



The behaviour of asphalt in adverse hot weather conditions

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Executive Summary

A programme of laboratory tests has been undertaken to support the development of specification clauses and associated advice on laying asphalt in adverse hot weather conditions. The laboratory programme assessed the influence of both temperature and traffic speed on the deformation resistance of hot rolled asphalt and stone mastic asphalt.

In the United Kingdom, the wheel-tracking test is generally carried out at either 45°C or 60°C. In the test programme, samples were tested at six temperatures over the range 20°C to 60°C. Two material types were used to identify if they performed differently over this temperature range. The equipment for the standard wheel-tracking test does not allow for the speed to be varied. Therefore, a non-standard test was developed using Road Machine No. 1. Samples, at 45°C, were tracked at two speeds and also using a stationary load and the resulting deformations were compared.

The findings, combined with previous work that reviewed measurements of site temperature, are equally applicable to both 'traditional' hot rolled asphalt and newer surfacing materials such as stone mastic asphalt. The principal findings are:

- The logarithm of the wheel-tracking rate increases approximately linearly with temperature up to about 50°C. Thereafter, it tends to remain at a constant value.
- The resultant deformation is more dependent on loading time than traffic speed. However, the low deformations due to static load shows that dynamic effects are important.
- A risk model can be used to assess the probability of unacceptable deformation. However, economic considerations are unlikely to justify the resources required to make use of the risk assessment model in most cases.
- The best relationship found to model deformation implies that the permanent deformation is proportional to the traffic flow, the wheel-tracking rate at 45°C and the logarithm of the age plus one. However, the value of the square of the correlation coefficient (after adjustment for the degrees of freedom) is a modest 0.46.
- There are various physical actions that can be taken when laying hot asphalt in adverse hot weather conditions to minimise the potential problems.
- Specification clauses and advice can be, and have been, prepared on the basis of these findings.

In one of the laboratory trials, the stone mastic asphalt samples were found to fret when subject to a turning load at the higher speed. This finding indicates that some stone mastic asphalt mixtures may not be suitable for use on tight roundabouts without adequate edge restraint, although the conditions simulated in the test are probably much more severe than those found on site.

1 Introduction

1.1 Need for consideration of hot weather

It is generally recognised that weather conditions have a significant influence on the laying and compaction of asphalt. Cold, wet and windy conditions during laying can result in poor quality asphalt that will perform badly in service. Most problems have occurred during the colder months of the year, so that laying difficulties were seen to be associated with low air temperatures. Understanding of the effects of wind speed and air temperature on the cooling of hot laid asphalt layers increased rapidly in the 1980s. The term 'Cold Weather Working' was replaced by 'Adverse Weather Working' to emphasise the influence of wind speed. In assessing adverse weather, the emphasis was still on adverse cold weather laying conditions and the effect of solar radiation was regarded as a benefit that was generally discounted in specifications.

Difficulties following the laying of asphalt in adverse hot weather became very apparent during the very hot summer of 1995 when early failure, in the form of excessive deformation and loss of texture depth, occurred on several occasions. The problems arose from paving materials being trafficked whilst the material was still too hot, although this has been partially alleviated by the current trend to use thinner layers that cool more quickly. Nevertheless, there is a need for advice about laying bituminous materials in hot weather when the time taken to cool sufficiently to permit trafficking can be critical. If the time allowed is too short, it can result in premature rutting by traffic. If adequate time is allowed, there may be considerable traffic congestion that will lead to pressure to open the site to traffic prematurely. Whilst this is primarily a problem associated with surface course materials, it can also affect the lower layers that are trafficked by site vehicles or are used as temporary running surfacings. Also, the temperature of lower layers will have an effect on the rate of cooling of any layer placed over it.

In order to provide authoritative advice, one needs to be able to estimate the time that a pavement course takes to cool sufficiently before it can be trafficked under various weather conditions. Hence, a model was developed to estimate the rate of cooling and a criterion established for the condition of the pavement layer that will not be detrimentally effected by trafficking. The cooling model, which incorporates the trafficking criterion, can be used as the basis for advice about whether the conditions are, or are not, suitable for laying bituminous materials within a specified time period before being exposed to traffic.

1.2 Laying asphalt in hot weather conditions

1.2.1 Potential problems

When hot asphalt is laid during weather conditions of high ambient temperature, particularly during continuous periods of strong sunlight, it can remain workable for a considerable time. During the laying and compaction it may be difficult to maintain profile and, in the case of hot rolled asphalt surface course with added pre-coated chippings, it may be difficult to achieve adequate texture depth.

During extended periods of hot, sunny conditions, the newly-laid surfacing layers of a pavement can maintain temperatures after opening to traffic that are sufficiently high to allow excessive rutting and the rapid embedment of any chippings, with the latter causing a reduction of texture depth. The conditions are compounded in conditions where traffic intensity is high and speeds are restricted. Excessive texture depth loss and rutting may affect vehicle steering and braking.

1.2.2 Cooling of asphalt layers

Heat is lost from a hot-laid asphalt layer by conduction into the cooler substrate and by convection and radiation from the top surface. As the hot asphalt layer cools, the heat flow into the substrate will reduce as the layer approaches a condition of temperature equilibrium with the environment.

The rate at which an asphalt layer cools depends on both environmental and asphalt factors. Both higher wind speeds and lower air temperatures increase the cooling rate and, hence, reduce the time available for compaction. Increasing incident solar radiation reduces the cooling rate, thus extending the time available for compaction. Asphalt factors that affect the cooling rate include its temperature, thermal conductivity, specific heat, surface albedo (reflection coefficient) and layer thickness. The most important material factor is asphalt layer thickness, followed by its temperature. For fixed conditions, the cooling time is proportional to the asphalt layer thickness raised to the power 1.8 (Daines, 1985). Calculations describing the cooling behaviour of hot laid asphalt layers are complex (Jordan and Thomas, 1976) and require the use of computers. However, there are simplified equations that are sufficiently accurate for practical purposes to predict the time available for compaction (Daines, 1985; Nicholls and Daines, 1993).

This method of estimating the cooling behaviour of a hot-laid asphalt layer is only applicable down to a mid-layer temperature of about 80°C for constant environmental conditions. Extrapolation using this method to lower temperatures is unreliable and an asphalt layer will not cool below about 50°C, twice the air temperature in degrees Celsius, on a day that is hot, calm and sunny. This temperature can be compared to the safe temperature for trafficking of below 50°C.

Some of the heat absorbed by the pavement from a newly laid hot asphalt layer remains when the next daily temperature cycle resumes. The temperature behaviour of the pavement, from the end of the compaction period until the new layer has cooled to ambient temperature, is influenced by the cyclic effect of solar radiation. This is extremely complex and, to date, has not been modelled. Nevertheless, in general a day must elapse before the heat from a 50mm thick layer is dissipated and three days for a 150mm thick layer.

1.2.3 Solar radiation

Solar radiation is stronger and endures for longer periods of the day during the summer months, although its

intensity can be reduced by cloud cover. Table 1 gives measurements of solar radiation at the Meteorological Office in Bracknell, Central Southern England, in which the 99th and first percentile figures relate to full sunshine and full cloud cover, respectively.

Table 1 Total incident energy averaged between 12:00 and 13:00 GMT

Month	Total incident energy (W/m^2)	
	99 th percentile (full sunshine)	1 st percentile (full cloud cover)
January	322	20
April	830	70
July	900	50
October	550	40

Table 1 shows that high levels of solar radiation can occur in the months from April to September, and that even in winter solar radiation can be appreciable. The risk of hot weather having an adverse effect on the laying of asphalt is obviously higher during the summer months of June to August, but it may be significant for shorter periods of the day in the spring and autumn.

New asphalt road surfacings, which can have an albedo (reflection coefficient) close to zero, are blacker than ‘weathered’ surfacings. Unfortunately, from the viewpoint of construction and early trafficking, a black new surfacing is more vulnerable to the effects of solar radiation and therefore at greater risk of deformation during the first summer compared with subsequent summers. Although, in the past, it was assumed that road surface temperatures rarely exceeded 45°C, recent hot summers have demonstrated that the asphalt surface temperature can reach, and may even exceed, 50°C, particularly for south-facing gradients in Southern England.

2 Road temperatures

2.1 Typical temperatures

The temperature of the pavement will vary due to the cyclic influence of solar radiation and changes in air temperature, wind speed, cloud cover and precipitation. An example of the effect of daily cyclic solar radiation is given in Figure 1 (Robinson, 1986), which covers two days at Alconbury in Central England during summer.

Table 2 includes the times of the day at which the highest and lowest temperatures are attained during extended periods of very hot and sunny weather, at depths of 10, 100 and 250mm. Below a depth of about 1m, the temperature remains within a few degrees of 10°C, depending on location, throughout the year.

2.2 Recent data

TRL requested the assistance of the CSS for records of the temperatures encountered on actual roads. Road temperatures are often monitored by highway authorities with ice-monitor systems during the winter and it was

Table 2 Approximate maximum and minimum pavement temperatures during very hot weather conditions

Depth (mm)	Maximum temperature		Minimum temperature	
	Temper- -ature (°C)	Time (24 hour clock)	Temper- -ature (°C)	Time (24 hour clock)
10	50	15.00	15	04.00
100	40	16.00	20	08.00
250	30	20.00	20	10.00
1000	10	–	10	–

hoped that these could also be used during the summer. However, the only responses were that Bedfordshire County Council generously agreed to monitor the temperature and associated environmental conditions for one site during the summer of 1998 and Cumbria County Council kindly provided records of the temperatures at two sites taken during the summer of 1993. The mean results are given in Tables 3 and 4, respectively.

The Bedfordshire data has the surface temperature together with environmental conditions recorded manually four times a day (08:00, 10:00, 12:00 and 15:30) for most weekdays between 27 March to 18 September 1998. The site was the road outside the Engineering Laboratory in Manton Lane, Bedford, where the surfacing is stone mastic asphalt, level and unshaded.

The Cumbria data has the temperatures both on the surface and 260 to 270 mm below the surface recorded for most hours of every day between 14 June and 29 August 1993. The locations of the sites are the southbound carriageway of the M6 at Catterlen, where the altitude is approximately 150m, and the northbound carriageway of the A74 at Floriston, where the altitude is 12m. The thickness of the bound pavements are 355mm on the M6 and 300mm on the A74.

