TRANSPORT RESEARCH LABORATORY

Specification trials of high-performance hot rolled asphalt wearing courses

Prepared for Pavement Engineering Group, Highways Agency

J C Nicholls

TRL REPORT 315

First Published 1998
ISSN 0968-4107

This report has been produced by the Transport Research Laboratory, under/as part of a Contract placed by the Highways Agency. Any views expressed are not necessarily those of the Agency.

Transport Research Foundation Group of Companies
Transport Research Foundation (a company limited by guarantee) trading as Transport Research Laboratory. Registered in England, Number 3011746.

TRL Limited. Registered in England, Number 3142272.
Registered Offices: Old Wokingham Road, Crowthorne, Berkshire, RG45 6AU.

CONTENTS

Executive Summary

This Report covers one facet of a research project that was carried out for the Highways Agency into various asphalt surfacings. The aim of the research was to assess the robustness of new techniques, materials and specifications for use on the surface course layer of trunk roads and motorways with particular reference to high-friction surfacing systems, thin surface course materials, stone mastic asphalt and performance-related specifications of slurry surfacings and hot rolled asphalt. The specific topic covered in this Report is the development of a performance-related specification for hot rolled asphalt wearing courses and the assessment of its effectiveness.

A draft specification clause for hot rolled asphalt wearing course was prepared based on performance-related properties of the in-situ material. The draft clause, Clause 943, specifies the material in terms of the following properties to ensure the appropriate quality of material is provided:

- maximum wheel-tracking rate and depth;
- maximum air voids content; and
- minimum binder content by volume.

This report examines the data from trials (where a single 'trial' is defined here as one mixture supplied from one asphalt mixing plant and laid at one construction site) using the draft clause to establish the practicability of the specification and its implications.

An extensive number of trials of Clause 943 have been undertaken. The hot rolled asphalt was laid successfully at each trial site that has been reported, with good compliance with the performance requirements and with the compositional requirements of BS 594: Part 1. There are some indications that the material suppliers have maintained tighter tolerances than normal in order to ensure that the contractual properties are consistently achieved. The analysis method by ignition was found useful by one materials supplier to maintain that compositional compliance.

The specification limits are consistent within themselves; however, the trials have not been in place long enough to ensure that the values of the set limits are correct in terms of minimising the risk of deformation of the pavement within its expected service life. The overall success of Clause 943 will not be fully validated until the trial sites are nearing the end of their expected services lives.

The nuclear density gauge can be used as a screening device because it indicates variations in the air voids content and, to a lesser extent, the wheel-tracking rate; however, with no non-compliances reported, it has not been possible to assess the ease with which one will be detected. Nevertheless, the use of such equipment minimises the destructive coring of the pavement. The nuclear density gauge can be used on a bed of sand or on areas of the surfacing left unchipped; given the practical difficulties of restoring texture on unchipped areas, the bed of sand procedure is preferred.

There is subjective evidence that hot rolled asphalt to Clause 943 is quieter than normal, but this attribute has not been confirmed by testing.

1 Introduction

Hot rolled asphalt (HRA) wearing courses have long been specified in terms of a recipe combination of component materials that are mixed, transported, laid and compacted to set rules. The only concession to mixture design is the determination of binder content for 'design' hot rolled asphalts with three classifications of 'Marshall' stability values for different traffic intensities. This specification is set out in Clause 911 of the *Specification for Highway Works* (MCHW 1) and BS 598: Parts 1 and 2 (BSI, 1992).

With the increasing flow and weight of commercial traffic, exacerbated by the advent of the 'super-single' axle construction, and recent hot summers, the ability of typical hot rolled asphalt to resist premature deformation on heavily trafficked roads has been called into question. Nevertheless, there are sufficient heavily-trafficked roads with hot rolled asphalt wearing courses that have little or no permanent deformation to provide assurance that some hot rolled asphalts can perform satisfactorily in the current conditions. Therefore, it has become necessary to specify hot rolled asphalt in terms of the required performance, and not by recipe alone.

The wheel-tracking test, now a full British Standard (BSI, 1996), has long been known to be a suitable method for ranking materials by their ability to resist permanent deformation. However, in selecting mixtures of hot rolled asphalt for particular jobs, the ability to resist permanent deformation, usually achieved by reducing binder contents and increasing the angularity of the fine aggregates, needs to be balanced by its durability. Durability is primarily affected by the permeability of the mixture with more permeable mixtures being more susceptible to oxidation; improved durability is usually achieved by increasing both the binder content and the workability of the mixture, the latter by reducing the angularity of the fine aggregates.

The ability to measure the density of hot rolled asphalt, and hence calculate the air voids content as an analogue for permeability, is complicated by the presence of pre-coated chippings. However, it has been shown that the air voids content can be determined from samples incorporating pre-coated chippings (Daines, 1995). Therefore, it is now possible to specify hot rolled asphalt in terms of both deformation resistance, as measured by the wheel-tracking rate, and air voids content, as an analogue for durability. Both these properties can be measured:

- on trial or laboratory mixtures in order to assess whether the material can meet the requirements; or
- on cores recovered from the actual pavement in order to assess whether the requirements have been met.

After consultation with industry and in collaboration with the Transport Research Laboratory (TRL), the Highways Agency (HA) drafted a performance-related specification clause for hot rolled asphalt surface courses, Clause 943. To assess the effectiveness of Clause 943, HA granted a series of specification departures from the standard to use Clause 943 on a number of (trial) sites with a requirement that TRL was informed when the work was to commence and that the results of the testing were sent to TRL. This report gives details of the findings from the trials using draft specification Clause 943; some initial findings have already been reported (Mercer & Nicholls, 1997; Whiteoak & Nicholls, 1998).

2 Specification

The first draft of the specification for performance-related hot rolled asphalt wearing courses was prepared in October 1994 and then circulated to relevant bodies and reviewed. The concept of specification Clause 943 was to limit the wheel-tracking rate and the air voids content of cores taken from the mat to upper bound values, the upper bounds being dependant on the traffic intensity at the site. Both these requirements were specified in terms of running mean values and of individual values.

However, concerns were expressed about the possibility of material which deformed excessively initially in the wheel-tracking test but then achieved sufficient secondary compaction not to deform in the last third of the test when the measurement takes place. To take account of this situation, a secondary requirement, limiting the total wheel-tracking depth, was included. The limiting value of wheel-tracking depth was initially set as the rut that would occur in 1 hour at the limiting value of wheel-tracking rate (although the test actually only lasts 45 minutes) but subsequently this limit was increased by the addition of 2 mm.

The requirement for air voids content was a surrogate for durability. The original limits were set at (2 to 4) per cent for the mean of 4 results and at (1 to 6) per cent for individual determinations. The lower bound was dropped because any instability due to low voids should be identified by the wheel-tracking requirements while the upper bounds were increased to 5.5 per cent and 7.5 per cent, respectively, following representation about the higher air voids content of mixtures from the north and west of the United Kingdom which have established durability. An additional requirement to ensure durability was a minimum binder content to avoid the possibility of a design in which the voids are filled by bitumen, fine aggregate and filler. The binder content was defined by volume, originally as 16 per cent but later refined to 15.5 per cent.

The problem foreseen by the assessment of the condition of a finished surfacing from extracted cores was that, by the time sufficient cores have been taken to ensure a consistent high quality, the pavement is peppered with core holes and is no longer satisfactory. Therefore, the nuclear density gauge was introduced as a screening tool to detect changes in density that could indicate possible changes in the material that influence the wheel-tracking rate and/or the air voids content. The coring can then be restricted to the minimum which allows calibration of the nuclear density gauge; additional cores have to be taken if the gauge detects any significant change in density.

Specification Clause 943 and the associated Notes for Guidance NG 943 are being published in the 1998 edition of the *Specification for Highway Works* (MCHW 1) and *Notes for Guidance on the Specification for Highway*

Works (MCHW 2), respectively. The principal criteria of the clause are set out in Table 1, in which the description of site classifications are:

- Classification 0 Lightly stressed sites not requiring specific design for deformation purposes (and therefore not covered in this report) other than air void content;
- Classification 1 Moderate to heavily stressed sites requiring high rut resistance; and
- Classification 2 Very heavily stressed sites requiring very high rut resistance.

A table is given in the Notes for Guidance to identify the relevant classification for any particular section of road.

In this review of the specification trials, comparisons are made with these requirements, irrespective of the specification against which the works were actually carried out.

3 Trial sites

3.1 Overview

The initial intention was to carry out trials at sites selected on the M5 in Somerset, the A21 in Kent, the A38 in Cornwall and possibly one other site during late 1995 and early 1996. Of these trials, only that on the A21 Sevenoaks bypass in Kent took place as intended because the other two schemes did not proceed to construction. However, following the hot summer of 1995, there were requests for permission to use the draft specification on several other sites, generally after significant deformation had occurred in the previous surfacing. A list of trials that have taken place and from which results been sent to TRL for use in this report is given in Table 2; other trials are known to have taken place but the results have not been forwarded to TRL. Details of some of the earlier trial sites are given in Sections 3.2 to 3.5.

As well as for analysis to support the specification of hot rolled asphalt by performance-related criteria, details of these trials have been used to set up a database of surfacings. It is intended to develop this database to cover a much wider range of types of wearing courses in a wider range of sites.

3.2 M5 J22, Somerset

When specification Clause 943 was being drafted, it was too late to include the clause in the tender document for a strengthening works contract near junction 22 on the M5 (this contract was for a different site to the proposed trial on the northbound carriageway between junctions 24 and 25, Huntworth and Blackwood). However, the contractor,

Table 1 Basic requirements of Clause 943

Requirement		*Classification 1*	*Classification 2*
Max^m wheel-tracking rate	Mean of 6	2.0 mm/h @ 45°C	5.0 mm/h @ 60°C
	Individual	3.0 mm/h @ 45°C	7.5 mm/h @ 60°C
Max^m wheel-tracking depth	Mean of 6	4.0 mm @ 45°C	7.0 mm @ 60°C
	Individual	6.0 mm @ 45°C	10.5 mm @ 60°C
Max^m air voids content	Mean of 4	5.5 per cent	5.5 per cent
	Individual	7.5 per cent	7.5 per cent
Min^m binder content (by volume)		15.5 per cent	15.5 per cent

Table 2 Trials of Clause 943 for which results are available

Classification	*Road*	*Location*	*Binder*	*Date laid*
n/a	M5	J22, Somerset	50 pen bitumen	June 1995
1	A21 n/b	Sevenoaks bypass northbound	70 pen plus EVA	October 1995
1	A21 s/b	Sevenoaks bypass southbound	Multiphalte	Jan to March 96
1	A14	Ipswich bypass, Copdock Mill	Flexxipave RA	July 1996
1	M6	J15-J14 lane 2, Staffordshire	Nypol ST 50	October 1996
1	M6	J39-J42, Cumbria	Crodapave HDA 500	August 1997
2	M11	J9-J10, Cambridgeshire	Cariphalte DM	April 1996
2	M11	J12-J14, Cambridgeshire	Cariphalte DM	July 1996
2	M25	J6-J8, Reigate Hill	Cariphalte DM	July to Sept 96
2	A14	Godmanchester	Cariphalte DM	-
2	A14	Ouse River Bridges	Cariphalte DM	-
2	M6	J15-J14 lane 1, Staffordshire	Nypol ST 50	October 1996
2	M6	J10-J10A, Staffordshire	Olexobit C60	October 1996
2	A14	Risby to Topstock	Cariphalte DM	November 1996
2	M25	J25-J26, Essex	Cariphalte DM	Nov to Dec ‘96
2	A14	Girton to Hemmingford	Not known	Nov to Dec ‘96
2	A14	Kentford to Nine Mile Hill	Cariphalte/Olexobit	Nov to Dec ‘96
2	A12	Coles Oak Bridge	Cariphalte DM	December 1996
2	A14	Bury St Edmonds to Kentford	Olexobit C60	Dec ’96/Jan ‘97
2	M6	J7-J8, Midlands Link	Olexobit C60	February 1997
2	A127	Halfway House, Essex	Olexobit C60	March 1997

Associated Asphalt, cooperated by taking cores and measuring their wheel-tracking rate, bulk density and maximum theoretical density and hence calculated their air voids contents.

The material was hot rolled asphalt with 35 per cent stone content using quartzite coarse aggregate, Hillhead fine aggregate, limestone filler and bitumen of 50 pen grade. The binder content was designed to BS 598: Part 107 (BSI, 1990) with a target value of 7.4 per cent, at which value the stability was 7.5 kN and the flow was 2.9 mm. Although not designed against the requirements of Clause 943, the material complied with the Classification 1 wheel-tracking requirement and generally complied with the more severe Classification 2 requirement; it also complied with the air voids requirements.

3.3 A21, Sevenoaks

The contract for the A21 Sevenoaks bypass in Kent was the first contract let with a section required to be laid under the performance-related design mixture clause for hot rolled asphalt wearing course. The contract required both a standard (control) mixture and a Classification 1 performance-related mixture. The contractor, R J Maxwell, wished to use Shell Multiphalte 30/50 bitumen (Nicholls, 1994) in the performance-related mixture, but it required a specific departure for its use. Because of the delay in obtaining the departure, the first section of performance-related mixture to be laid on the northbound carriageway was an ethylene vinyl acetate (EVA) modified mixture. However, the Multiphalte mixture was used for the performance-related section on the southbound carriageway; hence, the site effectively provides a trial for two different high-performance mixtures.

The component materials in the three mixtures, with 30 per cent coarse aggregate, used on the trials were as given in Table 3.

The materials approval of the EVA-modified mixture was carried out on the site adjacent to a crossover in October 1995, which demonstrated that it was acceptable. The mixture was laid on the northbound carriageway in October and November 1995, when the weather was mostly dry and sunny, with the ambient air temperature ranging from 7°C to 20°C and the wind speed from 0 km/h to 8 km/h.

The materials approval of the Multiphalte mixture was carried out in January 1996 but it was not as rut-resistant as expected. Nevertheless, the mixture was approved and laid on the southbound carriageway in February and March 1996, when the ambient air temperatures ranged from -2°C to 12°C and wind speeds from 0 km/h to 18 km/h. When the material was laid overnight, the surfacing contractor did not comply with the adverse weather criterion submitted with the mixture design. The mixture laid in the actual construction was significantly more rut-resistant than that in the approval trial.

3.4 M11 J9-J10, Cambridgeshire

The resurfacing of four locations on lane 1 of the M11 between junctions 9 and 10 in Cambridgeshire was the first job which required a Classification 2 performance-related mixture of hot rolled asphalt with the wheel-tracking being carried out at 60°C. The contract was awarded to Redland Contracting with the material being supplied from Redland Aggregate's Little Paxton mixing plant. Because of limited knowledge of precisely how their materials would behave in these tests, Redland Aggregates assessed various mixture designs, both before and after the tender was accepted.

