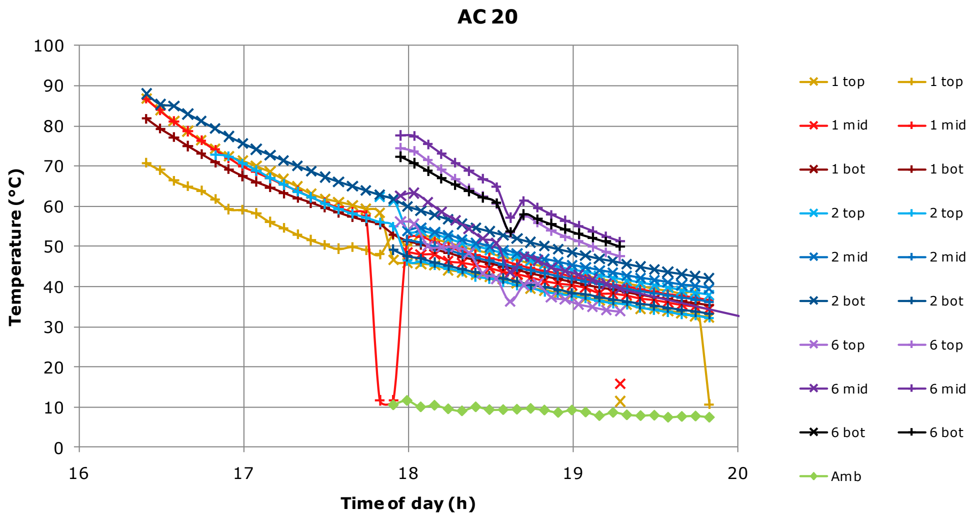


Figure 23: Raw data recorded for AC 20 on Day 1

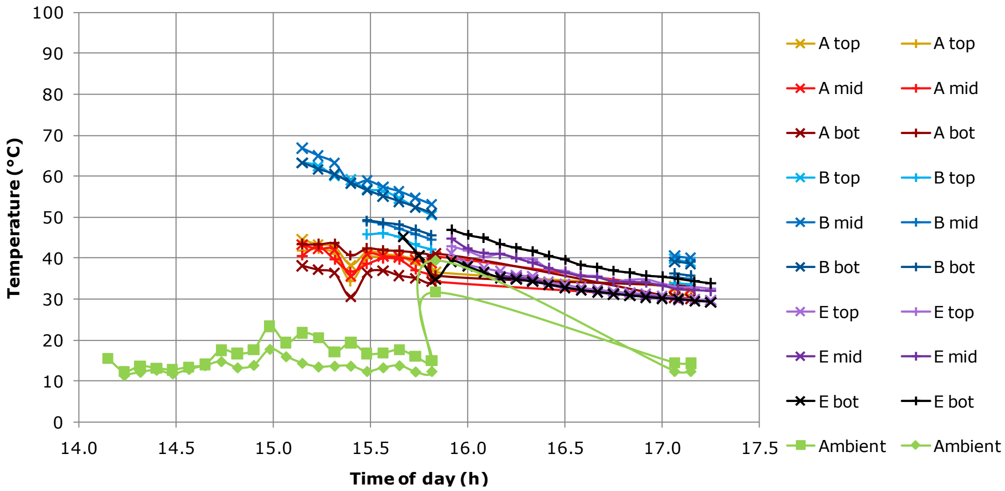


Figure 24: Raw data recorded for SMA 10 on Day 2

Using the model developed for two mixtures laid 40 mm and 80 mm thick at 100 °C rather than 140 °C, the time before the pavement could be opened to traffic at, say, 35 °C for a series of weather conditions would be as given in Table 5. Despite the different values for each of these cases, the model is such that the overall saving in reducing the initial temperature from 140 °C to 120 °C is 9.1 % for all of them. This reduction would be 21.5 % if the initial temperature was reduced further to 100 °C.
Whilst the time necessary and proportion of time saved are dependent on the maximum temperature of the mat at which it is permitted to open it to traffic, the actual time saving will not change. The saving is for the time that the mat will require to drop from the traditional initial laying temperature to the reduced laying temperature, after which the remaining drop in temperature is assumed to behave the same irrespective of the initial laying temperature. This assumption is probably not entirely valid because the surrounding substrate will have been heated during the cooling of the mat from a higher laying temperature and will not absorb as much heat in the remaining phase as a mat laid at that temperature. Hence, the model may be slightly conservative in its time saving estimates.