However, the Cumbria data was provided in graphical form so that the required temperatures had to be scaled off to the nearest half degree. In order to obtain some consistency with the measurements made at Bedford, the temperatures were extracted at 2 hour intervals between 10:00 and 16:00; where a value was missing, the value was interpolated from the adjacent hour’s values. However, it was noted that often the extracted points did not completely describe the behaviour during the period, with some maxima being lost due to peaks occurring at odd hours.

The data are not sufficiently extensive to draw any firm conclusions, being restricted in both area location and time period. Ideally, data from all over the UK for a number of years, including some with ‘good’ summers, are needed. Nevertheless, there are some interesting points that can be gleaned. These points are:

- The maximum road temperatures were of the order of 40°C even though the locations were not selected as ‘sun-traps’ and the years 1993 and 1998 were not particularly hot.

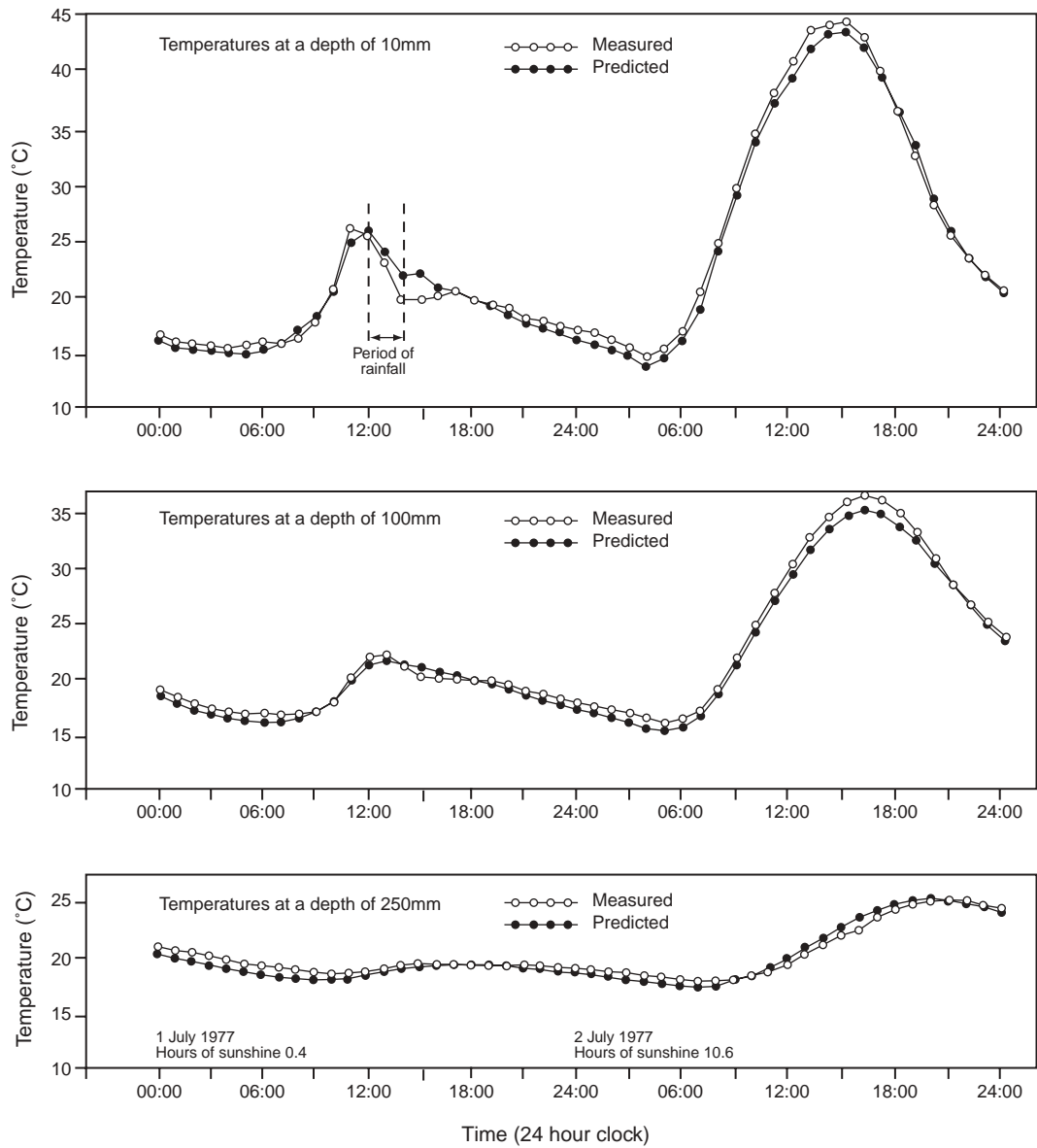


Figure 1 Comparisons of measured and predicted temperatures for the experimental pavement section at Alconbury By-pass in summer

Table 3 Summary of site temperatures in Bedford

Time	Statistic	Temperature (°C)				Wind speed (m/s)	Cloud cover (%)	Proportion wet (%)
		Road surface	Air	Difference	Ratio			
08:00	Mean	18.8	14.6	4.2	1.29	1.87	71	10
	Range	11.0–25.5	9.5–18.5	0.0–7.5	1.00–1.58			
10:00	Mean	22.9	16.9	6.0	1.35	2.28	73	12
	Range	13.5–32.5	10.0–22.5	1.5–11.0	1.08–1.69			
12:00	Mean	26.3	18.7	7.6	1.40	2.58	83	7
	Range	17.5–40.0	12.0–26.0	1.5–16.0	1.08–1.74			
15:30	Mean	27.9	20.7	7.2	1.35	2.61	82	5
	Range	18.0–43.5	12.5–31.0	1.0–15.0	1.06–1.66			
Combined	Mean	24.0	17.7	6.3	1.35	2.31	77	9
	Range	11.0–43.5	9.5–31.0	0.0–16.0	1.00–1.74			

Table 4 Summary of site temperatures in Cumbria

Time	Statistic	Temperature (°C)					
		M6, Catterlen			A74, Floriston		
		Road surface	Sub- surface	Difference	Road surface	Sub- surface	Difference
08:00	Mean	17.3	15.7	1.6	17.2	15.7	1.5
	Range	11.5–25.0	13.0–19.5	-4.0 – 10.0	11.0–29.0	12.0–20.0	-3.5 – 9.0
10:00	Mean	20.5	15.7	4.8	21.3	16.0	5.3
	Range	13.0–32.5	13.0–19.5	-2.5 – 15.5	13.0–36.0	13.0–21.5	-2.0 – 14.5
12:00	Mean	23.3	16.2	7.1	24.2	17.0	7.1
	Range	14.0–36.0	13.0–21.5	-0.5 – 17.5	15.0–39.0	14.0–23.5	-1.5 – 16.5
14:00	Mean	23.8	16.8	7.0	24.6	17.9	6.7
	Range	15.5–37.0	14.0–27.5	-4.0 – 17.5	16.0–38.0	11.0–25.0	-1.5 – 15.5
16:00	Mean	22.8	17.2	5.6	23.3	18.6	4.6
	Range	15.5–32.5	14.0–22.0	-1.5 – 12.0	13.5–35.0	12.0–25.5	-2.5 – 10.5
Combined	Mean	21.5	16.5	5.2	22.1	17.0	5.1
	Range	11.5–37.0	13.0–27.5	-4.0 – 17.5	11.0–39.0	11.0–25.5	-3.5 – 16.5

- The maximum temperature was at around 14:00, although it did vary between days.
- The road temperature was generally 35% higher than the air temperature, but was 75% higher on occasions.
- The temperature at about 265mm depth generally had a daytime difference of only about (5 – 7)°C, but it could be up to 17.5°C.

3 Laboratory studies

3.1 Deformation at differing temperatures

3.1.1 Test programme

In the UK, the wheel-tracking test (BSI, 1996) is generally carried out at either 45°C or 60°C. The properties of some asphalts can change significantly between these two temperatures (Nicholls, 1998a) with the relationship being material specific.

The test programme, to investigate the relationship between temperature and deformation rate, involved testing three replicate samples of three materials at each of six temperatures. The materials were stone mastic asphalt and hot rolled asphalt manufactured in the laboratory as slabs and hot rolled asphalt laid in a pilot-scale trial and cored. The test temperatures were 60°C, 50°C, 45°C, 40°C, 30°C and 20°C. Two material types were used in order to identify if there were any differences in performance between them over this temperature range.

The mixtures used for the manufacture of the laboratory prepared slabs are given in Table 5. The hot rolled asphalt laid at TRL in the pilot-scale trial for a wheel-tracking precision exercise in December 1991. The mixture was specified as 30/14 hot rolled asphalt in accordance with BS 594: Part 1: 1985, column 9, Table 3 with 50pen bitumen and Marshall stability of the complete mixture of (8 ± 2)kN.

Table 5 Mixture design for laboratory-manufactured slabs

Component material	Stone Mastic Asphalt			Type F 30/14 HRA		
	Percentage of			Percentage of		
	Aggre-gate	Total mixture	Mass (g)	Aggre-gate	Total mixture	Mass (g)
Bardon Hill						
20 – 14mm	7		840	5		600
14 – 10mm	52		6240	18		2160
10 – 6.3mm	13		1560	} 10		1200
6.3 – 2.36mm	6		720			
Compton Basset Sand						
2.36mm–600µm	} 13.4		1608	14		1680
600 – 212µm				16		1920
212 – 75µm				26		3120
<75µm	8.6		1032			
Filler						
<75µm				11		1320
Binder						
50pen		6.3	807		6.5	834
Totals		100	12807	100		12834

3.1.2 Results

The results from the test programme are summarised in Table 6 and shown graphically in Figure 2. They are repeated in Figure 3 but with the logarithm of the wheel-tracking rate, rather than the wheel-tracking rate, being plotted against temperature.

3.1.3 Analysis

Up to 40°C, the wheel-tracking rates for all the samples were broadly similar with a rate of change with increasing temperature in the range 0.048 to 0.055mm/h/°C (see Figure 2). However, the performance of the different

Table 6 Summary of wheel-tracking results

Temp. (range) (°C)	Material		
	SMA (slabs)	HRA (slabs)	HRA (cores)
Wheel-tracking rate (mm/h)			
20	0.005	n/a	0.016
30	0.35	0.25	0.49
40	1.1	0.8	1.0
45	1.1	4.6	3.6
50	2.4	3.5	8.5
60	3.3	11.2	11.1
Rate of increase in wheel-tracking rate with temperature (mm/h/°C)			
20 to 40	0.055	0.055*	0.048
40 to 60	0.12	0.49	0.52

n/a Result not available

* Temperature range 30 to 40°C

mixtures became markedly different above this temperature. At 40°C, the wheel-tracking rate for all the mixtures was in the range 0.8 to 1.1mm/h whilst, at 60°C, the wheel-tracking rate increased to 3.3mm/h for the stone mastic asphalt and to over 11mm/h for the hot rolled asphalt. These values imply a rate of increase of 0.12mm/h/°C for the stone mastic asphalt and of about 0.5mm/h/°C for the hot rolled asphalt. The difference between the laboratory-made hot rolled asphalt slabs and the cores was not significant.