The optimum binder content was determined using BS 598: Part 107 (BSI, 1990) for mixtures with two fine aggregates (Potton and Potton/Middleton blend) and two binder types (Shell Multiphalte 35/50 and Shell Cariphalte DM). The various mixtures identified with two binder contents (optimum and optimum plus 0.5 per cent) are summarised in Table 4.

Slabs of the Potton fine aggregate mixtures were manufactured using roller-compaction; a summary of the properties are given in Table 5, with the standard deviations in brackets.

The use of two binder contents demonstrated the sensitivity of the rut-resistance to binder content, with the wheel-tracking rate increasing but the air voids content reducing with increased binder. The mixture with Cariphalte DM, a styrene-butadiene-styrene (SBS) block co-polymer modified bitumen, had both a lower wheel-tracking rate and a lower air voids content, complying with the Classification 2 requirements at both binder contents, and so was selected for an in-house trial on a private road at the contractor's offices.

Cores were taken from areas laid both with and without pre-coated chippings with some of those taken from the chipped area having the chippings removed before testing. The rational for removing chippings was to get back to the material as mixed for density calculations, but the samples were also tested for wheel-tracking despite that test being carried out on the underside of the samples where the presence of chippings should not have an effect. A summary of the results from the tests on the cores are given in Table 6.

Table 3 Component materials for mixtures on A21, Sevenoaks bypass

	EVA mixture	*Multiphalte mixture*	*Control mixture*
Coarse aggregate	Arklow basalt	Arklow basalt	Arklow basalt
Fine aggregate	Brett Charing sand	80 % Charing sand 20 % Arklow crushed rock fines	80 % Charing sand 20 % Arklow crushed rock fines
Filler	Tilcon	Tilcon	Tilcon
Binder	70 pen + 5 % EVA	Multiphalte 35/50	50 pen bitumen
Binder content	7.0 per cent	6.9 per cent	6.7 per cent
Stability	6.5 kN	8 to 12 kN	8.0 kN

Table 4 Redland Aggregate test mixtures

Coarse aggregate		*Fine aggregate*		*Filler*		*Binder*	
Source	*Content*	*Source*	*Content*	*Source*	*Content*	*Type*	*Content*
14 mm Mountsorrel Granite	39.0 %	Potton	55.0 %	Cadeby limestone	6.0 %	Multiphalte 35/50 Multiphalte 35/50 Cariphalte DM Cariphalte DM	7.0 % 7.5 % 7.0 % 7.5 %
		Potton/ Middleton blend (60:40)	52.8 %	Cadeby limestone	8.2 %	Multiphalte 35/50 Multiphalte 35/50 Cariphalte DM Cariphalte DM	7.0 % 7.5 % 7.0 % 7.5 %

Table 5 Mean properties of laboratory-prepared samples

Binder type	*Binder content (per cent)*	*Bulk density (Mg/m³)*	*Theoretical max. density (Mg/m³)*	*Void content (per cent)*	*Wheel-tracking rate @ 60°C (mm/h)*
Multiphalte 35/50	7.0	2.20	2.40	8.3	2.9 (0.4)
Multiphalte 35/50	7.5	2.22	2.40	7.6	3.5 (0.8)
Cariphalte DM	7.0	2.29 (0.003)	2.40	4.6	1.7 (0.4)
Cariphalte DM	7.5	2.29 (0.010)	2.40	4.5	3.0 (0.8)

Table 6 Mean properties of Redland Aggregate in-house trial

Core treatment	*No. of Samples*	*Bulk density (Mg/m³)*	*Theoretical Max. Density (Mg/m³)*		*Void content (per cent)*		*W/T Rate @ 60°C (mm/h)*
			Core	*Loose*	*Core*	*Loose*	
With chippings	6	2.32 (0.02)	2.40	2.41 (0.01)	3.5	4.0	5.8 (0.4)
Chippings removed	4	2.30 (0.02)	2.40	2.41 (0.01)	4.1	4.6	7.3* (0.0)
Unchipped	5	2.28 (0.02)	2.40	2.41 (0.01)	5.1	5.6	5.2* (1.6)

**Not standard result, which is mean from 6 samples for wheel-tracking test*

The results from the cores with the chippings removed demonstrates that the disruption caused by this operation leads to lower bulk densities and higher air void contents and wheel-tracking rates. This demonstrates the need to measure the undisturbed material including the pre-coated chippings. The cores from the unchipped areas had lower bulk densities, possibly a result of a combination of:

- the difference in density between the hot rolled asphalt and the pre-coated chippings (although this effect should also apply to the cores with chippings removed); and
- the bridging effect from leaving small areas with chippings, effectively reducing the compaction applied.

Nevertheless, the wheel-tracking rates were also low which, by comparison with the results from the cores with the chippings removed, indicates that the disruption of removing chippings has a greater adverse affect on deformation resistance than high air voids contents due to limited compaction.

The material approval was carried out on a slip road adjacent to the site, although doubts were raised as to the suitability of the location because of the gradient. The mixture was laid in April 1996, when the weather was dry and sunny with light wind and an ambient air temperature ranging from 4°C to 20°C.

3.5 M25 J6-J8, Reigate

The contract for the widening of the M25 between junctions 6 and 8 included both sections to be surfaced with hot rolled asphalt and with porous asphalt. The consultant for the work was Parkman and the contractor was Laing, with Amey as laying sub-contractor using various suppliers, including Bardon Aggregates Limited at West Drayton and London Roadstone at Brentford. After premature permanent deformation of the hot rolled asphalt on Reigate Hill, the performance-related specification requirements to Classification 2 were applied to the job.

4 Compliance testing and analysis

4.1 Reported results

Summaries (in terms of the number, mean, standard deviation and range) of the results provided to TRL of the testing carried out during construction from each of the trials in Table 2 are given in Appendix A, split into Section A.1 for the wheel-tracking tests and Section A.2 for the density and air voids determinations. The resulting statistics for each trial in Appendix A are, wherever possible, given separately for mixture approval trials and for compliance checks on the construction itself together with the combined statistics. However, in the analysis in the rest of Section 4, the combined statistics for a trial are used unless explicitly stated otherwise in order to minimise the number of sets of data to be reported.

There were differences in the data that was reported from each site, including:

- the inclusion of data from the approval trial as well as from the construction;
- the proportion of different cores tested (200 mm diameter for wheel-tracking and 150 mm for bulk and theoretical maximum densities);
- the existence and extent of wheel-track testing at the second test temperature;
- the number of times the maximum theoretical density was calculated as well as the bulk density; and
- the adequacy of the information to correlate which wheel-tracking rates, core densities and nuclear density gauge readings referred to the 'same' location.

Therefore, the number of tests analysed for each parameter will also vary and cannot be assumed from the number of tests on a different parameter.

4.2 Compositional compliance

4.2.1 Objectives

Although the specification clause is performance-related, it still requires the composition to conform to the relevant British Standard grading. This recipe element remains because the assumptions about durability are based on the findings from research into hot rolled asphalt and there is no definitive of what is, and is not, a hot rolled asphalt other than the various gradings in BS 594: Part 1 (BSI, 1992).

An analysis of the gradings found on site compared to the required gradings was carried out in order to check that the grading and binder content were not having to be adjusted outside the prescribed limits to comply with the various performance criteria. If the compositional compliance was found to be unacceptable compared to that found with traditional specification approach, the tolerances may have needed to be reviewed. The opportunity was taken to use data from analysis using the ignition method in order to assess the suitability of this method of analysis as a screening tool to identify potentially non-compliant material or to use it as the compliance check itself.

4.2.2 Conventional analysis

The control of the materials on the early contracts on the M5, A21, M11 (J9-J10) and M25 (J6-J8) contracts, as reported, was good, with:

- all of the 40 analyses on the mixture for the M5 complying;
- 22 of the 24 analyses on the mixture for the A21 northbound complying (the exceptions were 1 per cent low on the 2.36 mm sieve for one sample and 0.1 per cent high on the binder content for another);
- all of the 24 analyses on the mixture for the A21 southbound complying;
- all of the 34 analyses on the mixture for the M11 (J9-J10) complying;
- 38 of the 42 analyses on the Bardon mixture for the M25 complying (the exceptions were 0.4 per cent and 0.7 per cent high on the filler and 6 per cent and 3 per cent low on the 2.36 mm sieve); and
- 16 of the 17 analyses on the London Roadstone mixture for the M25 complying (the exception was 2 per cent retained on the 20 mm sieve).

This good compositional compliance (96 per cent) shows that the consistency expected to be needed to minimise the possibility of non-compliance in the specified material properties due to variation in composition was achieved.

The control on the later trials was not checked to the same extent.

4.2.3 Binder content by ignition analysis

The 34 analyses carried out using the standard solvent method on the Cariphalte mixtures on the M11 (J9-J10) contract were repeated using the ignition method. A testing error occurred with one of the ignition analyses, but a summary of the remaining test results is given in Table 7 (where the 'difference' row gives the statistics for the value by the standard method minus that by the ignition method for individual samples).

Differences in the aggregate grading, over and above any testing error, could occur if one analysis method modifies the grading in a way that the other does not. The most obvious possible modifications are the breaking down of particles due to the high temperatures in the ignition method and some of the fine material being washed away with the solvent in the standard method.

The results show a bias of the ignition method to give higher binder contents and lower proportions passing each sieve than the standard method. However, the mean difference is only one quarter to one third of the standard deviation of individual methods for binder content, indicating that the bias is marginal. Furthermore, any bias could be due to errors in the standard test procedure as well as in those for the ignition method.

Table 7 Analysis by standard and ignition methods

	Binder content (per cent)	Proportion passing BS Sieve (per cent)					
		14 mm	*10 mm*	*2.36 mm*	*600 µm*	*212 µm*	*75 µm*
Standard Method:							
Mean	7.06	94.0	69.2	60.9	58.6	15.9	8.29
Std. Dev.	0.17	1.7	2.6	2.1	2.2	0.8	0.41
Range	6.8 to 7.4	90 to 97	60 to 74	56 to 65	53 to 63	14 to 19	7.6 to 9.2
Ignition Method:							
Mean	7.11	93.3	68.8	60.3	57.9	13.7	6.23
Std. Dev.	0.12	1.6	2.9	2.8	2.6	1.2	0.88
Range	6.9 to 7.5	91 to 96	63 to 75	55 to 64	53 to 62	12 to 16	4.8 to 9.9
Difference*:							
Mean	-0.04	0.6	0.4	0.7	0.7	2.2	2.06
Std. Dev.	0.17	2.5	3.3	3.1	3.1	1.5	1.01
Range	-0.4 to 0.3	-3 to 5	-6 to 7	-5 to 8	-6 to 7	0 to 7	-2.2 to 3.6

**Difference = Result from standard method - result from ignition method. (A positive value implies that the ignition method under-estimated the result from the standard method and a negative value implies that the ignition method over-estimated the result from the standard method; however, the standard method did not necessarily produce the 'true' result.)*

4.3 Wheel-tracking test

4.3.1 Objectives

The wheel-tracking test is the basis of the specification clause. Therefore, the initial investigation into the available data was to confirm that the performance-related requirements could be attained, both in terms of wheel-tracking rate and wheel-tracking depth.

If the test becomes part of the mix design procedure for hot rolled asphalt, which is one result of the relatively wide-spread use of the draft clause, there is a need to get a better understanding of the ability of laboratory-produced specimens to predict the property on site. Therefore, a comparison was made from the few trials where laboratory samples were manufactured to assess the value of any predictions.

Clause 943 has introduced the wheel-tracking depth as a secondary requirement to wheel-tracking rate. The relationship between the wheel-tracking depth and wheel-tracking rate needed to be examined both to see if the parameters are sufficiently interdependent for the wheel-tracking depth requirement to be superfluous and, if they are not interdependent, to assess the relative frequency that the two criteria will be triggered in order to ensure that the wheel-tracking depth requirement is secondary.

The temperature of the test is different for the two Classification categories. Classification 1 uses 45°C because that has been the traditional test temperature whereas Classification 2 uses 60°C because of a need for greater discrimination than would be possible at the very low wheel-tracking rates that would be achieved by the relevant mixtures at 45°C. However, the relationship between 2 mm/h at 45°C and 5 mm/h at 60°C needed to be investigated in order to confirm that the latter is the more stringent requirement for all mixtures.

4.3.2 Compliance

Figure 1 shows a typical plot from a wheel-tracking test from which the wheel-tracking rate is calculated from the predominately linear last third of the test and the maximum wheel-tracking depth at the end of the test is determined. The final wheel-tracking depth comprises any 'bedding-in' early in the test together with the steady increase in wheel-tracking depth.

Appendix A.1 provides a summary of the results from individual sites for tests carried out at 45°C and 60°C. Of the 420 cores taken from the actual construction and tested for wheel-tracking, only four (one at 45°C and three, all from the same trial, at 60°C) failed the individual wheel-tracking requirement, giving a 99 per cent overall level of compliance. There were no failures of the individual wheel-track depth requirement (out of 353 cores because of lack of results from three trials) nor of either requirement based on the running mean of six determinations. Therefore, the wheel-tracking requirements can be met provided an appropriate mixture is selected and the appropriate care is taken.

4.3.3 Laboratory and site specimens

The laboratory-prepared slabs of the Cariphalte DM mixture used on the M11 between junctions 9 and 10 (Table 5) gave a mean wheel-tracking rate at 60°C of 1.7 mm/h for 7.0 per cent binder content and 3.0 mm/h for 7.5 per cent. The binder content of the mixture used in the in-house trial (Table 6) was 7.06 per cent by the standard method and the mean wheel-tracking rate was 5.8 mm/h, over three times that of the laboratory-prepared slabs at 7.0 per cent binder content; the mean wheel-tracking rate was 3.8 mm/h in the construction but was higher at 4.4 mm/h for the mixture approval trial (Appendix A.1).

Laboratory-prepared slabs were also manufactured and wheel-tracked at a variety of test temperatures from the mixtures used on the A21. The results are plotted in Figure 2, which shows smaller differences between laboratory-prepared slabs and cores from site than were found on the M11 J9-J10. The EVA cores had wheel-tracking rates more than 50 per cent greater than those for the EVA slabs at 60°C whilst, for Multiphalte, the cores had lower rates than the slabs.