Table 5: Minimum time before pavement can be opened to traffic

Ambient temperature (°C)	5	5	15	15	25	25
Wind speed (km/h at 2 m height)	0	25	0	25	0	25
Time for 40 mm layer from 140 °C (h)	4.9	3.6	5.7	4.1	6.7	3.8
Time for 40 mm layer from 120 °C (h)	4.5	3.2	5.2	3.8	6.1	4.4
Time saving for 40 mm thick layer (min)	27	20	31	23	37	26
Time for 40 mm layer from 100 °C (h)	3.9	2.8	4.5	3.3	5.2	3.8
Time saving for 40 mm thick layer (min)	64	46	74	53	86	62
Time for 80 mm layer from 140 °C (h)	5.7	4.1	6.6	4.8	7.7	5.5
Time for 80 mm layer from 120 °C (h)	5.2	3.7	6.0	4.3	7.0	5.0
Time saving for 80 mm thick layer (min)	31	22	36	26	42	30
Time for 40 mm layer from 100 °C (h)	4.5	3.2	5.2	3.7	6.0	4.3
Time saving for 40 mm thick layer (min)	73	53	85	61	99	71

The reduction of around 30 min, whilst relatively short in terms of the time scale for a major roads project, can be very significant when planning night works with limited possession and strict timetables for opening the road to traffic.

5 CO_2 EMISSIONS

The contribution to climate change of the eight binder course mixtures and eight surface course mixtures used in the trial were analysed in order to assess the additional sustainability that can be achieved using the additive. The carbon footprints were generated using the life cycle based approach of asPECT [12] which interprets Publically Available Specification (PAS) 2050 [13] for the asphalt and related industries. 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 asPECT program covers all the life cycle steps up to and including site preparation, laying and compacting.
Steps 1 to 3 are acquisition, intermediate transport and processing of raw materials. The CO_{2e} generated by Steps 1 to 3 for the asphalts investigated are covered by 'cradle-to-gate' default emissions factors. The values for bitumen and fibres where sourced from Appendix D of the asPECT Protocol and aggregates and filler were assigned the industry average for aggregates from the Mineral Products Association's Sustainable Development Report 2009 [14]. The values used are presented in Table 6.

Table 6: Cradle to gate CO_{2e} values for non-Advera constituents

Constituent	$kgCO_{2e}/t$
Aggregate	4.32
Filler	4.32
Bitumen	280
Polymer Modified Bitumen	460
Fibre	0.78

The cradle-to-gate CO_{2e} value for the additive was sourced from a peer reviewed journal article [15]. This source presented a life cycle inventory for 80 % hydrated Zeolite A, the detergent product which is otherwise known as Advera. The energy mix used for production was converted to CO_{2e} using the Defra/DECC standard emissions factors [16], and the footprint was determined to be 2054 $kgCO_{2e}/t$ (including indirect emissions from fuel supply as specified by PAS 2050 and asPECT).
Step 4 is transport to the plant. The quarry and the asphalt plant were co-located, thus it was assumed that there was no transport of aggregates and filler to plant. Information was supplied on the location of the Advera factory in Eijsden, The Netherlands where the material for the trial was sourced. Transport was modelled as being via articulated lorry to Rotterdam, small container ship to Hull and a further journey by articulated lorry to Haughmond Hill. Should asphalt which utilises the additive be produced in the UK regularly in the future (it is understood that Advera may be produced in a Warrington factory), then transport to site would be significantly reduced. A scenario was modelled to determine the effect of this reduced transport contribution.
It was assumed that bitumen was sourced from Ellesmere Port and was transported to Haughmond Hill by articulated tanker. The cellulose fibres for the SMA were sourced from Pattensen-Schulenburg, Germany and transported to Haughmond Hill by articulated tanker via the Rotterdam to Hull ferry route.
Step 5 is the plant operations (heating and mixing). Consumption of gas oil and electricity in heating, mixing and other integral processes was monitored throughout the trial, specifically before and after the production of each 10-20 t batch of mixture. The process of before and after meter reading to record energy consumption is not strictly in adherence with the asPECT Protocol but is the most appropriate method for trial mixtures. The Protocol recommends monitoring energy consumption over a longer time period (for a greater quantity of asphalt) to limit potential variability associated with meter reading, or affects caused by residual heat in the equipment. The energy consumptions for each of the mixtures are presented in Figures 25 and 26. Notably, there was only one control AC and SMA mixture (M1-1 and