In studies using a more limited range of test temperatures, it has been suggested that the logarithm of the wheel-tracking rate may be proportional to the test temperature for any material (Section 4.1.3; Nicholls, 1998a). Figure 3, by comparing the individual lines with their linear trend line, shows that the line is not linear but flattens off as the temperature increases. This is probably because of a change

in mechanism of deformation resistance with increase in temperature. At high temperatures, the binder is ineffectual and all deformation is dependent on aggregate interlock, which is not temperature susceptible, so the deformation-resistance approaches a plateau value. At lower temperature, the binder plays an increasing role and the deformation-resistance will continue to increase as the temperature drops.

3.2 Deformation at differing speeds

3.2.1 Test programme

Another parameter that is known to affect the in-situ deformation but has not been quantified is the speed of application. If a vehicle is travelling slowly, it will apply a load to the pavement for longer, but will halving the speed equate to twice the deformation?

The equipment for the standard wheel-tracking test does not allow the speed to be varied. Therefore, a non-standard test was developed using Road Machine No. 1 (Figure 4). The road machine, consisting of a driven table that can rotate at 10rev/min, is capable of taking ten 305mm x 305mm x 50mm (nominal) test specimens. Two standard car wheels with 195/70 VR 14 tyres having a tread pattern similar to Michelin XDX are mounted vertically diametrically opposite one another with their centres (1.8 ± 0.1)m apart over the table so as to be able to run freely on the driven table whilst applying a dead load under each wheel of (5 ± 0.2)kN. The loading wheels are capable of moving laterally across the specimens by a total of (160 ± 25)mm and then returning whilst the road machine is in operation.

Three laboratory-manufactured slabs of each of stone mastic asphalt and hot rolled asphalt were placed onto the road machine and the temperature set to 45°C. The target

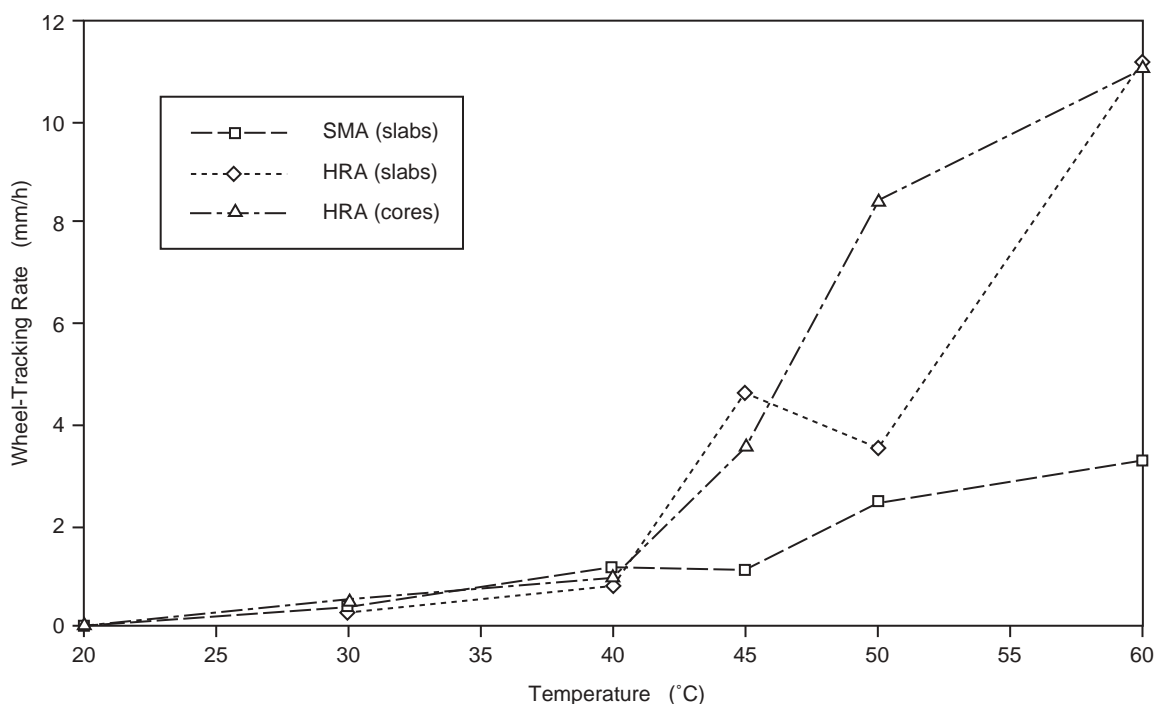


Figure 2 Change in wheel-tracking rate with temperature

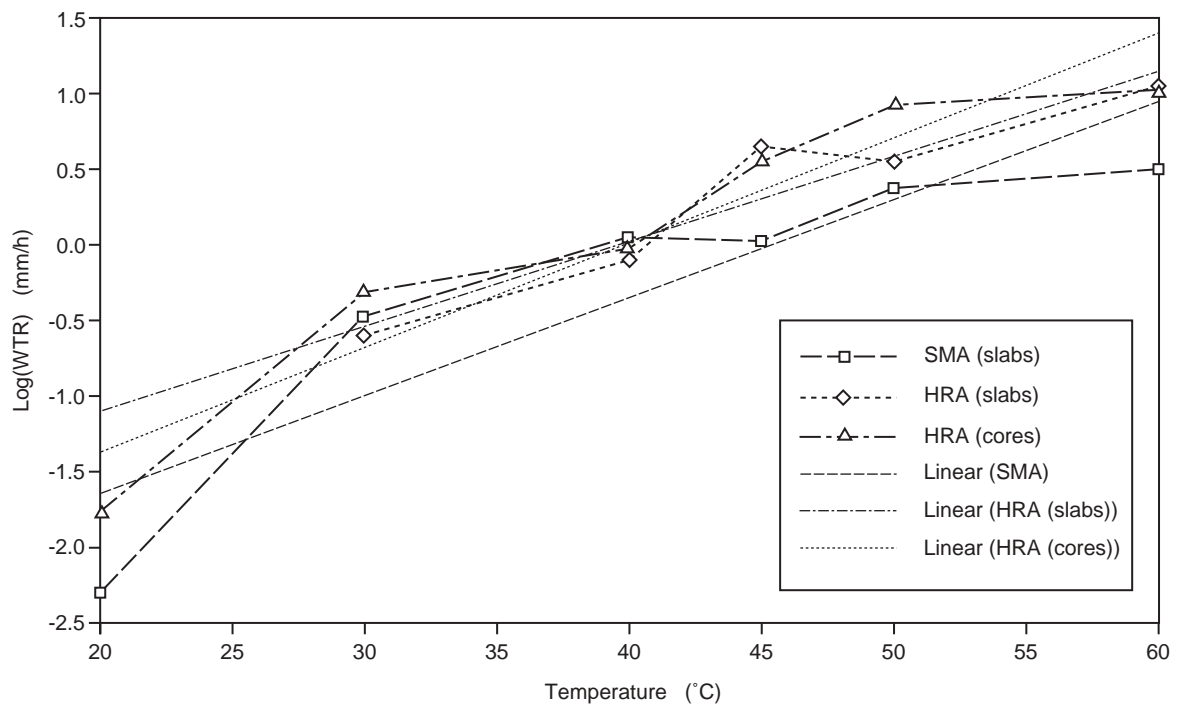


Figure 3 Change in log (wheel-tracking rate) with temperature

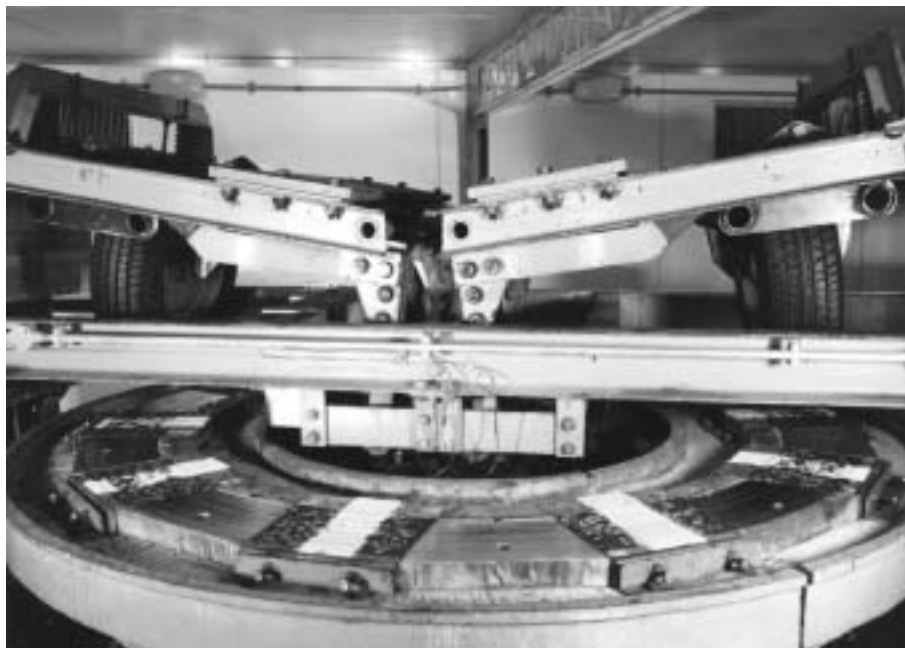


Figure 4 Road Machine No. 1

mixture composition of the slabs is given in Table 5. When the temperature of the sample had reached 45°C, a datum set of dial gauge readings were recorded using the set up shown in Figure 5.

The road machine was switched on and the rotational speed was then set to between 6 and 7 rev/min. The machine was then halted periodically to make repeat dial gauge measurements to assess the amount of rutting on each slab. The deformation, of up to 5mm, after 2,000 revolutions at this speed was thought to be significant, so

the test was halted at this point.