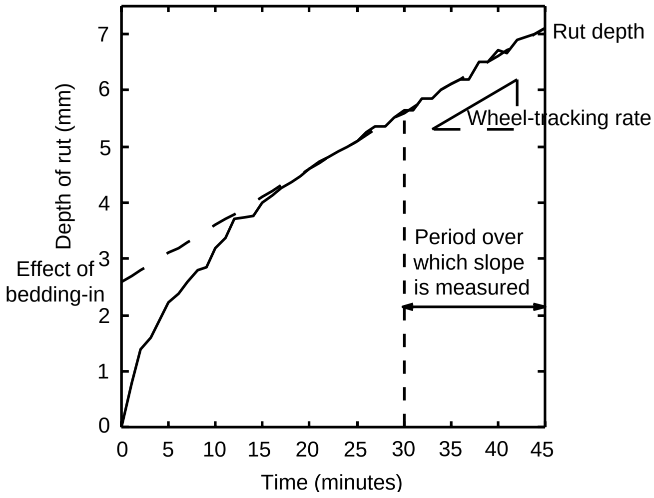


Figure 1 Schematic plot of the deformation development in a wheel-tracking test

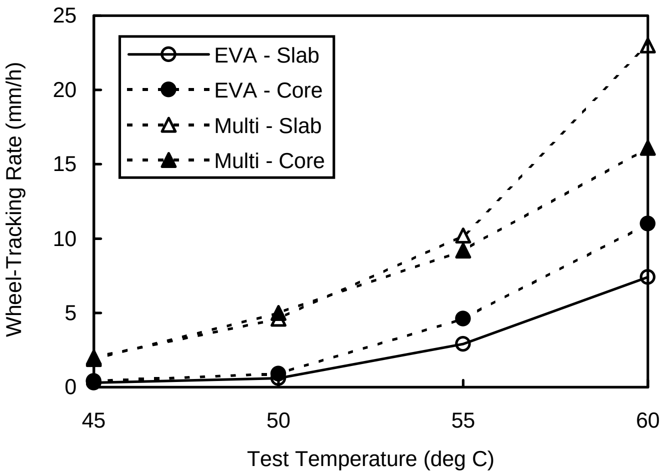


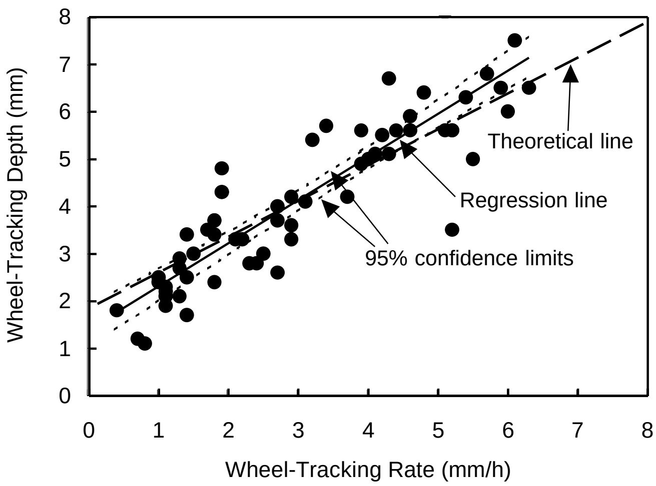
Figure 2 Change of wheel-tracking rate with test temperature

There is a significant difference between the results of wheel-tracking tests on slabs and cores but that difference is not consistent. The disparity must result from the difference in compaction method in the laboratory and on site, the variability of the material, the variability of the test method or a combination of these factors. The variabilities will have some influence because of the relatively limited number of specimens in these cases (the result from the standard test method is the mean of determinations from 6 samples to allow for these variabilities), but the extent of the disparity implies that it is primarily due to the method of compaction and its differing effects on different mixtures. Therefore, predictions as to the deformation-resistance of a mixture on site from laboratory-prepared samples must be treated with caution until samples prepared with the particular procedure for laboratory compaction has been calibrated against cores from site for a range of mixtures.

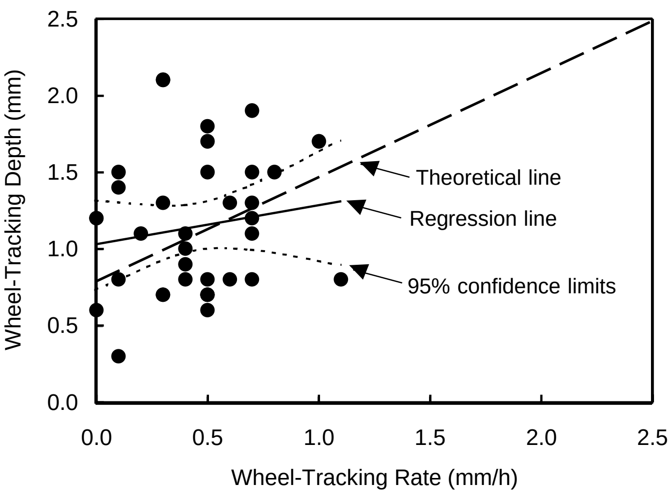
4.3.4 Relationship between wheel-tracking rate and wheel-tracking depth

For each set of wheel-tracking results from a trial (one mixture supplied from one mixing plant and laid at one construction site) at the same temperature, a graph was drawn of the (maximum) wheel-tracking depth against the wheel-tracking rate. Where there was a reasonable spread of wheel-tracking rate values, a reasonably linear relationship resulted, such as that shown in Figure 3(a). However, where the wheel-tracking rate values were all within a small range, there was no effective correlation between the wheel-tracking rate and wheel-tracking depth, as in Figure 3(b). The range of wheel-tracking rates tend to be closer for the results at 45°C than at 60°C because of the lower numerical value needed to be attained.

In the relationship between the wheel-tracking depth and the wheel-tracking rate, the slope would be 0.75 mm/{mm/h} if all the hot rolled asphalt samples deformed at a steady rate throughout each test after a consistent amount of bedding-in providing that bedding-in occurs during the first two thirds of the test. This value results from the test lasting 45 minutes. Therefore, a line with that slope is shown as the ‘theoretical line’ on both plots in Figure 3. It can be seen that the theoretical line falls within the 95 per cent confidence limits of the regression analysis for the trial.



(a) M6, J15-J14, tested at 60°C (correlation coefficient = 0.89)



(b) M6, J15-J14, tested at 45°C (correlation coefficient = 0.09)

Figure 3 Relationship between wheel-tracking rate and wheel-tracking depth for cores

Linear regression analyses were carried out for each trial and the correlation coefficients were determined, the square of which indicates the proportion of the variability of the dependent variable that is explained by the variation in the value of the independent variable. The correlation coefficients varied from 0.1, which indicates no correlation whatsoever, to 0.9, which explained 85 per cent of the variability. The average correlation coefficient was 0.7, so that about half the variation in measurements of the wheel-tracking depth was explained by the differences in the wheel-tracking rate of the specimen whilst the remaining variability was due to other factors.

The uncertainty can be regarded as a measure of the variability in the amount of bedding-in occurring which depends on the precise aggregate structure at the point of measurement. The variability in aggregate skeleton at the point of measurement could be minimised by modifying the test procedure to measure the deformation at a number of locations on the core along the line that the wheel tracks and then take the average. That procedure would require modification to the currently-used test equipment and would only reduce any very localised differences. In the standardisation trials carried out for the wheel-tracking, such averaging did not significantly improve the precision and so was not incorporated within the test method (BSI, 1996). Nevertheless, the remaining uncertainty means that the requirement on the maximum wheel-tracking depth is not made superfluous by the requirement on wheel-tracking rate.

Of the 542 wheel-tracking test results reported from approval trials and from construction with both wheel-tracking rate and wheel-tracking depth, only 42 (8 per cent) had a wheel-tracking depth that was numerically more than 2 greater than the wheel-tracking rate. Hence, in most cases the bedding-in depth was less than 2 mm plus a nominal fifteen minutes at the deformation rate achieved during the final third of the test. The numerical difference between the current limits on the running means in Clause 943 is 2 (Table 1), whilst the numerical difference between the individual results is greater at 3. Therefore, the current limits on wheel-tracking depth are confirmed as being secondary (in terms of their likelihood of classifying materials as non-compliant) to those for wheel-track rate and, hence, appropriate for their intended purpose.

4.3.5 Influence of temperature

The test temperature has a significant influence on the results of the wheel-tracking test. The change in wheel-tracking rate with test temperature from the A21 results, given in Figure 2, has been replotted in Figure 4 in terms of the logarithm of the wheel-tracking rate against temperature and best-fit lines applied.

Figure 4 shows that the relationship is approximately linear between temperature and the logarithm of the wheel-tracking rate. Hence, if the wheel-tracking rate of a mixture at temperatures of 45°C and 60°C are known to be WT_{45} mm/h and WT_{60} mm/h, the wheel-tracking rate at temperature t°C can be estimated as WT_t mm/h from Equation (1) (at least within a temperature range of 45°C to 60°C). Using Equation (1), it can be simply shown that

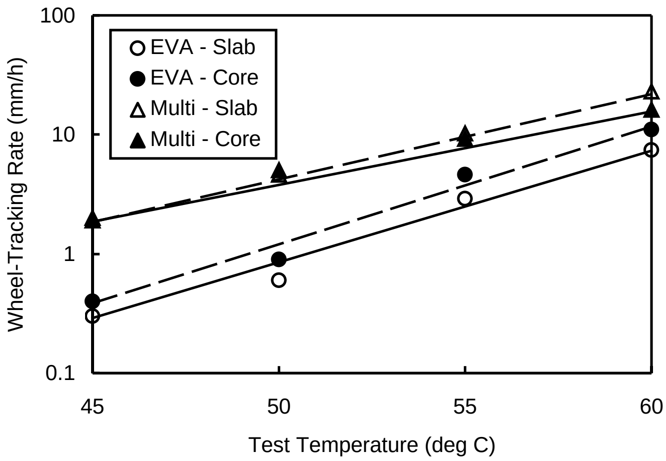


Figure 4 Change of log (wheel-tracking rate) with test temperature for A21 samples

the wheel-tracking rate of a material whose wheel-tracking rate is, say, 10 times as great at 60°C than it is at 45°C will change cumulatively by about 15 per cent for every one degree Celsius change in temperature.

Both Figure 2 and Figure 4 demonstrate how much more severe the 5 mm/h requirement at 60°C is relative to the 2 mm/h requirement at 45°C, at least for these two Classification 1 mixtures. To identify the typical ratio between tests at test temperatures of 45°C and 60°C (and the scatter about that value), the mean results of the tests on cores taken from the pavement for mixtures with results at both temperatures are given in Table 8.

Table 8 shows that the mean wheel-tracking rates can increase by between 3 and 22 times when the test temperature is increased from 45°C to 60°C. This variability in the extent to which a change of test temperature affects different mixtures can have implications for the choice of the temperature at which compliance is determined because any ranking of mixtures could change with temperature. The implications could be even more critical when there are different test temperatures for different classes, as at present.

Each of the values in Table 8 were determined from two wheel-tracking rates, a test for which the repeatability, r, and reproducibility, R, are r = 0.8 mm/h and R = 1.4 mm/h at a test level of 2.2 mm/h rising to r = 4.0 mm/h and R = 5.7 mm/h at a test level of 13.5 mm/h. The precision values (BSI, 1996) were calculated for the mean of six determinations, although in many of the cases in Table 8 the average results are means of more six than determinations. Nevertheless, given that the limit on the running mean at 60°C is 2½ times larger than the criterion at 45°C, the 60°C criterion varied between being only marginally more severe than the 45°C criterion to nine times more severe, depending on the mixture used. Given that mixtures with polymer-modified binders, as used on these trials, tend to be less susceptible to changes in temperature than those with unmodified bitumen, unmodified mixtures will find the change in criterion even more severe. This is demonstrated by the more heavily modified mixtures, those designed to comply with Classification 2, tending to be less susceptible to temperature.

Table 8 Change in mean wheel-tracking values with temperature

		Wheel-Tracking Rate (mm/h)			*Wheel-tracking Depth (mm)*		
Classification	*Trial*	*@ 45°C*	*@ 60°C*	*Ratio*	*@ 45°C*	*@ 60°C*	*Ratio*
1	M5 J22	0.5	3.9	7.8	-	-	-
1	A21 northbound	0.4	9.0	22.5	1.6	8.3	5.2
1	A21 southbound	1.6	11.5	7.2	1.7	12.2	7.2
1	A14 Copdock	0.5	5.7	11.4	1.3	6.2	4.8
2	M6 J15-J14	0.4	3.1	7.8	1.1	4.2	3.8
2	M11 J9-J10	1.4	4.0	2.9	-	4.8	-
2	M25 J25-J26	0.2	3.0	6.0	1.6	4.4	2.8
2	A127 Halfway	0.8	2.5	3.1	1.8	3.7	2.1
	Mean	-	-	8.6	-	-	4.3

The current limit for Classification 1 was based on testing at 45°C because that was the temperature generally used for the wheel-tracking test at the time when Clause 943 was developed, whilst that for Classification 2 was based on testing at 60°C in order to allow more discrimination. The different temperature susceptibility of different mixtures means that the difference in severity of the two limits depends on the temperature susceptibility of the mixture being used, and that the choice of test temperature can be critical. If the test temperature is selected to be, say, halfway between 45°C and 60°C at which the wheel-tracking rate should be limited to, say, 2 mm/h, then mixtures with the following wheel-tracking rates would all just be acceptable:

A 1 mm/h at 45°C and 4 mm/h at 60°C (giving a ratio of 4);

B 0.7 mm/h at 45°C and 5.6 mm/h at 60°C (giving a ratio of 8);

C 0.5 mm/h at 45°C and 8 mm/h at 60°C (giving a ratio of 16); or

D 0.4 mm/h at 45°C and 10 mm/h at 60°C (giving a ratio of 25).

However, if the test temperature was increased to 60°C and the maximum limit consequentially revised to 5.6 mm/h (on the assumption that a ratio of 8, as in Mixture B, was typical), Mixtures C and D would no longer comply whereas, if the test temperature was reduced to 45°C and the maximum limit consequentially revised to 0.7 mm/h, Mixture A would no longer comply. Therefore, the test temperature, as well as the limits set at the temperature, may need to be reviewed when suitable data become available.

4.4 Air voids content

4.4.1 Objective

The air voids content is the second performance-related requirement in Clause 943. Therefore, the initial investigation into the available data was to confirm that the performance-related requirements could be attained in terms of the air voids content as measured.

Clause 943 has separate requirements to check both the deformation resistance and the air voids content of the as-laid material. As a crude model, the wheel-tracking rate and air voids content can both be considered as being inversely proportional to the density of the mixture: the higher the density, the lower the voids and the deformation, provided the mixture is not overfilled with bitumen. Because a considerable amount of joint data has been generated, the opportunity was taken to investigate if the properties are statistically correlated over the ranges measured. If a strong relationship were established, the amount of testing required under the clause could be reduced with the value for one property being inferred from that of the other.