M2-1) which contained no additive and was mixed at a conventional hot mix asphalt temperature. Comparisons of energy and CO_{2e} savings relative to these control mixtures are therefore quite approximate.
The apparent increase in the energy consumption for M2-4 being greater than that for M2-3 despite being mixed at a lower temperature is probably a reflection on the limited accuracy of the readings, which were measured on equipment not normally used to identify the energy use of single batches.

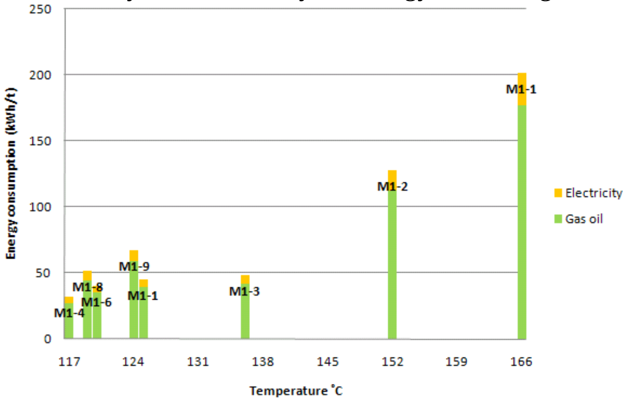


Figure 25: Energy consumption by fuel for AC 20 mixtures

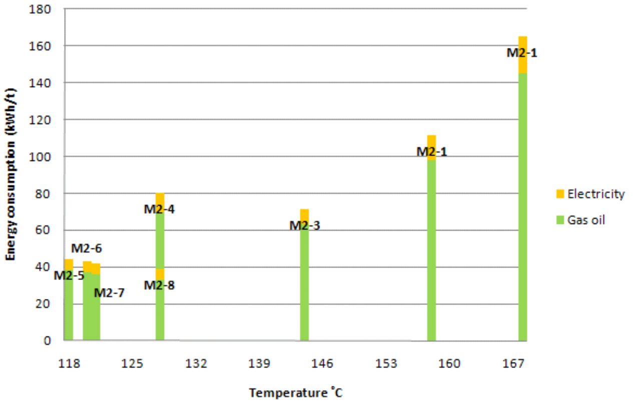


Figure 26: Energy consumption by fuel for SMA 10 mixtures

Step 6 is the transport to site. The asphalt was laid on the trial site; hence, it was assumed that there was no intermediate transport from plant to site. Where samples were trafficked post-plant, this transport was not included either, to maintain direct comparability between the footprints of all mixtures.
Step 7 is installation. In line with the asPECT protocol, laying and compacting impacts were included at a rate of 4.6 $kgCO_{2e}$ per tonne of asphalt.
The total carbon footprints of the mixtures investigated are presented in Figure 27. It can be observed that, on average, the SMA mixtures containing the additive have footprints which are approximately 20 % higher than the AC mixtures.