These samples were then removed from the machine and three further samples of each material placed onto the road machine and the experiment repeated at nominally twice the rotational speed for twice the number of revolutions. Effectively, this equates to the same contact time between tyre and sample for each of the tests.

A further experiment, using one sample of each material, was undertaken to establish the deformation caused by the static wheel loading from the road machine.

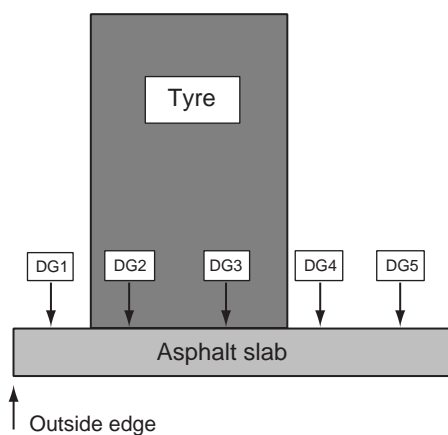


Figure 5 Schematic of dial gauge locations relative to slabs and tyres

3.2.2 Results

The results for dial gauges 2 and 3 (DG2 and DG3) are given in Table 7 and shown graphically for the development of rut-depth at 6.4rev/min and 12.9rev/min in Figures 6 and 7, respectively. The results for the other dial gauges (DG1, DG4 and DG5) were negligible because no trafficking took place at these locations.

Table 7 Mean deformation when trafficked at different speeds

Test speed (rev/min)	Number of revolutions	Deformation (mm)					
		Stone Mastic Asphalt			Hot Rolled Asphalt		
		DG2	DG3	Mean	DG2	DG3	Mean
6.4	0	0.0	0.0	0.0	0.0	0.0	0.0
	392	-1.4	-1.9	-1.6	-0.4	-2.1	-1.2
	999	-2.6	-2.5	-2.5	-1.3	-2.7	-2.0
	1461	-3.8	-4.6	-4.2	-1.7	-2.8	-2.2
	2000	-4.7	-4.8	-4.7	-2.2	-3.5	-2.8
12.9	0	0.0	0.0	0.0	0.0	0.0	0.0
	740	-1.3	-0.8	-2.2	-1.2	-1.5	-1.4
	1453	-4.4	-1.3	-2.9	-1.1	-1.5	-1.3
	2482	-7.6	-2.2	-4.9	-2.7	-1.8	-2.4
	4000	-9.4	-3.8	-6.7	-2.8	-2.1	-2.4
0	0	0.0	0.0	0.0	0.0	0.0	0.0
	Three days	-1.1	-1.2	-1.2	-1.2	-1.6	-1.4

3.2.3 Analysis

The initial rate of deformation for stone mastic asphalt was slightly greater than that for hot rolled asphalt. This is surprising because stone mastic asphalt is normally regarded as more deformation-resistant than hot rolled asphalt and, more specifically, the reverse ranking occurred in the wheel-tracking test at this temperature (Section 3.1.2).

Fretting occurred in the stone mastic asphalt samples during the trial, in particular on the side at the outside of the turntable (DG2 rather than DG3) at the higher speed. This led to higher rut depths being measured on these samples. As such, the rotational nature of the trafficking generated by the road machine was considered to have had a significant effect upon the measured deformation

characteristics and could raise doubts about the use of stone mastic asphalt, or this mixture in particular, on tight roundabouts. Nevertheless, the test replicates continual very tight turns and could be said not to be representative of field experience, particularly as problems have not arisen from the increasing use of stone mastic asphalt in such situations.

Ignoring the results from DG2 for the stone mastic asphalt at 12.9rev/min because of the fretting, the deformation at the higher speed was marginally less (about 20%) than at the lower speed. Therefore, if this difference occurs on site, slowing the traffic will increase the resulting permanent deformation by more than the increasing time spent on the road.

In the static test, the mean measured deformation after 3 days was 1.4mm on the hot rolled asphalt and 1.2mm on the stone mastic asphalt. The results from the dynamic tests are adjusted in Table 8 to allow direct comparison with those from the dynamic tests.

Table 8 Comparison of static and dynamic loading

Speed	Load	Deformation
HRA trial		
12.9rev/min = 2.7miles/h	8,000 wheel passes	2.8mm
2.7miles/h	4,000 wheel passes	1.4mm
30miles/h	45,000 wheel passes	1.4mm
HRA static trial		
–	3 days	1.4mm
SMA trial		
12.9rev/min = 2.7miles/h	8,000 wheel passes	3.8mm *
2.7miles/h	2,500 wheel passes	1.2mm
30miles/h	28,000 wheel passes	1.2mm
SMA static trial		
–	3 days	1.2mm

* Using DG3 readings only

From this comparison, on average 3 days static loading is equivalent to about 36,000 wheel passes at 30miles/h or one wheel pass at that speed is equivalent to a static load for 7s. This period is considerably greater than the time the load will be applied by a wheel passing at 30miles/h. This finding implies that there is a very complex and non-linear relationship between vehicle speed and the rate of rutting, especially at low speeds.

4 Mathematical and computer models

4.1 Estimation of deformation

4.1.1 Existing model

The currently used method of estimating the permanent deformation of rolled asphalt is the simple relationship developed for the maximum wheel-tracking rate that is required to limit the deformation to 10mm over 20 years (Szatkowski and Jacobs, 1977). This relationship is given in Equation (1).

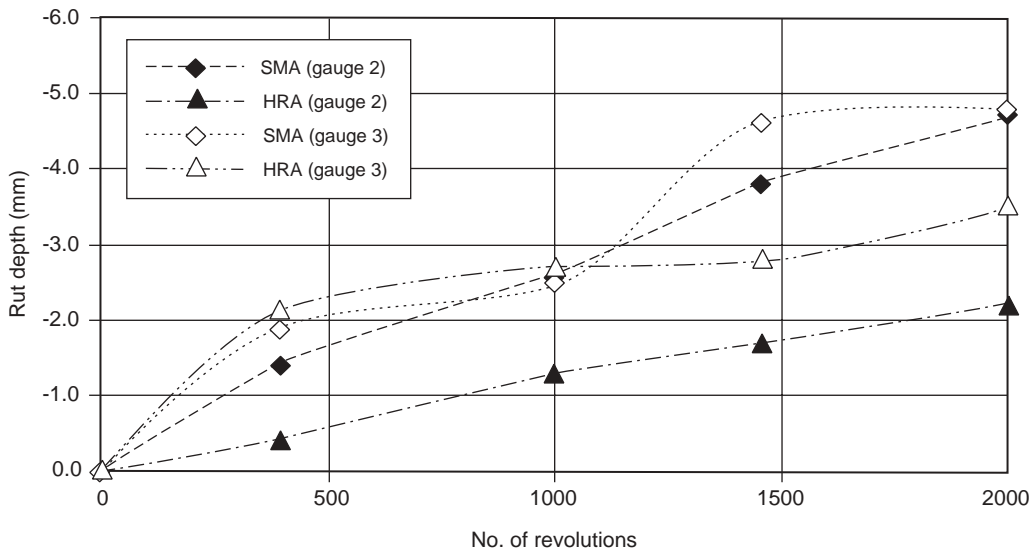


Figure 6 Development of rut-depth at 6.4 rev/min

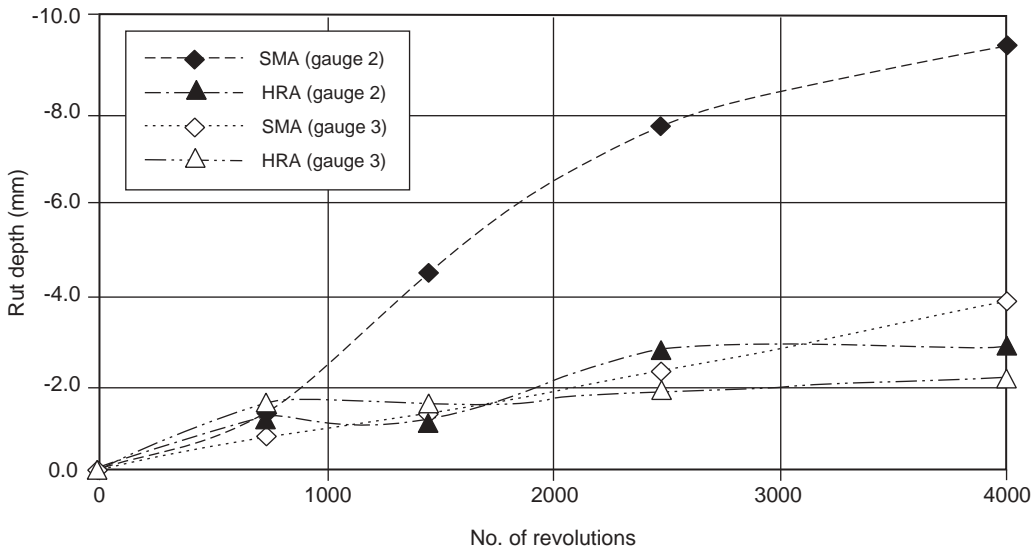


Figure 7 Development of rut-depth at 12.9 rev/min

$$wtr = \frac{14,000}{cvd + 100} \quad (1)$$

where wtr = the wheel-tracking rate at 45°C; and
 cvd = the flow of commercial vehicles per lane per day (cv/l/d).

Since 1977, the traffic intensity, in terms of numbers, axle weights and speed, has increased considerably and the requirements for wearing course mixtures have consequentially changed. As such, the extrapolation of the relationship to the current road conditions may not be valid. The equation has been reviewed (Daines, 1992; Nicholls, 1998b), but the relationships derived do not have the simplicity and universal applicability to gain general acceptance.

4.1.2 Available data

The records of several TRL trials were examined to see if they included wheel-tracking rates (measured or estimated) of the material(s) and measurements of the permanent deformation. The sites with suitable data are listed in Table 9.