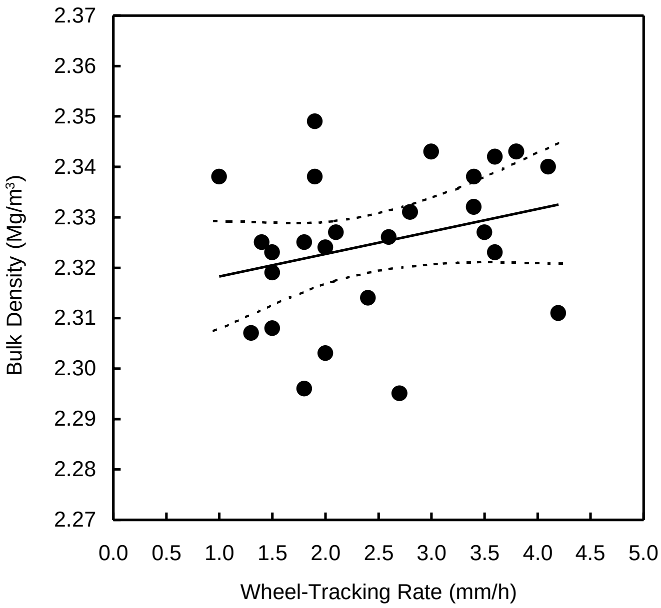
4.4.2 Compliance

Appendix A.2 provides a summary of the results from individual sites for tests carried out. Of the 548 air voids content determinations carried out on cores taken from the actual construction, none of them failed the individual air voids content requirement, giving a 100 per cent overall level of compliance. Of the 482 running means of four air voids content determinations checked in the analysis (although the order of the results used to calculate the running mean may not have been identical with that used on site), there was only one failure to comply with the requirement, giving a 99.8 per cent overall compliance. Hence, the requirement can be met without causing any problems and, if the durability of mixtures with the higher air voids contents was found to be inadequate, the limit could be lowered by, say, 0.5 per cent without making the requirement impractical.

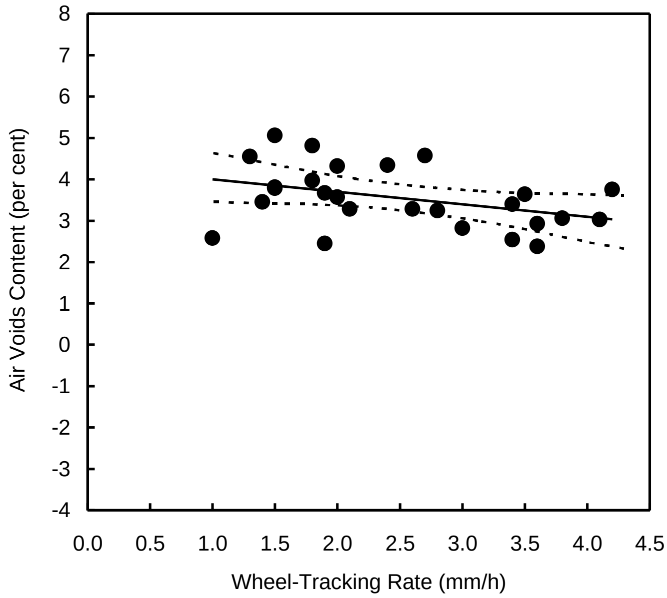
4.4.3 Relationship between wheel-tracking rate and air voids content

Plots were drawn for various trials of the wheel-tracking rates at the specified temperature separately against both the bulk density and the air voids content; linear regression analyses were also carried out on the data. Plots for two of the trials with different correlation coefficients are shown in Figure 5 for bulk density and Figure 6 for air voids content with their regression lines and associated 95 per cent confidence limits.

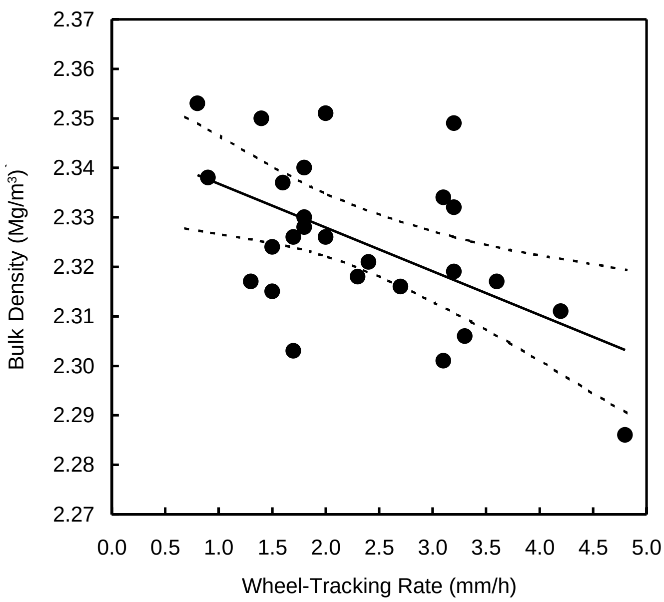
Both plots in Figure 5 show poor correlation, and opposite signs. As can be seen from the plots themselves, the reason for this is that there is no relationship between wheel-tracking rate and bulk density from the available data. However, the range of densities is very limited, so that any variability could easily mask a relationship that might be present with samples having a wide range of bulk densities, which would be needed in order to influence the wheel-tracking rate.



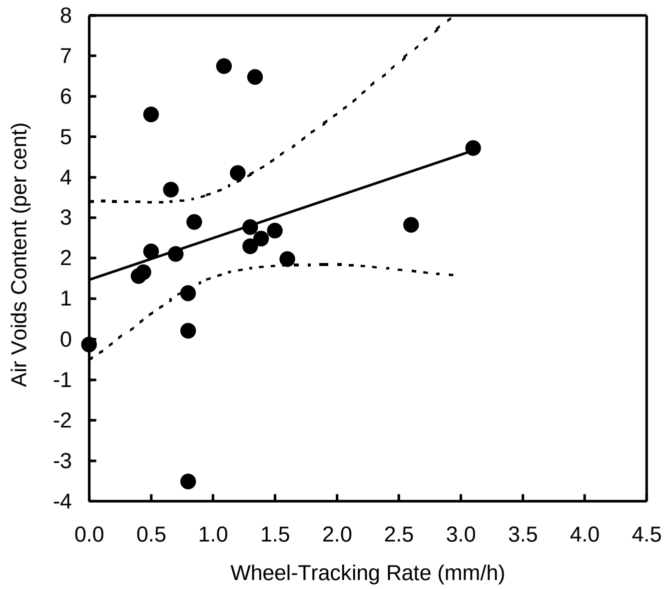
(a) M25, junctions 25 to 26 (correlation coefficient = +0.29)



(a) M25 junctions 25 to 26 (correlation coefficient = -0.39)



(b) A14 Nine Mile Hill (correlation coefficient = -0.54)



(b) M6 junctions 39 to 42 (correlation coefficient = +0.33)

Figure 5 Relationship between wheel-tracking rate and bulk density

Figure 6 Relationship between wheel-tracking rate and air voids content

The lack of correlation is also found between wheel-tracking rate and air voids content (Figure 6), as would be expected because the air voids content is derived from the bulk density. The plot for junctions 25 to 26 of the M25 initially appears to give a reasonable relationship, but this is only because of the narrower range of air void contents. Therefore, it would not be appropriate to restrict the testing to only one of the requirements (wheel-tracking rate or air voids content) even with a specified range rather than a maximum or minimum restriction (say just measure the wheel-tracking rate with a minimum requirement, as well as the current maximum, to try to ensure a minimum air voids content).

4.5 Nuclear density gauge

4.5.1 Objective

The nuclear density gauge was introduced into Clause 943 in order to minimise the amount of destructive testing that would otherwise have been required if the density was to be determined only from cores. As a screening tool, it could identify areas requiring further (destructive) testing to ensure that the required properties had been provided. The analysis of the relationships between the nuclear density gauge readings and each of the principal performance-related criteria, wheel-tracking rate and air voids content, were intended to identify the assurance that can be placed on the use of the nuclear density gauge as a screening tool.

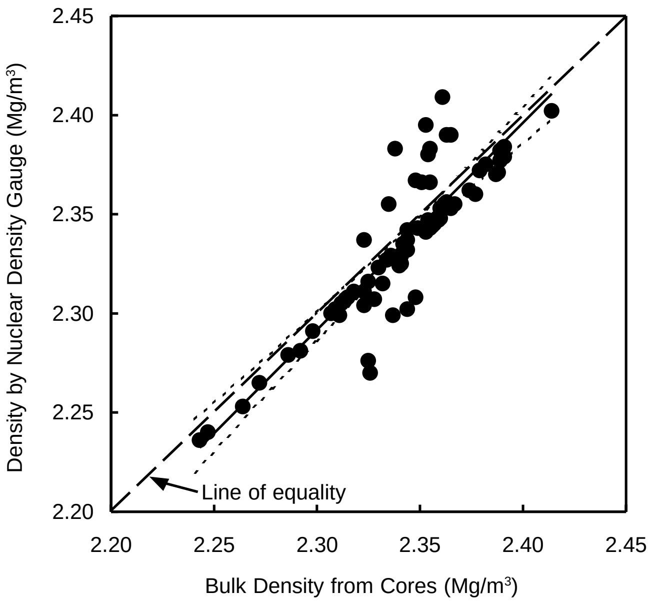
The bulk density can be determined using a nuclear density gauge but the surface of hot rolled asphalt with pre-coated chippings does not offer a suitable smooth surface on which to use it. When Clause 943 was drafted, two methods of providing a smooth surface were considered, these being to leave areas of the surface unchipped or to apply a thin bed of sand (just enough to cover the high spots from the chippings). Therefore, the effectiveness of these approaches needed to be assessed, with a pragmatic preference for the sand approach because the alternative will leave localised areas without the required texture.

The assessment was also intended to validate the use of the equipment for measuring the density of the surface layer. The nuclear density gauge in backscatter mode is largely influenced by the material closest to the gauge, but it is also influenced to some extent by the material underlying the wearing course. This influence, which can be minimised with a thin lift gauge, should be calibrated out providing the underlying layers are consistent across the works.

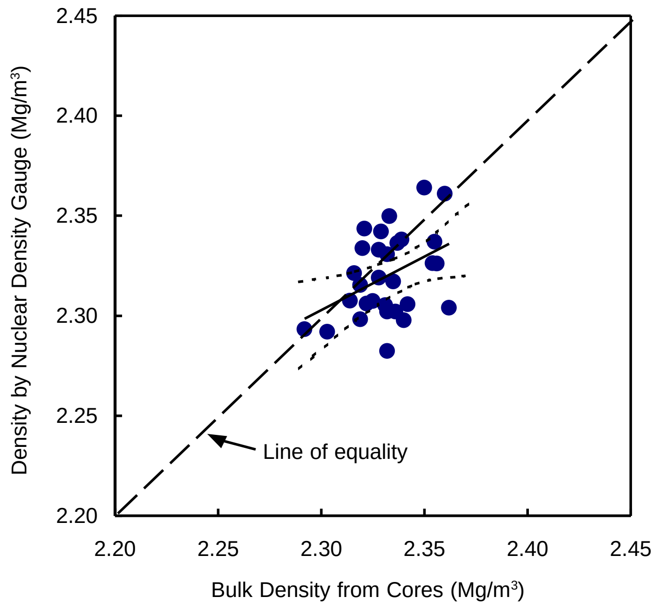
4.5.2 Calibration accuracy

Separate plots for the various trials were made of the relationships between the bulk density measured from cores and the density determined using the nuclear density gauge where both measurements had been made at approximately the same location. Two examples are shown in Figure 7 (with one extreme outlier omitted) with the nuclear density gauge measurements being made with the gauge on a bed of sand. The line of equality is also shown to indicate where the points should lie if both methods always gave the same result.

It can be seen that there is a relationship between the two methods, but that the limited range of density values can mask it, as in Figure 7(b). Nevertheless, regression analyses were carried out to quantitatively assess the relationship between the bulk density determined from cores and the results obtained from the nuclear density gauge. If there was total correlation between the density determined by the two methods, there would be an intercept of zero and a slope of unity. For most trials, the intercept was positive and the slope less than unity, which indicates that the calibration procedure carried out on the nuclear density gauges should have been more rigorous to avoid the gauge consistently underestimating the average density. This impression of imprecise calibration is reinforced by the mean correlation coefficient of 0.71 only accounting for about half the uncertainty. Some of the remaining uncertainty can be explained by the repeatability of the density test method, although none is given in BS 598: Part 104 (BSI, 1989), and possible lack of correlation of the correct nuclear density gauge reading with core sample. However, it appears probable that improvements in the equipment (such as restricting the use to thin-lift gauges only) or in the testing and calibration procedures could be beneficial.



(a) M25 J6 to J8, London Roadstone (correlation coefficient = +0.88)



(b) A14 Bury St Edmonds (correlation coefficient = +0.31, -0.09 including outlier off graph)

Figure 7 Relationship between bulk density of cores and nuclear density gauge readings

4.5.3 Test surface on which to operate nuclear density gauges

The use of local areas of unchipped hot rolled asphalt on which to measure the density by nuclear density gauge was only carried out at three trials; both the A21 trials and the trial on the A14 at Risby, although there were only two joint core/nuclear density gauge readings taken on the A14. The results from the A21, taken in isolation, indicated that an unchipped area was preferable to a bed of sand, mainly because of poorer correlation with the measurements from cores for the EVA mixture when the nuclear density gauge was on a bed of sand than on unchipped areas. However, the mean correlation with the gauge on a bed of sand (Section 4.5.2) is mildly encouraging and noticeably better than the relatively low correlation coefficients obtained on the A21 trials. Therefore, given the associated problems of leaving unchipped areas in the mat, the use of a sand bed should remain the preferred method.

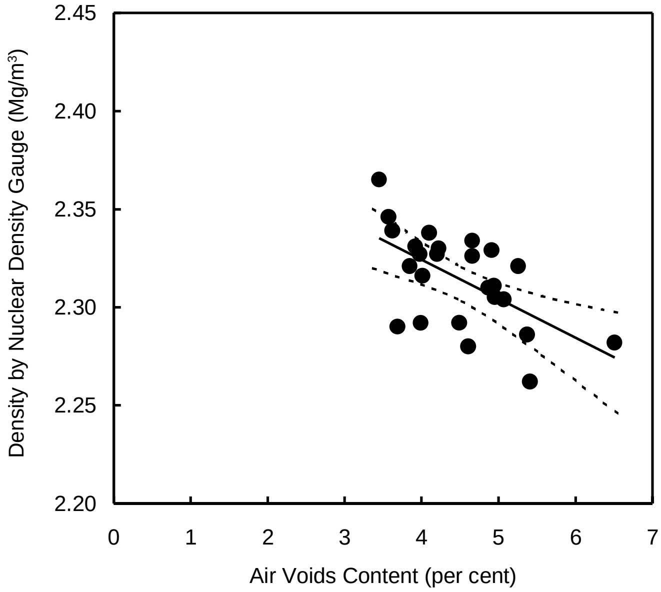
4.5.4 Identification in changes of properties by nuclear density gauge

The relationships between wheel-tracking rate and bulk density (Section 4.4.3) showed very limited correlation, and this was repeated for the analysis between wheel-tracking rate and density by nuclear density gauge. Therefore, it was not considered appropriate to describe the analysis further.