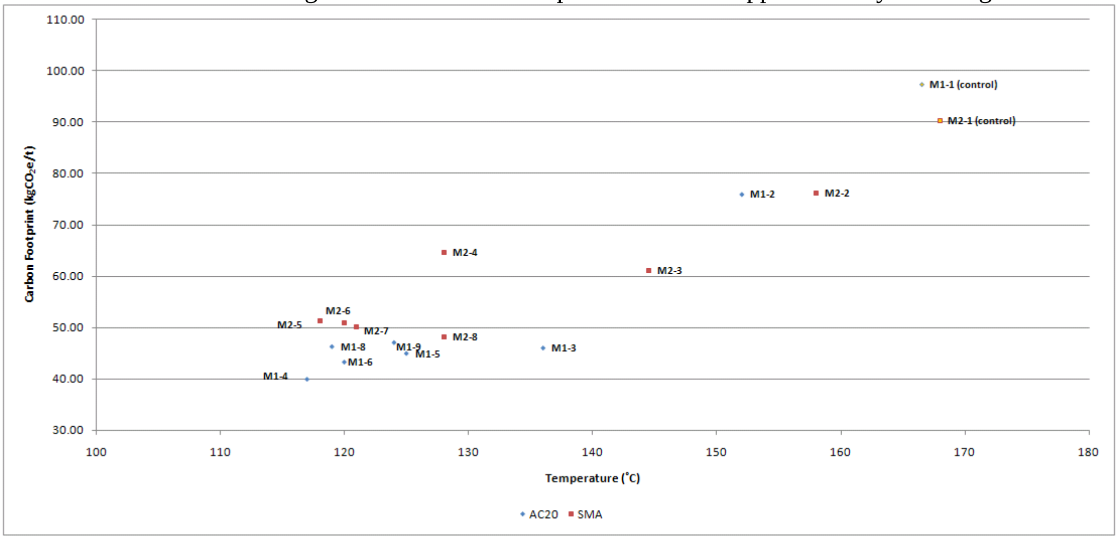


Figure 27: Total carbon footprints of the mixtures investigated

A breakdown of the relative contributions of the different life cycle steps to the carbon footprints of two of the materials investigated are presented in Figure 28. AC 20 mixtures M1-6 (Advera mixture) and M1-1 (conventional hot mix control), and SMA 10 mixtures M2-6 (Advera mixture) and M2-1 (conventional hot mix control) are presented. M1-6 and M2-6 were both mixed at 120 °C.
The breakdowns in Figure 28 show that the constituent material cradle-to-gate contributions to the carbon footprint are more significant for mixtures containing the additive. This is mainly due to the increased embodied CO_{2e} contribution from the additive itself and the reduction in the replant fuel consumption that results from its use. For the conventional hot mix asphalts used as control mixtures, the relative contribution from the constituent materials is significantly lower than the plant fuel consumption (electricity and gas oil combined). These results are slightly distorted by the fact that neither aggregates nor filler are transported in the scenarios investigated.
A number of pertinent points can be drawn from the carbon footprinting analysis. Firstly, when compared to the conventional hot mix control mixtures, the overall footprints of the mixtures containing the additive are up to 50 % lower for the AC 20 mixtures investigated and up to 40 % lower for the SMA mixtures investigated. These relative savings come with an important proviso, which is that they are based on a comparison with a single data point for conventional hot mix asphalt in both cases. The primary recommendation from the study is, therefore, to obtain energy data for hot mix asphalts to improve the confidence levels associated with the comparative savings.