4.1.3 Analysis for revised model

The sites all have information on four parameters that would be expected to influence the permanent deformation of a surfacing together with measurements of the observed deformation. Other factors, such as the gradient, also affect the permanent deformation but the values are not readily available from all the sites, and so were ignored for this analysis. The four independent parameters were:

- the load applied (as measured by the number of commercial vehicles per lane per day);

Table 9 Sites with wheel-tracking rate and permanent deformation data

Site	Number of materials/ sections	Number of lanes per section	Number of times deformation measured	Maximum age when deformation measured
A38 Burton	10	2	9	8 years
A1 Buckden	1	1	8	5.3 years
A73, A74, A77 & A80 Glasgow	6	2	2	4.2 years
A303 Mere	12	2	3	7.5 years
M4 Almondsbury	13	1	2	4 years
A30 Staines	24	1	3	6 years
M4 Acton Turville	7	2	2	5 years
M1 Wakefield	1	2	5	4 years
A33 Winchester	33	1	2	7 years

- the resistance to deformation of the surfacing material (as measured by the wheel-tracking rate at 45°C or, for the data from the A30 at Staines and the M4 at Acton Turville, an estimate of that from the Marshall Stability);
- the time that the loading has been applied; and
- the typical maximum temperature, at which most of the deformation will occur.

The maximum temperature is either taken as the typical July temperature (from The Ordinance Survey Atlas of Great Britain) or as a function of the longitude, as measured by the National Grid northerly co-ordinate of the location. The typical July temperatures were extracted to the nearest 0.5°C, but the complete range covered only 2.5°C.

Whenever there were measurements of deformation very early in the life of the pavement, the deformation is the difference between the rut at that time minus the apparent rut built into the pavement prior to trafficking. Because of the potential errors with each of the measurements, the values of permanent deformations calculated from the difference between two similar measurements (that is, when the actual deformations are small) will include some negative values. Any equation should be encouraged not to predict such negative deformations. Therefore, the data was also analysed with these negative values reset to zero.

A series of multiple linear and non-linear regression analyses (Benjamin and Cornell, 1970) were carried out on the data using the Statsgraphics computer package. From the results of these analyses, the 'best' fit was found to be an apparently realistic relationship, Equation (2), that predicts the development of permanent deformation in an asphalt surfacing with a correlation against site data of only $R^2_{adj} = 0.46$.

$$rut = 0.8 + 0.00019 \times (cvd + 900) \times \log(age + 1)^{1.91} \times wtr \quad (2)$$

where *rut* = the estimated permanent deformation (mm);

age = the time in service (years);

wtr = the wheel-tracking rate at 45°C; and

cvd = the flow of commercial vehicles per lane per day (cv/l/d).

The relationship would imply that the permanent deformation is proportional to the traffic flow, the wheel-tracking rate at 45°C and the logarithm of the age plus one.

The relationship developed is not as demanding as the relationship developed by Szatkowski and Jacobs in terms of the wheel-tracking rate necessary to prevent more than 10mm of deformation after 20 years. However, Equation (2) extrapolates from the available data of less than ten-year lives to the 20-year design life using a logarithmic relationship and is a best fit relationship whereas Szatkowski and Jacobs interpolated linearly and included a safety factor. Nevertheless, the proposed relationship has been developed from more data than the one currently used and, with an appropriate safety factor, should provide more appropriate predictions.

Other relationships were developed with higher correlations against existing data, but there were inconsistencies when the data was extrapolated to other potential situations. In particular, a parameter to model the site temperature gave unrealistic predictions, although it improved the correlation. Additional data would have allowed the relationship to be further developed with greater confidence in the results obtained, but it would involve long-term systematic monitoring of sites.

4.2 Computer cooling model

4.2.1 Basic approach

Computer programs to model the cooling of asphalt layers have been available for some time. The programs were written primarily to consider adverse cold weather conditions, but could equally well be used for adverse hot weather conditions. The program developed by TRL was written in the Fortran IV language and is reported in LR 729 (Jordan and Thomas, 1976).

The program uses a simplified model of the heat energy flows associated with the cooling of a hot-mix layer of a typical road pavement. In the model, heat energy is lost from the material surface by radiation and convection to the atmosphere and through the bottom by conduction to the supporting layers. The only heat energy gain is by absorption of solar radiation, which depends on the ambient conditions at the time. Heat losses from the sides and ends are assumed to be negligible, so that the heat energy is transferred in a single direction, perpendicular to the surface of the layer. It is assumed that good thermal contact exists between the layers in a pavement and that the thermal parameters are constant throughout each layer. Finally, although the cooling effect of continuous rain on the completed mat can be significant, it has not been incorporated into the model. However, asphalt should not be laid on surfaces covered by standing water and transient light rain showers are considered to have relatively little influence on the rate of cooling.

The equations developed by Jordan and Thomas were reviewed and reprogrammed in FORTRAN 77 to run on a modern PC. However, because it is anticipated that predictions will not be required on a routine basis, the program was not developed specifically to have a user-friendly interface. In particular, all input data has to be

listed in files, one for the environmental data and one for the material properties and user-defined program parameters, and the output is not presented in graphical form.

4.2.2 Input

The input data that are needed for the environmental file are:

- The interval of time during which each set of data applies;
- Mean ambient temperature for each interval;
- Mean wind speed for each interval; and
- Mean incident solar radiation for each interval.

There is a maximum of 48 intervals that can be input, after which the last set of data is reused.

The input data that are needed for the material properties and program parameters file are:

- The number of and distance between nodes (maximum of 1,000 nodes);
- The number and size of time increments to be used;
- The number of different asphalt and supporting layers (which must not be less than 2);
- The number of nodes in each layer;
- The density of the material in each pavement layer;
- The thermal conductivity of the material in each layer;
- The specific heat of the material in each layer; and
- The initial temperature of each layer.

The convection coefficient, which is also required, is derived from the wind speed whilst the coefficients of emission and absorption of solar radiation for the pavement surface are assumed to be 0.90. Also, the density, thermal conductivity and specific heat of a material can be derived from the properties of the component materials and their proportions in the mixture, although that is not within this program.

4.2.3 Output

The output is a data file of the temperature at selected nodes, updated after a fixed number of time intervals. The output can include every node at every time interval, but that tends to generate an excessive amount of data. This data can then be imported into a spreadsheet or other software package to allow manipulation of the information into the required format.

4.2.4 Validation

The original program was validated against temperature histories measured at four pavement construction sites together with a pavement experimental site situated within the Laboratory. A comparison between the predicted and measured temperatures showed that there was no significant difference at the 5% confidence level with a correlation coefficient of 0.95.

The new program was checked against the original program using the examples in LR 729. The correlation was reasonable, although some differences were found. The differences are believed to be due to:

- doubts about the accuracy of the results in LR 729 (for example, the initial rapid loss of temperature at one site is unexpected);
- uncertainties about how certain physical features were implemented (for example, whether the heat loss is restricted to the hot asphalt layer); and
- LR 729 does not give the precise position of the nodal points and the time increments used for the original predictions.

4.3 Risk assessment model

4.3.1 Requirement

The model was developed to help assess the risk of unacceptable deformation occurring when asphalt is laid in hot weather conditions.

4.3.2 Factors

The risk of a road surface deforming (and losing texture depth) is related to several parameters, of which the primary ones are:

- the temperature throughout the depth of the pavement;
- deformation resistance of the asphalt layers at those temperatures;
- the loading on the pavement from the traffic flowing over it;
- the speed of the traffic; and
- the length of time that the conditions persist.

To develop a risk assessment model, these parameters are rationalised into the following factors:

- Material & Temperature Factor:
the wheel-tracking rate at the maximum surface temperature, in mm/h;
- Traffic Load Factor:
the design commercial traffic flow, in cv/l/d;
- Traffic Speed Factor:
the time that wheels load the pavement, in s;
- Optional Action Factor:
an allowance for specific measures, in particular using light-coloured pre-coated chippings and/or cooling the surface; and
- Time Period Factor:
the period for which the other factors remain reasonably constant, in days.

The wheel-tracking rate of the top layer of the road pavement at the maximum surface temperature, in mm/h, is taken to reflect the material and temperature parameters. This will be conservative in that there is likely to be a temperature gradient through the depth with the material being cooler further down but optimistic because deformation in lower layers will not be considered. In the event of no better information for the particular circumstances, the maximum road surface temperature is assumed to depend on the latitude and the month of construction. Other factors that can affect it are the road direction, slope and extent of shading, both from sunlight and from winds that can cool the surface.

The applied load and loading time will influence the deformation. For asphalt binders showing Newtonian behaviour, the deformation will be proportional to the load and to the loading time. Bitumen binders, and more particularly modified binders, exhibit some non-Newtonian behaviour because the binder viscosity is reduced by increased shearing rate. Nevertheless, for the purposes of this risk assessment method, the risk of deformation due to traffic load is taken to be proportional to the duration of vehicle loading, estimated in terms of commercial vehicles per lane per day.

Loading time is also inversely related to the traffic speed. Deformation increases with loading time, particularly for long loading times when the visco-elastic properties of the binder are less applicable and the binder tends to behave as a Newtonian fluid. For the purposes of this method, deformation is taken to be inversely proportional to vehicle speed.

However, calculating the equivalent loading for stationary vehicle is more complicated. For the stationary phase, the loading and speed factors need to be combined into a single factor that can be regarded as the proportion of the time when a commercial vehicle is loading the area, in s per day. 7s of stationary loading is equivalent to 1 wheel-pass at 30 miles/h (Section 3.2.3) and that a commercial vehicle travelling at that speed has a Speed Factor of 0.08 s (Table A.5). Therefore, the combined factor for 3-axled commercial vehicles when permanently stationary is 3,000s/day. However, this factor must be reduced by the proportion of commercial vehicles in the traffic and by the proportion of the time when the traffic is stationary.

During the flowing phase, the total traffic loading must also be applied because each vehicle has to pass across each location, even if at a closer spacing due to the stationary phase. Therefore, the deformation due to any stationary phase is additional to the normal deformation, and does not replace part of it.

Clearly, deformation will increase with the length of time the other factors are extant. For the purposes of the risk assessment method, the time period is measured in days. The risk for the first day after opening to traffic can be assessed as well as the risk for an extended speed restricted period in, for example, a contra flow situation. For assessing the risk over an extended period some of the risk parameters may take different values.

4.3.3 Calculation procedure

An overall indication of asphalt deformation, summed over each period when the risk factors remain constant, may be estimated from the product of the individual factors in Equation (3).

$$\text{Expected deformation} = k \times \Sigma(R_T \times T_1 \times T_s \times P_d) \quad (3)$$

where k = the calibration coefficient;

R_T = Material & Temperature Factor (the wheel-tracking rate at the maximum surface temperature, in mm/h);

T_r = Traffic Load & Speed Factor (the commercial traffic flow, in cv/l/d, times the time that a wheel will load the pavement, in s); and

P_d = Time Period Factor (the period for which the other factors remain nearly constant, in days).

The definitions of these factors are given in Appendix A with a full explanation of the method; a worked example of its use is given in Appendix B..