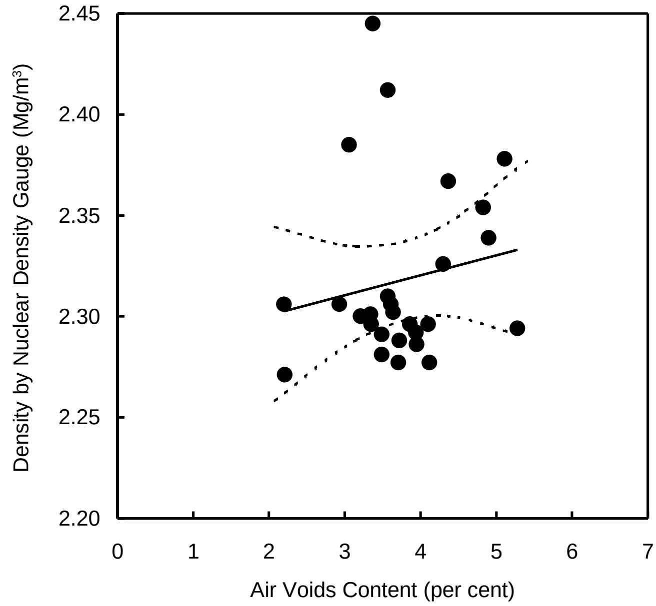
Nevertheless, plots were prepared and linear regression analyses carried out to identify if there were any relationships between the air voids content and the nuclear density gauge readings made with the gauge on a bed of sand; an illustrative plot is shown in Figure 8.

The plots in Figure 8 of air voids content and nuclear density gauge readings have correlation coefficients with different signs, showing the wide range of relationships found (-0.80 to +0.77). The extremely poor mean correlation coefficient showed that the analysis of the available data does not support the hypothesis that the nuclear density gauge is capable of monitoring the change in air voids content of the mat. However, the relative narrow range of density values and the (unknown) precision for density measurements means that the information collected here does not necessarily prove that the nuclear density gauge will not identify significant changes in the required parameters, should they occur.

Nevertheless, whilst the hypotheses is unproven that the nuclear density can identify changes in the air voids content (or the wheel-tracking rate), it is preferable to retain the use of the gauges as a screening tool, at least until evidence that they cannot identify significant changes, because the only alternative, that of taking more cores, is destructive.



(a) M11 junctions 9 to 10 (correlation coefficient = -0.60)



(b) A21 Multiphalte (correlation coefficient = +0.17)

Figure 8 Relationship between air voids content and nuclear density gauge readings

5 Monitoring

5.1 Repeat assessments of skid resistance, texture depth and visual condition

The A21 Sevenoaks bypass trials, constructed in November 1995, were monitored three times in both 1996 and 1997 by Sideway-force Coefficient Routine Investigatory Machine (SCRIM) fitted with a laser to determine the sensor-measured texture depth (SMTD). SCRIM uses a wheel running at an angle to the direction of travel following a controlled jet of water in order to measure the skid-resistance of the wetted road surface whilst SMTD is a measurement of the root-mean square (rms) of the variation in texture depth and, as such, measures a slightly different property to the sand-patch test.

Because some of the other early trials were constructed without concurrently laid control sections, only the A21 trials were monitored in this way. The trials were also visited by an independent Inspection Panel in August 1996 and 1997. Again, other early trials were not monitored, this time because of the difficulty in getting access for the Inspection Panel on motorways. The results of all three measurements are given in Table 9.

The main reason that relatively low Inspection Panel ratings were given was chipping loss, which was variable; further, some parts of all sections would have attained better ratings if they had been assessed separately. The loss of chippings was not necessarily associated with the specification, although the control sections remained in good condition, but the occurrence of the fault in such a high profile situation is of concern. The chipping loss may

Table 9 Change in surface properties with time for A21 trials

		Northbound carriageway		*Southbound carriageway*	
Property	*Year of measurement*	*North end (Control)*	*South end (Multiphalte)*	*North end (Control)*	*South end (EVA)*
Mean-Summer	1996	0.41	0.41	0.42	0.41
SCRIM Coefficient	1997	0.45	0.45	0.46	0.45
Sensor-Measure Texture	1996	1.26	1.34	1.42	1.55
Depth by SCRIM (mm)	1997	1.24	1.32	1.37	1.51
SMTD by HSV* (mm)	1997	1.27	1.38	1.27	1.49
Inspection	August 1996	*G*	*G/M*	*G*	*G/M*
Panel Rating	August 1997	*G*	*G/M*$_{-}$	*G/M*$_{-}$	*M/A*$_{-,v}$

Inspection panel marking system (Nicholls, 1997)	*E* = Excellent	*S* = Suspect
	G = Good	*P* = Poor
	M = Moderate	*B* = Bad
	A = Acceptable	
Suffixes	– = loss of chippings	*v* = variable

** Included for comparison, see Section 5.2.1*

also account for the higher texture depths values obtained on the southbound trial section.

5.2 Properties after two years

5.2.1 Survey

Whilst the analysis of the compliance test results demonstrates that Clause 943 is practicable and can ensure that the wearing course has certain laboratory properties, it does not ensure the road surface will not deform under traffic or suffer from loss of chippings. Many existing surfacings for which Clause 943 was not specified have not deformed prematurely, so that the ultimate demonstration of the effectiveness of Clause 943 will be the consistency with which Clause 943 has not deformed after, say, 10 or 15 years in service. Nevertheless, some indication can be obtained from measuring any ruts at an earlier stage on a limited number of trials.

Therefore, a survey of some of the early trials (both carriageways of the A21 Sevenoaks bypass, the M11 Junctions 9 to 10 and Junctions 12 to 14 and the M25 Junctions 6 to 8) was carried out in October 1997 using the high-speed survey vehicle (HSV), a development of the high-speed road monitor (HRM). The trials on the different roads had different types of control sections:

- the A21 had conventional, non-performance-related hot rolled asphalt;
- the M11 had existing hot rolled asphalt that had not deformed sufficiently to warrant replacement when the work was undertaken; and
- the M25 had sections of porous asphalt, a material generally regard as deformation resistant because of the aggregate interlock.

The survey was primarily devised to measure any rutting in Lane 1 on the sites after they had generally experienced two summers of trafficking but the opportunity was also taken to measure the sensor-measured texture depth and the 3 m, 10 m and 30 m profile variances. The statistics for the results from each 10 m sub-section length of the trial sites are given in Appendix B (in which the number in Section B.1 was the number of section lengths) with a summary, other than for the 30 m variances, in Table 10. The individual results are discussed in the following sections.

5.2.2 Rut depth

The transverse profile measured by the HSV is the average difference between the level in the two wheel-paths and the surrounding surfacing; it is critical to ensure that the HSV is driven in the wheel-paths to obtain a correct reading. Although the values of rut depth are often reported as negative when the level of the wheel-path is lower than that of the surrounding material, in this report a positive value of rut depth indicates a positive deformation. Hence, a negative rut depth indicates that the level of the wheel-path is higher than that of the surrounding material. However, the measurements recorded as the rut depth are not necessarily all caused by permanent deformation because no attempt has been made to deduct any initial irregularities that could be provide a positive or negative 'initial rut depth'. Nevertheless, the measured values can be used as a surrogate for rut depth providing the rut depths are significantly greater than any potential initial irregularities. The measured deformations are summarised in Appendix B.1.

The rut depths on the A21 were relatively shallow, with the average on the southbound trial section actually being effectively zero and that for the northbound trial and control sections being no greater than 0.5 mm. At this stage given the uncertainty as to initial profile, the values do not indicate that the performance-related specification is any different to the recipe specification. However, differences were not expected at this stage in the life of the surfacings because the recipe specification has produced many surfacings that have not rutted, as well as some that did.

The rut depths on the M11 were generally greater, both for the existing sections and the new, performance-related materials, although most were still within Category 0 (Sound, no visible distress) according to Table 2.2 of

Table 10 Summary of high-speed survey vehicle results

Trial		Rut dept		n/s texture depth		o/s texture depth	
		Mean (mm)	Std dev (mm)	Mean (mm)	Std dev (mm)	Mean (mm)	Std dev (mm)
A21	Cl. 943 n/b	0.5	0.7	1.5	0.2	1.5	0.2
	Cl. 943 s/b	-0.1	0.9	1.3	0.3	1.4	0.2
	Control	0.6	0.6	1.2	0.2	1.3	0.2
M11 J9-J10	Cl. 943	2.2	1.0	1.4	0.2	1.3	0.2
	Existing	2.6	1.3	1.1	0.2	1.1	0.2
M11 J12-J14	Cl. 943	1.3	0.9	1.4	0.5	1.4	0.3
	Existing	3.1	1.0	1.5	0.5	1.6	0.2
M25	Cl. 943	1.5	0.6	0.9	0.2	1.2	0.2
	Porous asphalt	2.8	1.6	0.9	0.1	1.1	0.1

Trial		3 m Variance			10 m Variance		
		Mean (mm^2)	Std dev (mm^2)	Category*	Mean (mm^2)	Std dev (mm^2)	Category*
A21	Cl. 943 s/b	1.5	0.7	0.82	3.2	1.7	0.09
	Cl. 943 n/b	1.1	0.7	0.29	2.6	3.2	0.16
	Control	0.9	0.4	0.02	2.6	1.5	0.02
M11 J9-J10	Cl. 943	1.1	0.5	0.23	2.8	1.8	0.09
	Existing	0.7	0.3	0.01	1.9	1.1	0
M11 J12-J14	Cl. 943	1.1	0.7	0.35	3.0	3.8	0.16
	Existing	1.1	0.5	0.19	3.4	2.3	0.26
M25	Cl. 943	0.9	0.5	0.13	2.8	2.3	0.14
	Porous asphalt	0.6	0.5	0.03	2.9	2.8	0.19

**Mean category for 100 m lengths to Table 2.3(a) of HD 29/94 (DMRB 7.3.2) for motorways and dual carriageways using running means of the 10 m sub-section lengths.*

HD 29/94 (DMRB 7.3.2), reproduced in Table 11. The average values of both materials were very similar on the Junction 9 to 10 section, as were those for the existing materials on the other section, whilst the Clause 943 material on the Junction 12 to 14 section was significantly less. However, the size of these deformations are still relatively small given the uncertainty as to the initial profile which is included in the values.

The rut depths on the M25 were, surprisingly, less for the performance-related hot rolled asphalt than the porous asphalt of approximately the same age. The deformation in the Clause 943 hot rolled asphalt averaged 1.5 mm, similar to that on the M11 between Junctions 12 to 14, which is relatively limited in that, if the deformation continued at that rate for twenty, rather than two, years, the final rut would be 15 mm. However, the rate of development of deformation normally reduces with time (Nicholls, 1998). The majority of the deformation in the porous asphalt, if it was not due to the initial performance, could have occurred in the basecourse layer. This exemplifies the concern that, to minimise permanent deformation, all the surfacing layers need to be rut resistant, with the requirement being greater nearer the surface.

5.2.3 Sensor-measured texture depth

Sensor-measured texture depth (SMTD) is a measurement of the root-mean square (rms) of the variation in texture depth and, as such, measures a slightly different property to the sand-patch test. The measured sensor-measured texture depths, summarised in Appendix B.2, are all in

Table 11 Defect categories for high-speed road monitor data from HD 29/94 (DMRB 7.3.2)

Property	*Table in HD 29/94*	*Category 0*	*Category 1*	*Category 2*	*Category 3*
Rutting	2.2	< 5 mm	5 - 10 mm	10 - 20 mm	> 20 mm
SMTD	2.2	> 1.0 mm	1.0 - 0.5 mm	> 0.5 mm	-
3 m Variance*	2.3(a)	< 1.25 mm^2	1.25 - 3.75 mm^2	3.75 - 7.5 mm^2	> 7.5 mm^2
10 m Variance*	2.3(a)	< 4 mm^2	4 - 16 mm^2	16 - 36 mm^2	> 36 mm^2
30 m Variance*	2.3(a)	<55 mm^2	55 - 165 mm^2	165 - 275 mm^2	> 275 mm^2

**For motorways and dual carriageways; different criteria for other types of road.*

Category 0 (Sound, no visible distress) or Category 1 (visible distress, lower level of concern) in accordance with Table 2.2 of HD 29/94 (DMRB 7.3.2) and do not indicate any significant difference between the Clause 943 hot rolled asphalt and the other sections. The low texture depth of the porous asphalt, for which initial texture depth is not required in the *Specification for Highway Works* (MCHW 1), is due to the measurement being sensor-measured rather than sand-patch, with ratio of sand-patch to sensor-measured being greater for porous asphalt than hot rolled asphalt.

5.2.4 Profile variance

The results of the measured 3 m, 10 m and 30 m variances, summarised in Appendix B.3, are generally marginally greater for the Clause 943 hot rolled asphalt than the control or existing material for the variance over each length. However, all the results are within the Category 0 (sound, no visible distress) or Category 1 (visible distress, lower level of concern) levels for in-service roads for motorways and dual carriageways (DMRB 7.3.2). The greater variance may be due to:

- the unevenness of the existing surfaces before the new wearing course was applied; and/or
- the material being relatively ‘stiffer’ and harder to work in order to produce an even profile.

5.3 Noise

Currently, the noise generated on roads is becoming increasingly important. The selection of porous asphalt for a wearing course is usually justified on the reduced noise that will be generated, and most of the proprietary thin surfacings are advertised to give reduced noise relative to hot rolled asphalt with pre-coated chippings. Therefore, it is interesting that there have been several reports of the high performance hot rolled asphalt being quieter that traditional mixtures, although the observations are all subjective.

The possible explanation for the reduced noise is that, with a maximum air voids content requirement, the contractor needs to ensure that a sufficient degree of compaction has been provided. With this compaction, there should be better chipping embedment and less chance of chippings being excessively proud of the surface. However, in order to confirm the subjective observations, some relative measurements of noise will be needed on hot rolled asphalts of the same age that were laid to the new and old specification requirements. However, this explanation implies that the texture depth is likely to be less, which was not found to be the case (Section 5.2.3).

6 Conclusions

The overall success of draft specification Clause 943 will be determined by the long-term performance of the trials. However, the principal conclusions that can be drawn from the results obtained to date are as follows:

1 Hot rolled asphalt which complies with both the wheel-tracking and air voids content requirements of draft Clause 943 can be, and has been, laid successfully.

2 Hot rolled asphalt to draft Clause 943 can be produced to comply with the compositional requirements of BS 594: Part 1. There are some indications that the material suppliers are maintaining tighter tolerances in order to ensure that the specified properties are achieved consistently.

3 The analysis method by ignition can be used successfully by materials suppliers to monitor compositional compliance.

4 The specification limits are consistent within themselves; however, the trials have not been in place long enough to ensure that the levels are fully appropriate.

5 The available statistics do not support the assumption that the nuclear density gauge can be effectively used as a screening device to indicate variations in the air voids content or the wheel-tracking rate.

6 The accuracy of the nuclear density gauge is not unduly influenced by whether it is used to take measurements when on a bed of sand or on areas of the surfacing that have been left unchipped. However, given the practical difficulties of restoring texture to unchipped areas, the bed of sand procedure is considered preferable.