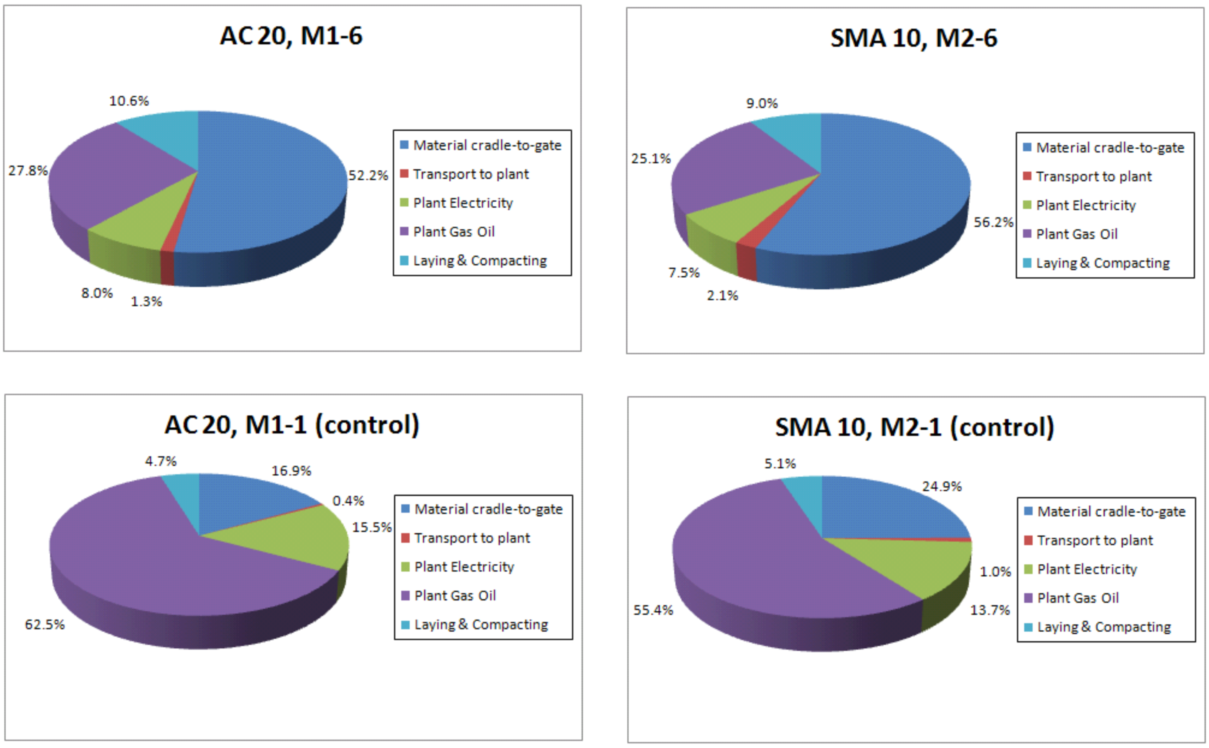


Figure 28: Relative contributions of different life cycle steps to overall carbon footprints

The overall footprints of the SMA mixtures when compared to the AC mixtures were slightly higher. This is primarily due to the higher CO_{2e} content of bitumen, relative to aggregate. Also, if the aggregate used to produce the SMA mixtures on Day 2 had a higher moisture content, then this increase would also be a reason for a higher required energy input.

Production of the additive is an energy intensive process; its cradle-to-gate carbon footprint is several times that of the other constituent materials. Including 0.3 % Advera in asphalt mixtures contributes approximately 6 kg CO_{2e}/t to the footprint, but this contribution appears to be far outweighed by the savings that its inclusion can deliver.

Moving production of the additive from Eijsden to Warrington would reduce the contribution of it to mixtures very marginally in terms of transport (<0.5 %). However, moving production would require utilisation of the UK electricity which, at present, is more CO_{2e} intensive than the Netherlands supply and this difference would nullify the reduced transport benefits completely.

A theoretical asphalt mixture containing polymer-modified bitumen would have a carbon footprint of approximately 100 kg CO_{2e}/t. The mixture composition and plant energy consumption would be very similar to that of SMA mixture M2-1. The key difference would be the higher cradle-to-gate footprint of the polymer modified bitumen that is 460 kg CO_{2e}/t.

6 CONCLUSIONS

The trial demonstrated that successful mixtures can be mixed and compacted at lower temperatures than would be normal with the inclusion of the additive. To achieve success, the mixing time may have to be extended when the mixture includes the additive. However, although the mixtures incorporating the additive were less sensitive to the mixing temperature than the conventional mixtures, there were some property changes. In particular:

- The air voids content of mixtures mixed and compacted at lower temperatures are increased even with the inclusion of the additive, but not to the same extent as mixtures without it.
- The stiffness of mixtures mixed and compacted at lower temperatures is reduced even with the inclusion of the additive, but not to the same extent as mixtures without it.
- The resistance to deformation of mixtures, as measured by wheel-tracking, is generally improved with the addition of the additive, even when mixed and compacted at lower temperatures.
- Overall, the results imply that, with the addition of 0.3 % Advera, the mixtures trialled can be used successfully provided the mixing temperature is above 120 °C, the temperature at the screw is above 115 °C and the temperature at the screed is above 110 °C. Under these conditions, the modified mixtures have properties comparable with those of conventional hot mix asphalt. The one-year visual inspection showed no difference between the various surface course sections, showing (short-term) durability of the modified mixtures but laid at reduced temperatures compared to the control hot mix asphalt.
- The use of the additive to reduce the laying temperature by 20 °C will allow opening to traffic between 20 min and 40 min earlier. The model for time to opening to traffic does need validation from other sites to refine it; however, it will allow estimates to be made.

- The use of lower mixing and compaction temperatures by the inclusion of the additive also reduces the carbon footprint of asphalt. In particular, the overall CO_2 footprints of the modified mixtures are up to 50 % lower for the AC 20 mixtures investigated and up to 40 % lower for the SMA mixtures investigated (although these values are from limited data and need to be confirmed).

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