4.3.4 Calibration of relative risk factor

A wheel-tracking rate at 45°C of 2mm/h is required to achieve a deformation rate of 0.5mm per year for a traffic flow of 6000cv/l/d (Daines, 1992). In a typical year, about 90 per cent of the deformation occurs during about 15 hot summer days when the road surface temperature attains about 45°C. A typical speed for a commercial vehicle is about 60miles/h. Therefore, for the conditions in this example:

$$\begin{aligned} \text{Estimated deformation} \\ = k \times 2 \times 6000 \times 0.04 \times 15 = 7200k = 0.9 \times 0.5 \quad (4) \end{aligned}$$

Therefore, the calibration coefficient, k , equals 6.2×10^{-5} .

5 Discussion

5.1 Laboratory trials

The laboratory trials investigating the change in the rate of deformation with both temperature and speed provided general confirmation of the expected relationships whilst indicating that they are not strictly accurate. The findings are equally applicable to both 'traditional' hot rolled asphalt and the newer surfacing materials such as stone mastic asphalt.

With regard to temperature, the easiest way of modelling the relationship is to take the logarithm of the wheel-tracking rate to be proportional to the temperature. However, this is not completely accurate, with the relationship flattening off to reach a plateau at higher temperatures.

The tests showed that relatively little deformation resulted from a stationary wheel load compared to a moving wheel load. However, experience shows that more rutting develops when traffic speeds are reduced. This dichotomy suggests that loading time is important but, at the same time, a dynamic component is essential for the formation of ruts.

5.2 Mathematical models

There is no single solution to the problems of trafficking newly laid asphalt during hot weather. Nevertheless, there are ways of reducing the risks to manageable levels by use of a procedure such as the proposed risk assessment model. By minimising the risks at all stages of the work, from mixture production to traffic control, the amount of damage induced should be within acceptable limits. Not

all the measures are necessarily applicable to all schemes and, therefore, the optional measures that are most appropriate and that provide the greatest cost benefit both to the Contractor and the road user should be selected.

However, in general the conditions are unlikely to justify the use of the risk assessment model. The position should be to have conservative requirements that are simple to understand and operate with the use of the risk assessment model retained for those limited cases when its use can be justified.

On the more specific aspect of limiting the permanent deformation of asphalt, the currently used model was developed by Szatkowski and Jacobs in 1977 for hot rolled asphalt by specifying a maximum wheel-tracking rate sufficient to limit the deformation to 10mm over 20 years. However, the traffic conditions in the United Kingdom have changed since 1977 and more data are available for analysis. A review of the records of various road trials of rolled asphalt were used to develop an equation to predict the development of permanent deformation in an asphalt surfacing that correlates with site data with an R^2_{adj} value of 0.46. The relationship implies that the permanent deformation is proportional to the traffic flow, the wheel-tracking rate at 45 °C and the logarithm of the age plus one. The correlation is not very good, and other relationships were developed that had higher correlations with existing data, up to an R^2_{adj} value of 0.72. However, there were inconsistencies when the data was extrapolated to other potential situations. In particular, the site temperature was not satisfactorily incorporated.

The use of the proposed relationship should allow better estimates to be made of the extent and development of permanent deformation under typical conditions; it cannot assist in forecasting under exceptionally hot weather conditions. New data would allow the equation to be further developed with greater confidence in the results obtained, but to obtain such data would involve long-term systematic work, ideally over a twenty year period to obtain the full life history of successful surfacings.

5.3 Actions to minimise the potential problems

Within the research that has been undertaken, certain actions have been identified that are believed will help to minimise potential problems that can arise when laying hot asphalt material in adverse hot weather conditions. These actions are described below.

5.3.1 Mixture selection

The selection of deformation-resistant mixtures can mitigate, to a limited extent, the effect of premature deformation in adverse hot weather conditions, although lower stability materials are more likely to remain workable for longer periods. Rutting is often attributed just to surface courses but road bases, and particularly binder courses, can also deform significantly. The requirements of the wheel-tracking test for hot rolled asphalt binder course should be similar to those for surface course because, although the binder course will not attain temperatures as high as the surface course during service, it is expected to have double the life. The counter is that, when the surface course is

replaced, any permanent deformation in the lower layers will be taken out. Nevertheless, the use of more deformation resistant materials, such as macadam and, in particular, heavy duty macadam or high modulus base rather than rolled asphalt, is advisable.

5.3.2 Delivery temperature

Asphalt mixtures delivered to site at temperatures higher than necessary not only increase the time available for compaction but can also render the asphalt too workable to lay; it also wastes energy and promotes binder hardening. The delivery temperatures during hot weather should only be high enough to achieve the required workability. Reducing the delivery temperature for hot rolled asphalt from 160°C to 140°C reduces the time available for compaction by about 30%.

5.3.3 Layer thickness

The laid thickness markedly effects the time available for compaction, although contract specifications will normally have stipulated thicknesses for each asphalt layer. More flexible contract specifications would allow thinner layers to be used in hot weather conditions and thicker layers in cold weather conditions. A 150mm thickness of 40mm dense bitumen macadam (DBM) roadbase could be replaced by two 28mm DBM roadbase layers, each 75mm thick. The time for cooling of each 75mm thick layer will be about 30% of that for the thicker layer.

5.3.4 Rollers

The use of a relatively light roller for initial compaction could be considered during hot weather conditions, particularly when rolling hot rolled asphalt with pre-coated chippings. A reduction in roller mass would diminish the risk of non-compliance with texture depth requirements due to excessive embedment of the chippings.

5.3.5 Time of day

Laying during the evening and night has additional advantages during hot weather. The lower air temperatures, and a reduced level or absence of solar radiation, will enable the substrate to cool more rapidly. The cooling time of a subsequent hot overlay is then considerably reduced. Road closures at this time will reduce any traffic delays and deformation.

If the weather and traffic conditions are such that the risk of premature damage to a newly opened surface is unacceptable in, for example, a speed-restricted contraflow system, a cessation of laying should be considered. Cessation of laying during the hottest part of the day, say when the road surface temperature exceeds 45°C, will not only help the Contractor to minimise problems of achieving asphalt compliance in terms of profile and texture depth, but will also enable the surface to cool more rapidly in the evening when laying can be resumed. Laying can then be resumed when the surface temperature has fallen to 30°C, usually at about 20:00, when the temperature at a depth of 100mm is also likely to be less than 30°C. Laying earlier at higher surface temperatures increases the overall cooling time of the pavement and, therefore, it is not advisable.

5.3.6 Chipping colour with hot rolled asphalt

Pre-coated chippings cover about 70% of the surfacing with hot rolled asphalt. Therefore, the use of chippings coated with a clear or light-coloured binder will reduce the albedo of the surfacing and result in a lower surface temperature under prolonged solar radiation. Research has shown a reduction of as much as 8°C (Pholmann, 1996) but a more conservative estimate of 3°C would achieve a 35% reduction in the rate of deformation.

5.3.7 Parking restrictions

After completion of laying and prior to opening to traffic, construction traffic should not be allowed on the newly laid asphalt. The parking of construction traffic on asphalt during hot weather may cause unacceptable, saucer-shaped, depressions under the wheels (Haydon, 1994).

6 Conclusions

The main conclusions of this study, which are applicable to both 'traditional' hot rolled asphalt and the newer surfacing materials such as stone mastic asphalt, are:

- 1 Below about 50°C, the logarithm of the wheel-tracking rate is approximately proportional to the temperature. Above this temperature, the wheel-tracking rate flattens off.
- 2 The loading time, and not the speed, influences the resultant deformation. However, the low deformations due to static load shows that dynamic effects are important.
- 3 A risk model can be used to assess the probability of unacceptable deformation. However, economic considerations are unlikely to justify the effort required to make use of the risk assessment model in most cases.
- 4 The best relationship found to model deformation implies that the permanent deformation is proportional to the traffic flow, the wheel-tracking rate at 45°C and the logarithm of the age plus one. However, the value of the square of the correlation coefficient (after adjustment for the degrees of freedom) is a modest 0.46.
- 5 There are various physical actions that can be taken when laying hot asphalt in adverse hot weather conditions to minimise the potential problems.

Specification clauses and advice have been prepared on the basis of these findings.

In addition, it was found in a simulative laboratory test that (at least) some stone mastic asphalt mixtures may not be suitable for use on tight roundabouts without adequate edge restraint. However, the test conditions very probably do not accurately represent conditions found on site.

7 Acknowledgements

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Appendix A: Method for risk of damage assessment

A.1 Purpose

The method can be used at the planning stage to provide estimates of the risk of deformation in an asphalt surfacing after opening to traffic under conditions of high surface temperatures and restricted traffic speeds during contracts. The estimates of deformation can be judged against a criterion for maximum allowable deformation. Alternatively, the method can be used to investigate the effect of alternative options with a view to minimising the risk of deformation or may be used as the works proceed to predict the effects of changing conditions.

A.2 Risk factors

The following risk factors are used in the assessment:

- a Material & Temperature Factor, R_T
- b Traffic Load & Speed Factor, T_r
- d Optional Action Factor, O_p
- e Time Period Factor, P_d

The risk factors represent their relative effects on the expected deformation of a hot rolled asphalt surfacing. The expected deformation, in millimetres, is calculated as the product of the individual risk factors together with a calibration factor.

A.3 Maximum road surface temperatures

For the purposes of this method, and in the absence of more specific records, the standardised road surface temperatures in Table A.1 should be used for the relevant time of year and the latitude categories in Figure A.1. The road surface temperatures in Table A.1 represent the typical maximum road surface temperatures that can be attained during the hottest part of an exceptionally hot and sunny day from about 12:00 to 18:00, when most deformation is likely to occur.

Table A.1 Standardised maximum road surface temperatures

Latitude category	North	Central	South
Month	Temperature (°C)		
May	40	40	45
June/July	45	45	50
August	40	45	45
September	40	40	45

During hot weather, higher maximum road surface temperatures are attained on the first day after laying hot asphalt and, to a lesser extent, on the second day because of the residual heat. Therefore, there is an increased risk of deformation if the road is opened to traffic within 2 days of laying. In hot weather conditions, the road surface temperature is likely to fall during the evening and night to a minimum of about 15°C before sunrise.



Figure A.1 Latitude categories in the British Isles

Therefore, if the road is opened to traffic at a road surface temperature not exceeding 25°C, on the day of laying, or during the morning after laying, then:

- The standardised maximum road surface temperature for the corresponding day should be the value in Table A.1 increased by 10°C for that day.
- The standardised maximum road surface temperature should be the value from Table A.1 increased by 5°C for the next day.