7 Acknowledgements

The work described in this paper was carried out in the Civil Engineering Resource Centre (Resource Centre Manager Mr P G Jordan) of the Transport Research Laboratory with Mr J C Nicholls as Project Manager and Mr J F Potter as Quality Audit and Review Officer. The assistance of the various Regional Offices of the Highway Agency, their agents and the contractors in providing data, sometimes over and above that actually requested, is gratefully acknowledged.

8 References

Manual of Contract Documents for Highway Works. Stationery Office, London.

Volume 1: Specification for Highway Works (MCHW 1).

Volume 2: Notes for Guidance on the Specification for Highway Works (MCHW 2).

Design Manual for Roads and Bridges. (DMRB) Stationery Office, London.

HD 29/94: Structural Assessment Methods (DMRB 7.3.2).

British Standards Institution (1989). *Sampling and examination of bituminous mixtures for roads and other paved areas; Part 104, Methods of test for the determination of density and compaction*. BS 598: Part 104: 1989. British Standards Institution, London.

British Standards Institution (1990). *Sampling and examination of bituminous mixtures for roads and other paved areas; Part 107, Method of test for the determination of the composition of design wearing course rolled asphalt.* BS 598: Part 107: 1990. British Standards Institution, London.

British Standards Institution (1992). *Hot rolled asphalts for roads and other paved areas; Part 1, Specification for constituent materials and asphalt mixtures; Part 2, Specification for transport, laying and compaction of rolled asphalt.* BS 594: Part 1: 1992, BS 594: Part 2: 1992. British Standards Institution, London.

British Standards Institution (1996). *Sampling and examination of bituminous mixtures for roads and other paved areas; Part 110, Methods of test for the determination of the wheel-tracking rate of cores of bituminous wearing courses*. BS 598: Part 110: 1996. British Standards Institution, London.

Daines M E (1995). *Tests for voids and compaction in rolled asphalt surfacings.* Project Report PR78. Transport Research Laboratory, Crowthorne.

Mercer J and Nicholls J C (1997). *Binder requirements for performance-related specification of rolled asphalt.* 2nd European Symposium on Performance and Durability of Bituminous Materials, University of Leeds (Editor J G Cabrera). Aedificatio Publishers, Zurich.

Nicholls J C (1994). *Assessment of multiphalte, the Shell multigrade bitumen.* Project Report PR61. Transport Research Laboratory, Crowthorne.

Nicholls J C (1997). *Laboratory tests on high-friction surfaces for highways: Appendix R, procedure for visual assessment of trial sites*. TRL Report TRL176. Transport Research Laboratory, Crowthorne.

Nicholls J C (1998). *Results from the trial of modified rolled asphalts on the A38 Burton Bypass.* The Asphalt Yearbook 1998. The Institute of Asphalt Technology, Stanwell.

Whiteoak C D and Nicholls J C (1998). *Performance-related specification of HRA wearing course for heavily trafficked roads.* The Asphalt Yearbook 1998. The Institute of Asphalt Technology, Stanwell.

Appendix A: Summary of results from compliance test

A.1 Wheel-tracking results on cores removed from the pavement

		Wheel-tracking @ 45°C		*Wheel-tracking @ 60°C*	
		Rate (mm/h)	*Depth (mm)*	*Rate (mm/h)*	*Depth (mm)*
M5 J22,	Number	32	0	11	0
Somerset	Mean	0.5		3.9	
(const.)	Std. Dev.	0.3		1.9	
	Range	0.0 to 1.3		1.8 to 6.8	
A21,	Number	12	12	6	6
Sevenoaks	Mean	0.5	1.2	9.8	8.3
(n/b trial)	Std. Dev.	0.2	0.6	1.9	1.6
	Range	0.3 to 0.8	0.6 to 2.1	6.9 to 12.9	5.6 to 10.5
A21,	Number	10	10	3	3
Sevenoaks	Mean	0.4	2.1	7.4	8.1
(n/b const.)	Std. Dev.	0.2	1.2	4.3	4.3
	Range	0.2 to 0.6	0.6 to 3.5	2.9 to 11.4	3.6 to 12.1
A21,	Number	22	22	9	9
Sevenoaks	Mean	0.4	1.6	9.0	8.3
(northbound	Std. Dev.	0.2	1.0	2.9	2.5
combined)	Range	0.2 to 0.8	0.6 to 3.5	2.9 to 12.9	3.6 to 12.1
A21,	Number	12	12	6	6
Sevenoaks	Mean	2.3	2.0	14.9	16.1
(s/b trial)	Std. Dev.	0.5	0.6	2.3	2.7
	Range	1.5 to 2.9	1.3 to 3.6	10.7 to 17.2	11.9 to 19.2
A21,	Number	9	9	3	3
Sevenoaks	Mean	0.7	1.2	4.9	4.3
(s/b const.)	Std. Dev.	0.2	0.4	3.0	3.3
	Range	0.3 to 1.2	0.5 to 1.8	2.3 to 8.1	1.5 to 8.0
A21,	Number	21	21	9	9
Sevenoaks	Mean	1.6	1.7	11.5	12.2
(southbound	Std. Dev.	0.9	0.7	5.5	6.5
combined)	Range	0.3 to 2.9	0.5 to 3.6	2.3 to 17.2	1.5 to 19.2
A14,	Number	6	6	6	6
Copdock	Mean	0.5	1.2	5.7	6.2
Mill	Std. Dev.	0.1	0.3	2.0	1.4
(trial)	Range	0.4 to 0.6	0.8 to 1.5	3.7 to 8.4	4.5 to 8.0
A14,	Number	8	8	0	0
Copdock	Mean	0.5	1.3		
Mill	Std. Dev.	0.2	0.3		
(const.)	Range	0.3 to 0.8	0.9 to 1.7		
A14,	Number	14	14	6	6
Copdock	Mean	0.5	1.3	5.7	6.2
Mill	Std. Dev.	0.1	0.3	2.0	1.4
(combined)	Range	0.3 to 0.8	0.8 to 1.7	3.7 to 8.4	4.5 to 8.0
M6 J15-J14,	Number	18	18	36	36
Staffs	Mean	0.5	1.3	3.6	4.7
(trial)	Std. Dev.	0.2	0.5	1.6	1.7
	Range	0.1 to 1.1	0.7 to 2.1	1.1 to 6.3	1.7 to 8.6
M6 J15-J14,	Number	18	18	28	28
Staffs	Mean	0.4	1.0	2.5	3.6
(const.)	Std. Dev.	0.3	0.4	1.6	1.6
	Range	0.0 to 1.0	0.3 to 1.7	0.4 to 6.1	1.1 to 7.5

Continued ....

A.1 Wheel-tracking results on cores removed from the pavement — Continued

		Wheel-tracking @ 45°C		*Wheel-tracking @ 60°C*	
		Rate (mm/h)	*Depth (mm)*	*Rate (mm/h)*	*Depth (mm)*
M6 J15-J14, Staffs (combined)	Number	36	36	64	64
	Mean	0.4	1.1	3.1	4.2
	Std. Dev.	0.3	0.5	1.7	1.7
	Range	0.0 to 1.1	0.3 to 2.1	0.4 to 6.3	1.1 to 8.6
M6 J39-J42, Cumbria (target binder content)	Number	12	12	6	6
	Mean	0.8	1.4	5.8	7.1
	Std. Dev.	0.4	1.0	0.9	1.0
	Range	0.0 to 1.4	0.2 to 3.3	4.9 to 7.2	6.0 to 8.4
M6 J39-J42, Cumbria (target plus 0.35%)	Number	6	6	0	0
	Mean	1.2	2.6		
	Std. Dev.	0.2	0.4		
	Range	0.8 to 1.3	2.1 to 3.1		
M6 J39-J42, Cumbria (const.)	Number	18	18	0	0
	Mean	1.3	1.5		
	Std. Dev.	0.8	1.0		
	Range	0.0 to 3.1	0.5 to 4.2		
M6 J39-42, Cumbria (combined)	Number	36	36	6	6
	Mean	1.1	1.7	5.8	7.1
	Std. Dev.	0.6	1.0	0.9	1.0
	Range	0.0 to 3.1	0.2 to 4.2	4.9 to 7.2	6.0 to 8.4
M11 J9-10, Cambs (trial)	Number	0	0	32	14
	Mean			4.4	5.2
	Std. Dev.			1.5	1.7
	Range			2.1 to 7.7	2.8 to 7.6
M11 J9-10, Cambs (const.)	Number	7	0	47	47
	Mean	1.4		3.8	4.7
	Std. Dev.	1.0		1.1	1.0
	Range	0.6 to 3.3		1.8 to 6.2	2.0 to 7.4
M11 J9-10, Cambs (combined)	Number	7	0	79	61
	Mean	1.4		4.0	4.8
	Std. Dev.	1.0		1.3	1.2
	Range	0.6 to 3.3		1.8 to 7.7	2.0 to 7.6
M11 J12-14, Cambs.	Number	0	0	30	30
	Mean			4.2	4.6
	Std. Dev.			1.2	1.2
	Range			1.9 to 7.4	2.5 to 7.8
M25 J6-J8, Reigate (Bardon Aggregates)	Number	0	0	63	63
	Mean			2.7	3.8
	Std. Dev.			1.6	1.4
	Range			0.4 to 7.9	1 to 7
M25 J6-J8, Reigate (London Roadstone)	Number	0	0	9	9
	Mean			3.1	3.9
	Std. Dev.			0.8	0.6
	Range			2.0 to 4.0	3 to 5
M25 J6-J8, Reigate (combined)	Number	0	0	72	72
	Mean			2.8	3.8
	Std. Dev.			1.5	1.3
	Range			0.4 to 7.9	1.0 to 7.0
A14, Godman-chester	Number	0	0	8	8
	Mean			2.2	3.0
	Std. Dev.			0.7	1.2
	Range			1.5 to 3.3	1.5 to 5.3

Continued ....

A.1 Wheel-tracking results on cores removed from the pavement — Continued

		Wheel-tracking @ 45°C		*Wheel-tracking @ 60°C*	
		Rate (mm/h)	*Depth (mm)*	*Rate (mm/h)*	*Depth (mm)*
A14, Ouse River Bridges	Number	0	0	8	8
	Mean			2.1	2.8
	Std. Dev.			0.8	0.8
	Range			1.1 to 3.7	1.4 to 4.0
M6 J10-10A, Staffs (trial)	Number	0	0	12	12
	Mean			2.1	3.4
	Std. Dev.			0.6	0.7
	Range			1.0 to 2.9	2.4 to 4.7
M6 J10-10A, Staffs (const.)	Number	0	0	12	12
	Mean			1.2	2.0
	Std. Dev.			0.5	0.6
	Range			0.3 to 2.0	1.1 to 3.2
M6 J10-10A, Staffs (combined)	Number	0	0	24	24
	Mean			1.6	2.7
	Std. Dev.			0.7	1.0
	Range			0.3 to 2.9	1.1 to 4.7
A14, Risby to Topstock	Number	0	0	15	15
	Mean			1.4	2.5
	Std. Dev.			0.5	1.0
	Range			0.7 to 2.5	1.6 to 5.1
M25 J25-26, Essex (trials)	Number	6	6	12	12
	Mean	0.2	1.6	4.2	5.3
	Std. Dev.	0.1	0.2	0.6	0.6
	Range	0.1 to 0.2	1.4 to 1.8	2.9 to 4.8	4.2 to 6.2
M25 J25-26, Essex (Northfleet plant)	Number	0	0	19	19
	Mean			2.2	3.4
	Std. Dev.			0.8	0.9
	Range			1.0 to 4.1	1.8 to 4.8
M25 J25-26, Essex (Greys plant)	Number	0	0	7	7
	Mean			3.4	5.4
	Std. Dev.			0.5	1.0
	Range			2.6 to 4.2	4.2 to 6.7
M25 J25-26, Essex (combined const.)	Number	0	0	26	26
	Mean			2.5	4.0
	Std. Dev.			1.0	1.3
	Range			1.0 to 4.2	1.8 to 6.7
M25 J25-26, Essex (combined)	Number	6	6	38	38
	Mean	0.2	1.6	3.0	4.4
	Std. Dev.	0.1	0.2	1.2	1.3
	Range	0.1 to 0.2	1.4 to 1.8	1.0 to 4.8	1.8 to 6.7
A14, Girton to Hemming-ford	Number	0	0	11	0
	Mean			1.8	
	Std. Dev.			1.3	
	Range			0.5 to 5.2	
A14, Kentford to Nine Mile Hill	Number	0	0	27	0
	Mean			2.3	
	Std. Dev.			1.0	
	Range			0.8 to 4.8	
A12, Coles Oak Bridge	Number	0	0	8	8
	Mean			2.6	3.2
	Std. Dev.			0.7	0.6
	Range			1.6 to 3.4	2.4 to 4.1

Continued ....