Similarly, if the road is opened to traffic at a road surface temperature not exceeding 20°C, during the day or morning following laying, then the standardised maximum road surface temperature for the corresponding day should be the value from Table A.1 increased by 5°C for that day.

If opening to traffic is delayed for more than one day for the 20 °C option, and for more than two days for the 25 °C option, then no addition is necessary to the standardised road surface temperatures in Table A.1.

Although most deformation occurs during the daytime, some will occur during the evening and night, particularly if stationary traffic is permitted, or the normal trafficking at night is exceptionally high. An estimate of deformation that might occur during the evening and night can be made by using the appropriate maximum road surface temperature for that period.

A.4 Material & Temperature Factor

The Material & Temperature Factor, R_T , is the wheel-tracking rate of the top layer of asphalt (which may not necessarily be the surface course) measured in accordance to BS 598: Part 110: 1996 at the standardised maximum road surface temperature on cores taken from trial areas or previous sites laid within 18 months using identical material. The wheel-tracking rates at all possible temperatures are unlikely to be known for most mixtures, but the value for at least one of the standard test temperatures of 45°C and 60°C should be available from which the Material & Temperature Factor can be estimated.

If the wheel-tracking rate of the top asphalt layer is available at two or more temperatures of which one temperature is not less than 45°C, the Material & Temperature Factor can be estimated on the basis that there is a linear relationship between the test temperature and the logarithm of the wheel-tracking rate. The Material & Temperature Factor, R_T , for a maximum road surface temperature of T °C derived from wheel-tracking rates, wtr_1 and wtr_2 , at test temperatures t_1 °C and t_2 °C, respectively, is given by Equation (A.1).

$$\log(R_T) = \frac{\log(wtr_1) \times [T - t_2] - \log(wtr_2) \times [T - t_1]}{t_1 - t_2} \quad (\text{A.1})$$

If the wheel-tracking rate of the top asphalt layer is available at only one temperature and that temperature is not less than 45°C, the Material & Temperature Factor, R_T , can be determined from Equation (A.2).

$$R_T = \frac{F_T}{F_t} \times wtr \quad (\text{A.2})$$

where wtr is that wheel-tracking rate and T and F_t are the factors in Table A.2 for temperatures, T , equal to the standardised maximum road surface temperature and the temperature, t , at which the wheel-tracking rate was measured, respectively.

Table A.2 Influence of temperature on the rate of wheel-tracking

Temperature, T (°C)		30	35	40	45	50	55	60		
Factor, F_t		0.031	0.062	0.125	0.25	0.5	1	2	4	8

The default values in Table A.2 are likely to be more representative for unmodified asphalts.

If the wheel-tracking rate is less than about 1 mm/h, the accuracy of the result may be poor and the wheel-tracking rates at higher temperatures should be used to provide a better estimate of the rate at the relevant temperature.

A.5 Traffic Load and Speed Factor

The Traffic Load Factor, T_L , is the design traffic flow of commercial vehicles, in cv/l/d. Where traffic control is such

that traffic flow is diverted from its normal pattern, the Traffic Load Factor should be the traffic flow, in cv/l/d, using the relevant lanes during each traffic control period.

For flowing traffic, the Traffic Speed Factor, T_s , in seconds, should be determined from Table A.3 according to the mean speed of the traffic. The speeds in Table A.3 should refer to those operative during the traffic control period.

Table A.3 Traffic speed factors, T_s

Vehicle speed							
(km/h)	16	32	48	64	80	97	113
(miles/h)	10	20	30	40	50	60	70
Speed factor							
(s)	0.24	0.12	0.08	0.06	0.05	0.04	0.035

For flowing traffic, the Traffic Load & Speed Factor, T_r , is the product of the Traffic Load Factor, T_L , and the Traffic Speed Factor, T_s .

Where traffic lights are installed or where there is stationary traffic during part of the time, the Traffic Load & Speed Factor, T_r , should be the sum of:

- the Traffic Load & Speed Factor as indicated above for the time whilst the traffic is moving; and
- 3000 s/day multiplied by the proportion of the time that the traffic is stationary during the period under consideration and by the proportion of the traffic in that lane is commercial.

Moving cars and light vans having a nominal mass of 1 tonne will not normally contribute more than 0.1 mm/day of deformation, under a 'worst-case' scenario. However, under stationary conditions on a hot surfacing, significant deformation could occur. An estimate of the deformation in these circumstances can be made by increasing the value for the Traffic Load Factor by the daily total number of cars per lane divided by 40.

The Traffic Speed Factor is the approximate time that the wheels on a vehicle will load a particular point on the wheel-path. In calculating the Traffic Speed Factor for traffic which is stationary, the average factor over a minute is calculated in which the stationary phase is assumed to be 6 s rather than 60 s because, generally, the wheels will not always stop at the same location on the road surface. Locally, this may not always be the case and, when the wheels always reside at the same location (such as just before the actual stop line for fixed traffic lights), a value nearer 60 s may be more appropriate.

A.6 Optional Action Factor

Generally, the value of O_p should be taken as 1.0. However, when light coloured chippings are used or when water spraying is applied, the value of the Optional Action Factor, O_p , should be 0.7. When both light coloured chippings are used and water spraying is applied, the value of the Optional Action Factor, O_p , should be 0.5 for each day that water is applied.

A.7 Time Period Factor

The Time Period Factor, P_d , should be the number of days during which the other risk factors can be regarded as being effectively constant. When the risk is being assessed for an extended period of time, covering changes in maximum road surface temperatures, or when speed limits or other factors which have a substantial influence on the traffic speed are changed, the total time should be divided into separate time periods during each of which the other risk factors can be regarded as constant. Part days when the remainder of the day is not covered by a separate time period, such as opening to traffic on the same day, should be counted as 1 day.

The value of each risk factor should be determined for each time period.

A.8 Expected deformation

The expected deformation should be calculated to the nearest 0.1 mm in accordance with Equation A.3 for which the summation is over the individual time periods that make up the total time for which the risk is being assessed.

$$\text{Expected deformation} = 6.2 \times 10^{-5} \times \Sigma(R_T \times T_r \times O_p \times P_d) \quad (\text{A.3})$$

where R_T = material & Temperature Factor, the wheel-tracking rate at the maximum surface temperature, in mm/h;

T_r = Traffic Load & Speed Factor, the time that wheels load the pavement, in s.cvd/l/d;

O_p = Optional Action Factor; and

P_d = Time Period Factor, the period for which the other factors remain nearly constant, in days.

Appendix B: Worked example of assessment for risk of damage

B.1 Scope

The following example illustrates the use of the method for risk of damage assessment to evaluate various laying options. The intention is to demonstrate the principles of the method rather than to investigate a large contract involving complex traffic control measures. Because the exercise is intended to show the process of selecting the best option, the calculated estimated deformations will be the maximum deformation that would be expected if the weather was hotter than normal, but not to an exceptional extent.

B.2 Preconditions

A 3 km length of a 2-lane single carriageway of total width 7.4 m in the south of England is to be strengthened with a 50 mm overlay of hot rolled asphalt. The speed limit is 60 miles/h and the traffic flow is 3000 commercial vehicles per day in each direction, representing 20% of the total traffic. The work is expected to be carried out during July/August, and to take 10 working days. A 30miles/h speed limit will be imposed during traffic control periods, and because it is the holiday period, no works or closures will be permitted at weekends.

B.3 General considerations

According to Clause 943 of the *Specification for Highway Works*, this site requires a hot rolled asphalt having a wheel-tracking rate not exceeding 2.0mm/h at 45°C. An unmodified asphalt, having a wheel-tracking rate of 1.9mm/h at 45°C, is selected.

The intention is to lay 600 lane-metres per day (about 250 tonnes per day), for which the estimate is that laying and compaction will take about 6 hours. Three options are considered with deformation limits set as in Table B.1.

Table B.1 Deformation limits*

Period of traffic control	Deformation (mm) not exceeding
1 day	1.0
2 days	1.5
Up to 1 week	2.0
Up to 1 month	3.0
More than 1 month	4.0

* These deformation limits have been set arbitrarily for this example, but are considered to be of the appropriate order.

B.4 Option 1

Lay asphalt morning and afternoon. The usual method is that 300m of asphalt would be laid on one lane during the morning and 300m of asphalt laid adjacent to it, on the other lane, during the afternoon. This option involves a lane closure of 300m with all traffic using the adjacent lane at a speed limit of 30miles/h, and traffic lights allowing 2min in each direction with a 30s delay between lights changing. Traffic will pass over newly laid asphalt in the afternoon, and on the second and following days,

traffic will queue on new asphalt as the works proceed along the carriageway.

Separate time periods need to be assessed for moving traffic in the 300m length and for traffic queuing at the traffic lights.

(a) First 300m length:

The maximum road surface temperature = 50°C

Table A.1, south in July) + 10°C = 60°C

$$R_T = 1.9 \times 8/1 = 15.2\text{mm/h}$$

$$T_l = 6000\text{cv/l/d} \quad (\text{Sum of traffic for both directions})$$

$$T_s = 0.08\text{s} \quad (\text{Table A.3, 30miles/h})$$

$$O_p = 1.0$$

$$P_d = 1 \text{ day} \quad (1^{\text{st}} \text{ day only})$$

(b) First day of queuing traffic:

The maximum road surface temperature = 50 °C (Table A.1, south in July) + 10°C (assuming road surface temperature was about 25°C the following morning) = 60°C

$$R_T = 1.9 \times 8/1 = 15.2\text{mm/h}$$

$$T_l = 3000\text{cv/l/d}$$

$$T_r = (3000 \times 3/5 \times 0.2 + 3000 \times 0.08)$$

(The 'Go' time is 2min and the 'Stop' time is

$$= 600\text{s/d} \quad 3 \text{ min, with a traffic speed of 30miles/h, Table A.3})$$

$$O_p = 1.0$$

$$P_d = 1 \text{ day} \quad (1^{\text{st}} \text{ day of queuing on new asphalt})$$

The estimated deformation over the first two days using the formula

$$\text{Expected deformation} = 6.2 \times 10^{-5} \times \Sigma(R_T \times T_r \times O_p \times P_d)$$

$$\begin{aligned} \text{is} &= 6.2 \times 10^{-5} \times (15.2 \times 6000 \times 0.08 \times 1 \times 1 + \\ &15.2 \times 600 \times 1 \times 1) \\ &= (0.45 + 0.57) \text{ mm} = 1.0\text{mm} \end{aligned}$$

If it is assumed that regular queuing will not occur thereafter, the deformation is acceptable as less than the limit of 1.5 mm in Table B.1 for a period of two days. However, if there were regular queuing for more than one day, the calculated deformation would exceed the permitted maximum of 2 mm for a period of up to one week after the third day of queuing.