A.1 Wheel-tracking results on cores removed from the pavement — Continued

		Wheel-tracking @ 45°C		*Wheel-tracking @ 60°C*	
		Rate (mm/h)	*Depth (mm)*	*Rate (mm/h)*	*Depth (mm)*
A14, Bury St. Edmonds to Kentford	Number	0	0	15	15
	Mean			1.1	2.1
	Std. Dev.			0.3	0.3
	Range			0.8 to 1.6	1.5 to 2.8
M6 J7-J8, Midland Link	Number	0	0	12	12
	Mean			1.9	3.0
	Std. Dev.			0.2	0.2
	Range			1.7 to 2.2	2.7 to 3.4
A127, Halfway House (trial)	Number	6	6	11	11
	Mean	0.8	1.8	2.7	4.0
	Std. Dev.	0.4	0.4	1.0	1.1
	Range	0.5 to 1.6	1.3 to 2.3	1.4 to 4.8	2.8 to 6.2
A127, Halfway House (const.)	Number	0	0	10	10
	Mean			2.2	3.3
	Std. Dev.			0.8	0.9
	Range			0.3 to 3.0	1.9 to 5.1
A127, Halfway House (combined)	Number	6	6	21	21
	Mean	0.8	1.8	2.5	3.7
	Std. Dev.	0.4	0.4	0.9	1.0
	Range	0.5 to 1.6	1.3 to 2.3	0.3 to 4.8	1.9 to 6.2

A.2 Density and air void results

		Density (Mg/m^3)		Air voids	NDG density (Mg/m^3)	
		Bulk	*Max. theoretical*	*(per cent)*	*On sand*	*On flat*
M5 J22, Somerset (const.)	Number	43	43	43	0	0
	Mean	2.31	2.38	3.3		
	Std. Dev.	0.02	0.01	0.7		
	Range	2.27 to 2.34	2.36 to 2.40	1.9 to 4.9		
A21, Sevenoaks (n/b trial)	Number	18	18	18	18	18
	Mean	2.38	2.44	2.8	2.26	2.29
	Std. Dev.	0.01	0.01	0.6	0.03	0.03
	Range	2.36 to 2.40	2.41 to 2.46	1.0 to 3.6	2.19 to 2.30	2.23 to 2.35
A21, Sevenoaks (n/b const.)	Number	13	13	13	12	0
	Mean	2.38	2.45	3.1	2.38	
	Std. Dev.	0.02	0.02	0.6	0.04	
	Range	2.34 to 2.40	2.42 to 2.47	2.2 to 4.0	2.33 to 2.45	
A21, Sevenoaks (northbound combined)	Number	31	31	31	30	18
	Mean	2.38	2.45	2.9	2.31	2.29
	Std. Dev.	0.02	0.01	0.6	0.07	0.03
	Range	2.34 to 2.40	2.41 to 2.47	1.0 to 4.0	2.19 to 2.45	2.23 to 2.35
A21, Sevenoaks (s/b trial)	Number	18	18	18	18	18
	Mean	2.36	2.45	3.6	2.29	2.33
	Std. Dev.	0.02	0.01	0.7	0.01	0.02
	Range	2.31 to 2.40	2.43 to 2.47	2.2 to 5.3	2.27 to 2.31	2.30 to 2.36
A21, Sevenoaks (s/b const.)	Number	12	12	12	38	0
	Mean	2.38	2.48	4.2	2.39	
	Std. Dev.	0.02	0.01	0.7	0.04	
	Range	2.35 to 2.41	2.46 to 2.50	3.1 to 5.1	2.31 to 2.51	
A21, Sevenoaks (southbound combined)	Number	30	30	30	56	18
	Mean	2.37	2.46	3.8	2.36	2.33
	Std. Dev.	0.02	0.02	0.8	0.06	0.02
	Range	2.31 to 2.41	2.43 to 2.50	2.2 to 5.3	2.27 to 2.51	2.30 to 2.36
A14, Copdock Mill (trial)	Number	6	6	6	18	0
	Mean	2.37	2.43	2.6	2.36	
	Std. Dev.	0.01	0.01	0.5	0.02	
	Range	2.36 to 2.39	2.42 to 2.44	1.9 to 3.2	2.32 to 2.41	
A14, Copdock Mill (const.)	Number	16	16	16	56	0
	Mean	2.39	2.42	1.5	2.37	
	Std. Dev.	0.01	0.01	0.5	0.02	
	Range	2.36 to 2.41	2.40 to 2.44	0.8 to 2.6	2.30 to 2.42	
A14, Copdock Mill (combined)	Number	22	22	22	74	0
	Mean	2.38	2.42	1.8	2.37	
	Std. Dev.	0.02	0.01	0.7	0.03	
	Range	2.36 to 2.41	2.40 to 2.44	0.8 to 3.2	2.30 to 2.42	
M6 J15-J14, Staffs (trial)	Number	18	9	18	18	0
	Mean	2.35	2.43	3.2	2.29	
	Std. Dev.	0.02	0.01	1.2	0.06	
	Range	2.31 to 2.38	2.41 to 2.45	1.9 to 5.6	2.21 to 2.40	
M6 J15-J14, Staffs (const.)	Number	38	38	38	12	0
	Mean	2.35	2.45	4.3	2.27	
	Std. Dev.	0.03	0.02	1.0	0.03	
	Range	2.30 to 2.40	2.42 to 2.50	2.2 to 6.3	2.21 to 2.31	
M6 J15-J14, Staffs (combined)	Number	56	47	56	30	0
	Mean	2.35	2.45	3.9	2.29	
	Std. Dev.	0.02	0.02	1.2	0.05	
	Range	2.30 to 2.40	2.41 to 2.50	1.9 to 6.3	2.21 to 2.40	

Continued ....

A.2 Density and air void results — Continued

		Density (Mg/m³)		*Air voids*	*NDG density (Mg/m³)*	
		Bulk	*Max. theoretical*	*(per cent)*	*On sand*	*On flat*
M6 J39-42,	Number	16	7	14	27	0
Cumbria	Mean	2.30	2.37	2.8	2.23	
(target binder	Std. Dev.	0.06	0.01	2.9	0.04	
content	Range	2.20 to 2.44	2.36 to 2.38	-3.5 to 6.7	2.13 to 2.30	
M6 J39-42,	Number	0	0	0	6	0
Cumbria	Mean				2.22	
(target plus	Std. Dev.				0.04	
0.35%)	Range				2.17 to 2.29	
M6 J39-42,	Number	18	9	18	54	0
Cumbria	Mean	2.32	2.40	3.2	2.21	
(const.)	Std. Dev.	0.02	0.02	0.9	0.02	
	Range	2.29 to 2.35	2.38 to 2.44	1.6 to 4.7	2.16 to 2.25	
M6 J39-42,	Number	34	16	32	87	0
Cumbria	Mean	2.31	2.38	3.0	2.22	
(combined)	Std. Dev.	0.04	0.02	2.0	0.03	
	Range	2.20 to 2.44	2.36 to 2.44	-3.5 to 6.7	2.13 to 2.30	
M11 J9-10,	Number	36	18	18	0	0
Cambs.	Mean	2.34	2.43	4.0		
(trial)	Std. Dev.	0.02	0.01	0.6		
	Range	2.29 to 2.36	2.41 to 2.45	3.1 to 5.0		
M11 J9-10,	Number	62	25	25	31	0
Cambs.	Mean	2.33	2.44	4.5	2.32	
(const.)	Std. Dev.	0.02	0.01	0.7	0.02	
	Range	2.28 to 2.38	2.42 to 2.46	3.5 to 6.5	2.26 to 2.37	
M11 J9-10,	Number	98	43	43	31	0
Cambs.	Mean	2.34	2.44	4.3	2.32	
(combined)	Std. Dev.	0.02	0.01	0.7	0.02	
	Range	2.28 to 2.38	2.41 to 2.46	3.1 to 6.5	2.26 to 2.37	
M11 J12-14,	Number	15	1	15	13	0
Cambs.	Mean	2.32	2.42	4.2	2.31	
	Std. Dev.	0.01	-	0.6	0.03	
	Range	2.29 to 2.34	-	3.3 to 5.3	2.25 to 2.36	
M25 J6-J8,	Number	494	59	118	703	0
Reigate	Mean	2.42	2.48	2.6	2.40	
(Bardon	Std. Dev.	0.04	0.02	1.0	0.04	
Aggregates)	Range	2.25 to 2.54	2.44 to 2.53	0.3 to 5.2	2.23 to 2.52	
M25 J6-J8,	Number	72	9	52	99	0
Reigate	Mean	2.34	2.40	2.6	2.34	
(London	Std. Dev.	0.03	0.01	1.5	0.04	
Roadstone)	Range	2.24 to 2.41	2.38 to 2.43	-0.7 to 6.4	2.24 to 2.42	
M25 J6-J8,	Number	566	69	170	802	0
Reigate	Mean	2.41	2.47	2.6	2.39	
(combined)	Std. Dev.	0.05	0.04	1.2	0.05	
	Range	2.24 to 2.54	2.38 to 2.53	-0.7 to 6.4	2.24 to 2.52	
A14,	Number	4	1	4	4	0
Godman-	Mean	2.35	2.43	4.1	2.35	
chester	Std. Dev.	0.04	-	0.3	0.04	
	Range	2.31 to 2.39	-	3.6 to 4.4	2.31 to 2.39	
A14, Ouse	Number	8	8	8	0	0
River	Mean	2.32	2.40	3.5		
Bridges	Std. Dev.	0.01	0.01	0.6		
	Range	2.31 to 2.33	2.38 to 2.42	2.8 to 4.4		

Continued ....

A.2 Density and air void results — Continued

		Density (Mg/m³)		Air voids	NDG density (Mg/m³)	
		Bulk	Max. theoretical	(per cent)	On sand	On flat
M6 J10-10A, Staffs (trial)	Number	5	5	5	0	0
	Mean	2.352	2.42	2.7		
	Std. Dev.	0.017	0.03	1.5		
	Range	2.337 to 2.38	2.39 to 2.45	1.2 to 4.6		
M6 J10-10A, Staffs (const.)	Number	12	8	8	0	0
	Mean	2.31	2.36	2.0		
	Std. Dev.	0.004	0.02	0.7		
	Range	2.31 to 2.32	2.34 to 2.38	1.4 to 3.0		
M6 J10-10A, Staffs (combined)	Number	17	13	13	0	0
	Mean	2.33	2.38	2.3		
	Std. Dev.	0.02	0.04	1.1		
	Range	2.31 to 2.38	2.34 to 2.45	1.2 to 4.6		
A14, Risby to Topstock	Number	30	2	30	170	2
	Mean	2.33	2.40	2.9	2.31	2.24
	Std. Dev.	0.02	0.03	1.1	0.05	0.02
	Range	2.29 to 2.36	2.38 to 2.43	1.1 to 5.0	2.21 to 2.39	2.23 to 2.25
M25 J25-26, Essex (trials)	Number	6	6	6	6	0
	Mean	2.35	2.39	2.0	2.30	
	Std. Dev.	0.01	0.0	0.6	0.02	
	Range	2.33 to 2.36	2.39 to 2.40	1.6 to 31	2.28 to 2.32	
M25 J25-26, Essex (Northfleet plant)	Number	20	20	20	70	0
	Mean	2.32	2.41	3.7	2.31	
	Std. Dev.	0.02	0.01	0.8	0.02	
	Range	2.30 to 2.35	2.39 to 2.43	2.5 to 5.1	2.25 to 2.36	
M25 J25-26, Essex (Greys plant)	Number	7	7	7	39	0
	Mean	2.33	2.41	3.0	2.38	
	Std. Dev.	0.01	0.01	0.5	0.07	
	Range	2.31 to 2.34	2.40 to 2.42	2.4 to 3.8	2.28 to 2.52	
M25 J25-26, Essex (combined const.)	Number	27	27	27	109	0
	Mean	2.33	2.41	3.5	2.33	
	Std. Dev.	0.02	0.01	0.8	0.05	
	Range	2.30 to 2.35	2.39 to 2.43	2.4 to 5.1	2.25 to 2.52	
M25 J25-26, Essex (combined)	Number	33	33	33	115	0
	Mean	2.33	2.41	3.2	2.33	
	Std. Dev.	0.02	0.01	0.9	0.05	
	Range	2.30 to 2.36	2.39 to 2.43	1.6 to 5.1	2.25 to 2.52	
A14, Girton to Hemming-ford	Number	11	10	10	0	0
	Mean	2.37	2.44	2.8		
	Std. Dev.	0.01	0.01	0.5		
	Range	2.36 to 2.39	2.42 to 2.46	2.1 to 3.4		
A14, Kentford to Nine Mile Hill	Number	26	26	26	0	0
	Mean	2.33	2.39	2.9		
	Std. Dev.	0.02	0.02	1.0		
	Range	2.29 to 2.35	2.36 to 2.45	1.1 to 4.9		
A12, Coles Oak Bridge	Number	16	16	16	26	0
	Mean	2.34	2.39	2.3	2.30	
	Std. Dev.	0.03	0.02	0.9	0.02	
	Range	2.28 to 2.38	2.35 to 2.41	0.0 to 4.1	2.27 to 2.34	
A14, Bury St. Edmonds to Kentford	Number	31	1	31	172	0
	Mean	2.33	2.41	3.2	2.33	
	Std. Dev.	0.02	-	0.7	0.05	
	Range	2.29 to 2.36	-	1.9 to 4.8	1.83 to 2.38	

Continued ....

A.2 Density and air void results — Continued

		Density (Mg/m³)		*Air voids*	*NDG density (Mg/m³)*	
		Bulk	*Max. theoretical*	*(per cent)*	*On sand*	*On flat*
M6 J7-J8, Midland Link	Number	24	1	24	0	0
	Mean	2.31	2.36	2.2		
	Std. Dev.	0.01	-	0.5		
	Range	2.28 to 2.32	-	1.4 to 3.5		
A127, Halfway House (trial)	Number	6	1	6	0	0
	Mean	2.35	2.43	3.0		
	Std. Dev.	0.01	-	0.3		
	Range	2.34 to 2.36	-	2.6 to 3.3		
A127, Halfway House (const.)	Number	10	0	10	65	0
	Mean	2.36		2.7	2.32	
	Std. Dev.	0.01		0.5	0.13	
	Range	2.34 to 2.38		1.9 to 3.5	2.21 to 3.14	
A127, Halfway House (combined)	Number	16	1	16	65	0
	Mean	2.36	2.43	2.8	2.32	
	Std. Dev.	0.01	-	0.4	0.13	
	Range	2.34 to 2.38	-	1.9 to 3.5	2.21 to 3.14	

Appendix B: Results from survey by high-speed survey vehicle

B.1 Summary of rut-depth results

Trial	*Location*	*Material*	*Number of 10 m sections*	*Rut depth (mm)* *Mean (mm)*	*Std. dev. (mm)*	*Range (mm)*
A21	Northbound	Cl. 943	150	0.5	0.7	-1.6 to 2.4
		Control	80	0.3	0.6	-1.1 to 1.3
A21	Southbound	Cl. 943	155	-0.1	0.9	-2.5 to 2.4
		Control	47	1.1	0.6	-1.1 to 2.1
M11	69/5-71/0 NB	Cl. 943	150	2.9	1.4	-0.8 to 5.9
J9-J10	71/0-72/6 NB	Existing	159	3.7	1.0	0.2 to 6.6
	72/6-73/6 NB	Cl. 943	100	0.9	0.7	-0.9 to 2.7
	73/6-73/9 NB	Existing	30	2.9	1.7	-0.5 to 5.4
	73/9-74/4 NB	Cl. 943	50	2.9	0.7	0.1 to 4.5
	76/4-74/6 SB	Cl. 943	181	2.3	1.2	-2.4 to 5.1
	74/6-73/0 SB	Existing	157	1.1	1.3	-2.0 to 4.2
	73/0-71/0 SB	Cl. 943	199	2.3	1.0	-1.0 to 4.3
M11	85/3-85/8 NB	Existing	51	4.2	1.0	1.8 to 6.1
J12-J14	85/8-91/9 NB	Cl. 943	607	1.5	0.8	-1.8 to 3.9
	91/9-88/0 SB	Cl. 943	369	1.7	1.0	-1.6 to 3.8
	88/0-86/5 SB	Cl. 943	148	0.8	0.9	-2.1 to 2.6
	86/4-85/9 SB	Existing	49	2.1	0.9	-0.3 to 4.0
M25	52/7-52/5 EB	Cl. 943 reconstruct	19	2.6	0.4	1.9 to 3.2
J6-J8	52/4-51/8 EB	Cl. 943 overlay	60	1.2	0.5	0.0 to 2.4
	51/8-48/6 EB	Cl. 943 replacement	324	1.4	0.8	-0.4 to 3.5
	48/4-46/9 EB	Porous asphalt	151	2.1	1.5	-2.4 to 5.5
	46/8-44/6 EB	Porous asphalt	214	3.3	1.4	-5.8 to 7.0
	44/6-48/4 WB	Porous asphalt	379	3.0	1.8	-4.9 to 7.0
	48/6-51/8 WB	Cl. 943 replacement	324	1.0	0.7	-1.2 to 3.2
	51/8-52/4 WB	Cl. 943 overlay	62	1.2	0.8	-1.5 to 2.7
	52/5-52/9 WB	Cl. 943 reconstruct & overlay	38	1.3	0.5	0.4 to 2.8