B.5 Option 2

The second option is to lay 600m of asphalt on one lane from 6.00 a.m. to mid-day and leave the hot asphalt coned off until it has cooled to a surface temperature of 25°C before opening to traffic in the evening. The intention is to complete the 3km of one lane before overlaying the adjacent lane. Whilst surfacing the first lane, traffic in the 30miles/h zone of 600m between the lights and the

queuing (providing the direction of surfacing is against that of the traffic) are on the old surfacing and any deformation of it is not considered directly (although it could deform more than the usual rate due to the doubling of traffic and halving of speed). Given that the queues at the traffic lights do not exceed 600m in length, the section at most risk will be the first 600m of the first lane of new asphalt to be laid. This section has five time periods, trafficking for first day, normal trafficking for 5 days in July (the remaining 3 days of the first week plus 2 days of the weekend), trafficking at 30miles/h for 1 day, queuing for one day, and normal trafficking for 3 days in August.

(a) Trafficking for first day:

The maximum road surface temperature = 50°C (Table A.1, south in July) + 5°C (assuming road surface temperature was about 20°C the following morning) = 55 °C

$$R_T = 1.9 \times 4 = 7.6\text{mm/h}$$

$$T_l = 3000\text{cv/l/d}$$

$$T_s = 0.04\text{s} \quad (\text{Traffic speed of 60miles/h, Table A.3})$$

$$O_p = 1.0$$

$$P_d = 1 \text{ day} \quad (\text{first day})$$

(b) Normal trafficking in July:

The maximum road surface temperature = 50°C (Table A.1, south in July)

$$R_T = 1.9 \times 2 = 3.8\text{mm/h}$$

$$T_l = 3000\text{cv/l/d}$$

$$T_s = 0.04\text{s} \quad (\text{Traffic speed of 60miles/h, Table A.3})$$

$$O_p = 1.0$$

$$P_d = 5 \text{ days}$$

(c) Trafficking at 30miles/h:

The maximum road surface temperature = 45°C (Table A.1, south in August)

$$R_T = 1.9\text{mm/h}$$

$$T_l = 6000\text{cv/l/d} \quad (\text{Sum of traffic for both directions})$$

$$T_s = 0.08\text{s} \quad (\text{Traffic speed of 30miles/h, Table A.3})$$

$$O_p = 1.0$$

$$P_d = 1 \text{ day}$$

(d) Queuing:

The maximum road surface temperature = 45°C (Table A.1, south in August)

$$R_T = 1.9\text{mm/h}$$

$$T_l = 3000\text{cv/l/d}$$

$$T_r = (3000 \times 4.5/7.5 \times 0.2 + 0.08 \times 3000)$$

(The 'Go' time is increased to 3min but the 'Stop' time is also increased to 4.5min, with a traffic speed of 30miles/h, Table A.3)

$$= 600 \text{ s/day}$$

$$O_p = 1.0$$

$$P_d = 1 \text{ day}$$

(e) Normal trafficking in August:

The maximum road surface temperature = 45°C (Table A.1, south in August)

$$R_T = 1.9\text{mm/h}$$

$$T_l = 3000\text{cv/l/d}$$

$$T_s = 0.04\text{s} \quad (\text{Traffic speed of 60miles/h, Table A.3})$$

$$O_p = 1.0$$

$$P_d = 3 \text{ days}$$

The estimated deformation over the two weeks

$$= 6.2 \times 10^{-5} \times (7.6 \times 3000 \times 0.04 \times 1 \times 1 + 3.8 \times 3000 \times 0.04 \times 1 \times 5 + 1.9 \times 6000 \times 0.08 \times 1 \times 1 + 1.9 \times 600 \times 1 \times 1 + 1.9 \times 3000 \times 0.04 \times 1 \times 3)$$

$$= (0.57 + 1.41 + 0.03 + 0.07 + 0.04) \text{ mm} = 2.4\text{mm}$$

The deformation rate is less than the limit of 3mm in Table B.1 for a period of up to one month.

B.6 Option 3

The third option is to lay 600m of asphalt on one lane from 21:00 to 03:00 on each day, and open the road to traffic at 06:00, when it is expected that the new asphalt road surface temperature will have fallen to 25°C. There is effectively no queuing because of the limited traffic flow whilst the work is in progress. Hence, the first 600m of the first lane of new asphalt to be laid has four time periods, normal trafficking for first day, normal trafficking for second day, normal trafficking for the remaining 5 days in July, and normal trafficking for 5 days in August.

(a) Trafficking for first day:

The maximum road surface temperature = 50°C (Table A.1, south in July) + 10°C (assuming road surface temperature was about 25°C the following morning) = 60°C

$$R_T = 1.9 \times 8 = 15.2\text{mm/h}$$

$$T_l = 3000\text{cv/l/d}$$

$$T_s = 0.04\text{s} \quad (\text{Traffic speed of 60miles/h, Table A.3})$$

$$O_p = 1.0$$

$$P_d = 1 \text{ day} \quad (\text{first day})$$

(b) Trafficking for second day:

The maximum road surface temperature = 50°C (Table A.1, south in July) + 10°C (assuming road surface temperature was about 20°C the following morning) = 55°C

$$R_T = 1.9 \times 4 = 7.6\text{mm/h}$$

$$T_l = 3000\text{cv/l/d}$$

$$T_s = 0.04\text{s} \quad (\text{Traffic speed of 60miles/h, Table A.3})$$

$$O_p = 1.0$$

$$P_d = 1 \text{ day} \quad (\text{first day})$$

(c) Normal trafficking in July:

The maximum road surface temperature = 50°C

(Table A.1, south in July)

$$\begin{aligned}R_T &= 1.9 \times 2 = 3.8\text{mm/h} \\T_1 &= 3000\text{cv/l/d} \\T_s &= 0.04\text{s} \quad (\text{Traffic speed of 60miles/h, Table A.3}) \\O_p &= 1.0 \\P_d &= 5 \text{ days}\end{aligned}$$

(d) Normal trafficking in August:

The maximum road surface temperature = 45°C

(Table A.1, south in August)

$$\begin{aligned}R_T &= 1.9\text{mm/h} \\T_1 &= 3000\text{cv/l/d} \\T_s &= 0.04\text{s} \quad (\text{Traffic speed of 60miles/h, Table A.3}) \\O_p &= 1.0 \\P_d &= 5 \text{ days}\end{aligned}$$

The estimated deformation over the two weeks

$$\begin{aligned}&= 6.2 \times 10^{-5} \times (15.2 \times 3000 \times 0.04 \times 1 \times 1 + 7.6 \times \\&\quad 3000 \times 0.04 \times 1 \times 1 + 3.8 \times 3000 \times 0.04 \times 1 \times 5 + \\&\quad 1.9 \times 3000 \times 0.04 \times 1 \times 5) \\&= (0.11 + 0.06 + 0.05 + 0.07) \text{ mm} = 0.3\text{mm}\end{aligned}$$

This estimate is for the deformation that the first laid strip would experience throughout the duration of the contract, 12 days, and represents the maximum for the job. Subsequently laid strips are ‘at risk’ for fewer days. The deformation experienced by laying the adjacent lane in August would be lower still because of the lower maximum road surface temperature. The estimated total maximum deformation of 0.3mm is well within the 3mm limit for schemes up to one month in Table B.1, and traffic is unrestricted during the daytime.

This exercise demonstrates the great benefits of laying asphalt during the evening and night in periods of hot weather.

- It avoids daytime closures that can lead to drastic early failure.
- It avoids costly traffic delays.

Imposition of traffic restrictions during late evening and night-time does not normally lead to significant deformation by standing traffic because the traffic between 21:00 and 06:00 is only about 10 per cent of the daily total, and the road surface temperature is likely to be less than 30 °C. Using the conditions in these examples, the overnight risk could be estimated thus:

$$\begin{aligned}R_T &= 1.9 \times 0.125 = 0.24\text{mm/h} \\&\quad (\text{Maximum road surface temperature} \\&\quad = 30^\circ\text{C}) \\T_1 &= 600 \quad (10\% \text{ of } 6000) \\T_s &= 3.6\text{s} \quad (\text{Traffic light sequence as in Option 2}) \\O_p &= 1.0 \\P_d &= 1 \text{ day}\end{aligned}$$

Estimated deformation

$$= 6.2 \times 10^{-5} \times 0.24 \times 600 \times 3.6 \times 1 \times 1 = 0.3\text{mm}$$

This is almost a ‘worst case’ example because the road surface temperature would normally cool below 30°C to about 15°C during the night, reducing the Material & Temperature Factor considerably. Nevertheless, where night-time commercial traffic flows are significant (such as on roads servicing docks), it might be worthwhile estimating the effects of night-time closures on deformation, and adding the estimates to daytime values.

Abstract

During the hot summer of 1995, there were a series of rutting failures on roads during construction and early trafficking of asphalt pavements that were ascribed to problems associated with laying in hot weather conditions. Based on previous research into the cooling behaviour of freshly laid layers of asphalt and in consultation with representatives from the Industry, a proposal for a method for risk of damage assessment in such conditions has been prepared. To validate the approach taken, various laboratory studies have been undertaken to gain additional insight into the influence that various parameters have on the deformation of asphalt.

Related publications

- TRL314 *Specification trials of high-performance hot rolled asphalt wearing courses* by J C Nicholls.
1998 (price £35, code H)
- PR13 *Acceptable weather conditions for laying bituminous materials* by J C Nicholls and M E Daines.
1993 (price £25, code E)
- RR298 *The performance of hot rolled asphalt containing crushed rock fines: A303 Mere* by M E Daines.
1992 (price £25, code E)
- RR44 *A model for calculating pavement temperatures from meteorological data* by R G Robinson.
1986 (price £20, code B)
- RR4 *Cooling of bituminous layers and time available for their compaction* by M E Daines.
1985 (price £20, code AA)
- LR729 *Prediction of cooling curves for hot-mix paving materials by a computer program* by P G Jordan and M E Thomas. 1976 (price £20)

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