B.2 Summary of sensor-measured texture depth results

			Sensor-measured texture depth (mm)					
			Nearside wheel-path			Offside wheel-path		
Trial	*Location*	*Material*	*Mean*	*Std. dev.*	*Range*	*Mean*	*Std. dev.*	*Range*
A21	Northbound	Cl. 943	1.5	0.2	0.8 to 2.1	1.5	0.2	0.9 to 2.0
		Control	1.2	0.2	1.0 to 2.0	1.3	0.2	0.8 to 1.6
A21	Southbound	Cl. 943	1.3	0.3	0.7 to 2.0	1.4	0.2	0.7 to 2.3
		Control	1.3	0.2	0.7 to 1.6	1.3	0.2	0.8 to 1.7
M11	69/5-71/0N	Cl. 943	1.4	0.2	0.8 to 1.9	1.2	0.2	0.9 to 1.6
J9-J10	71/0-72/6N	Existing	1.0	0.1	0.6 to 1.5	1.0	0.2	0.6 to 1.4
	72/6-73/6N	Cl. 943	1.5	0.2	1.0 to 2.0	1.3	0.2	1.0 to 1.8
	73/6-73/9N	Existing	1.1	0.2	0.8 to 1.6	1.1	0.1	0.7 to 1.4
	73/9-74/4N	Cl. 943	1.4	0.2	0.9 to 2.0	1.3	0.2	0.9 to 1.7
	76/4-74/6S	Cl. 943	1.4	0.2	0.9 to 2.2	1.3	0.2	0.9 to 1.9
	74/6-73/0S	Existing	1.3	0.3	0.7 to 2.0	1.2	0.2	0.7 to 1.7
	73/0-71/0S	Cl. 943	1.4	0.2	0.7 to 2.1	1.3	0.2	0.9 to 1.9
M11	85/3-85/8N	Existing	1.8	0.5	0.6 to 3.0	1.7	0.2	1.3 to 2.3
J12-J14	85/8-91/9N	Cl. 943	1.4	0.4	0.2 to 2.8	1.4	0.3	0.7 to 2.3
	91/9-88/0S	Cl. 943	1.5	0.4	0.4 to 2.7	1.5	0.3	0.8 to 2.3
	88/0-86/5S	Cl. 943	1.5	0.4	0.4 to 2.7	1.5	0.3	0.8 to 2.3
	86/4-85/9S	Existing	1.3	0.4	0.3 to 2.3	1.4	0.2	1.0 to 1.8
M25	52/7-52/5E	Cl. 943 recon.	1.0	0.2	0.7 to 1.4	1.2	0.1	1.0 to 1.4
J6-J8	52/4-51/8E	Cl. 943 ov'lay	0.7	0.1	0.4 to 1.0	1.0	0.2	0.6 to 1.6
	51/8-48/6E	Cl. 943 rep'nt	0.8	0.2	0.4 to 1.6	1.1	0.3	0.6 to 1.9
	48/4-46/9E	Porous asphalt	0.9	0.1	0.5 to 1.4	1.1	0.2	0.7 to 1.6
	46/8-44/6E	Porous asphalt	0.9	0.1	0.6 to 1.3	1.1	0.1	0.8 to 1.4
	44/6-48/4W	Porous asphalt	0.9	0.1	0.6 to 1.3	1.1	0.1	0.7 to 1.6
	48/6-51/8W	Cl. 943 rep'nt	0.8	0.1	0.5 to 1.4	1.1	0.2	0.7 to 1.6
	51/8-52/4W	Cl. 943 ov'lay	0.9	0.2	0.6 to 1.4	1.3	0.2	1.0 to 1.9
	52/5-52/9W	Cl. 943 recon. & overlay	1.0	0.2	0.7 to 1.4	1.4	0.1	1.1 to 1.7

B.3 Summary of profile variance results

Trial	*Location*	*Material*	*Mean*	*Standard deviation*	*Range 10 m length*	*Range 100 m length*	*Mean category*
3 m Variance (mm²)							
A21	Northbound	Cl. 943	1.5	0.7	0.5 to 5.5	0.9 to 2.3	0.82
		Control	0.9	0.4	0.4 to 2.1	0.6 to 1.3	0.03
A21	Southbound	Cl. 943	1.1	0.7	0.3 to 5.9	0.6 to 2.1	0.29
		Control	0.9	0.4	0.4 to 2.7	0.7 to 1.2	0
M11	69/5-71/0N	Cl. 943	0.9	0.5	0.3 to 5.6	0.6 to 1.4	0.06
J9-J10	71/0-72/6N	Existing	0.5	0.2	0.2 to 1.3	0.4 to 0.7	0
	72/6-73/6N	Cl. 943	1.0	0.4	0.4 to 2.8	0.7 to 1.4	0.04
	73/6-73/9N	Existing	0.5	0.2	0.2 to 1.4	0.4 to 0.5	0
	73/9-74/4N	Cl. 943	1.0	0.5	0.4 to 2.6	0.7 to 1.6	0.27
	76/4-74/6S	Cl. 943	1.2	0.6	0.4 to 4.1	0.9 to 1.6	0.33
	74/6-73/0S	Existing	1.0	0.4	0.3 to 2.7	0.7 to 1.4	0.03
	73/0-71/0S	Cl. 943	1.3	0.6	0.5 to 4.3	0.9 to 2.0	0.44
M11	85/3-85/8N	Existing	1.2	0.6	0.5 to 3.4	0.8 to 1.8	0.38
J12-J14	85/8-91/9N	Cl. 943	1.1	0.7	0.3 to 11.6	0.5 to 2.5	0.23
	91/9-88/0S	Cl. 943	1.2	0.7	0.3 to 10.5	0.6 to 2.3	0.29
	88/0-86/5S	Cl. 943	1.2	0.5	0.5 to 3.5	0.8 to 1.8	0.52
	86/4-85/9S	Existing	0.9	0.3	0.4 to 2.2	0.7 to 1.1	0
M25	52/7-52/5E	Cl.943 recon	0.8	0.4	0.2 to 1.5	0.8 to 1.0	0
J6-J8	52/4-51/8E	Cl.943 o'lay	0.6	0.3	0.2 to 1.8	0.5 to 0.8	0
	51/8-48/6E	Cl.943 rep'nt	0.9	0.6	0.2 to 4.5	0.5 to 2.2	0.14
	48/4-46/9E	Porous as'lt	0.7	0.7	0.2 to 3.8	0.3 to 1.8	0.07
	46/8-44/6E	Porous as'lt	0.6	0.4	0.2 to 3.6	0.3 to 1.4	0.02
	44/6-48/4W	Porous as'lt	0.7	0.5	0.2 to 3.1	0.3 to 1.3	0.003
	48/6-51/8W	Cl.943 rep'nt	0.8	0.5	0.2 to 4.0	0.5 to 1.8	0.10
	51/8-52/4W	Cl.943 o'lay	1.0	0.4	0.2 to 2.2	0.9 to 1.4	0.11
	52/5-52/9W	Cl.943 recon & overlay	1.2	0.8	0.5 to 5.1	0.8 to 1.8	0.41
10 m Variance (mm²)							
A21	Northbound	Cl. 943	3.2	1.7	1.0 to 11.0	2.3 to 4.8	0.09
		Control	2.6	1.4	0.6 to 7.8	1.7 to 3.7	0
A21	Southbound	Cl. 943	2.6	3.2	0.5 to 24.4	1.2 to 8.6	0.16
		Control	2.5	1.6	0.6 to 8.9	1.4 to 4.1	0.03
M11	69/5-71/0N	Cl. 943	2.8	2.3	0.7 to 17.9	1.3 to 4.8	0.02
J9-J10	71/0-72/6N	Existing	1.7	1.2	0.4 to 8.5	0.8 to 2.6	0
	72/6-73/6N	Cl. 943	1.9	1.0	0.4 to 6.3	1.5 to 2.7	0
	73/6-73/9N	Existing	1.5	0.9	0.6 to 4.6	1.1 to 1.8	0
	73/9-74/4N	Cl. 943	3.0	2.5	0.9 to 14.9	1.8 to 5.9	0.24
	76/4-74/6S	Cl. 943	3.0	1.7	0.6 to 9.0	2.0 to 4.5	0.03
	74/6-73/0S	Existing	2.5	1.4	0.5 to 9.2	1.6 to 3.5	0
	73/0-71/0S	Cl. 943	3.1	1.8	0.9 to 11.1	1.4 to 4.9	0.18
M11	85/3-85/8N	Existing	4.1	3.2	1.1 to 17.2	2.1 to 5.9	0.52
J12-J14	85/8-91/9N	Cl. 943	2.9	3.2	0.5 to 36.7	1.8 to 8.1	0.17
	91/9-88/0S	Cl. 943	2.9	2.1	0.6 to 17.2	1.4 to 6.4	0.13
	88/0-86/5S	Cl. 943	3.2	6.0	0.6 to 68.9	1.6 to 11.3	0.17
	86/4-85/9S	Existing	2.7	1.5	0.9 to 6.9	1.6 to 3.7	0
M25	52/7-52/5E	Cl.943 recon	3.4	3.2	0.9 to 15.6	2.3 to 4.2	0.20
J6-J8	52/4-51/8E	Cl.943 o'lay	1.5	0.8	0.4 to 3.6	1.2 to 2.1	0
	51/8-48/6E	Cl.943 rep'nt	2.8	2.4	0.4 to 19.2	1.2 to 6.8	0.14
	48/4-46/9E	Porous as'lt	3.0	3.3	0.3 to 24.2	1.2 to 6.6	0.21
	46/8-44/6E	Porous as'lt	2.5	2.1	0.4 to 16.9	1.1 to 5.9	0.07
	44/6-48/4W	Porous as'lt	3.3	3.0	0.4 to 20.0	1.4 to 7.7	0.28
	48/6-51/8W	Cl.943 rep'nt	3.0	2.4	0.4 to 15.9	1.1 to 7.1	0.13
	51/8-52/4W	Cl.943 o'lay	2.4	1.6	0.5 to 8.2	1.5 to 4.0	0
	52/5-52/9W	Cl.943 recon & overlay	3.8	3.5	0.8 to 14.6	1.5 to 6.4	0.38

Continued ....

B.3 Summary of profile variance results — Continued

Trial	*Location*	*Material*	*Mean*	*Standard deviation*	*Range 10 m length*	*Range 100 m length*	*Mean category*
30 m Variance (mm²)							
A21	Northbound	Cl. 943	13.7	9.7	1.4 to 60.5	5.5 to 25.3	0
		Control	12.9	8.9	1.7 to 54.6	5.5 to 19.5	0
A21	Southbound	Cl. 943	11.7	9.8	0.7 to 77.4	3.8 to 35.3	0
		Control	11.2	9.5	0.9 to 69.4	4.2 to 23.6	0
M11	69/5-71/0N	Cl. 943	16.1	16.1	1.1 to 188	4.6 to 35.4	0
J9-J10	71/0-72/6N	Existing	10.4	6.6	0.8 to 70.4	3.3 to 19.3	0
	72/6-73/6N	Cl. 943	8.8	5.5	0.9 to 39.3	4.2 to 17.9	0
	73/6-73/9N	Existing	8.3	4.1	1.8 to 29.6	4.8 to 10.9	0
	73/9-74/4N	Cl. 943	23.7	29.7	2.2 to 184	9.3 to 59.4	0.17
	76/4-74/6S	Cl. 943	16.2	12.4	0.9 to 95.6	6.0 to 29.5	0
	74/6-73/0S	Existing	11.6	7.6	0.7 to 55.7	4.0 to 23.0	0
	73/0-71/0S	Cl. 943	13.8	10.1	1.2 to 74.4	4.6 to 33.0	0
M11	85/3-85/8N	Existing	16.7	20.0	1.7 to 153	7.9 to 26.3	0
J12-J14	85/8-91/9N	Cl. 943	22.2	36.4	0.6 to 478	3.2 to 174	0.11
	91/9-88/0S	Cl. 943	24.4	26.9	1.0 to 244	5.9 to 89.5	0.09
	88/0-86/5S	Cl. 943	21.2	45.2	0.8 to 413	3.3 to 99.3	0.13
	86/4-85/9S	Existing	20.0	14.5	1.1 to 90.0	7.5 to 37.8	0
M25	52/7-52/5E	Cl.943 recon	32.6	46.9	2.3 to 256	10.8 to 43.2	0
J6-J8	52/4-51/8E	Cl.943 o'lay	6.7	3.9	1.0 to 42.2	3.6 to 12.5	0
	51/8-48/6E	Cl.943 rep'nt	13.9	13.0	0.8 to 161	4.5 to 48.2	0
	48/4-46/9E	Porous as'lt	15.7	16.8	0.6 to 161	4.5 to 49.7	0
	46/8-44/6E	Porous as'lt	18.5	17.2	0.7 to 144	3.9 to 48.8	0
	44/6-48/4W	Porous as'lt	18.4	18.9	0.4 to 157	6.6 to 76.4	0.02
	48/6-51/8W	Cl.943 rep'nt	16.4	16.8	0.8 to 195	4.6 to 54.7	0
	51/8-52/4W	Cl.943 o'lay	9.7	6.2	0.5 to 37.4	3.6 to 13.5	0
	52/5-52/9W	Cl.943 recon & overlay	21.6	34.2	1.2 to 210	2.9 to 38.3	0

Abstract

A specification clause, Clause 943, and associated notes for guidance was prepared for hot rolled asphalt in terms of its resistance to permanent deformation, as measured by the wheel-tracking test, and durability, as measured by the air voids content. Clause 943 was trialled on a series of road contracts, during which the specific requirements of the clause were refined. The results of the testing carried out during the construction of the trials, together with subsequent monitoring of the earliest trials laid, are analysed to show that the approach employed by the clause is practicable. Nevertheless, the reported results allow further conclusions to be drawn as to the development and use of Clause 943.

Related publications

TRL176 *Laboratory tests on high-friction surfaces for highways* by J C Nicholls. 1997 (price £30, code H)

PR114 *A quantitive assessment of a nuclear method for binder content determination* by J Carswell. 1995 (price £20, code E)

PR78 *Tests for voids and compaction in rolled asphalt surfacing* by M E Daines. 1995 (price £20, code £)

PR61 *Assessment of Multiphalte, the shell Multigrade bitumen* by J C Nicholls. 1994 (price £20, code E)

CT40.1 Bituminous road design & construction update (1993-1996). *Current Topics in Transport: selection abstracts from TRL Library's database*. (price £15)

Prices current at July 1998

For further details of these and all other TRL publications, telephone Publication Sales on 01344 770783 or 770784, or visit TRL on the Internet at http://www.trl.co.uk.