TRANSPORT RESEARCH LABORATORY

Trials of high-friction surfaces for highways

Prepared for Quality Services (Civil Engineering) Pavement Engineering Group, Highways Agency

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Executive Summary

High-friction surface systems are used to support the Department of Transport's (now Department of the Environment, Transport and the Regions) skidding standard on high-stress sites such as approaches to roundabouts and pedestrian crossings. These systems use calcined bauxite held in place by a resin binder to obtain the necessary skid resistance. Until recently, the resin was always a bitumen-extended epoxy-resin, as is reflected in the wording of the relevant clause in the Department of Transport's specification. With the increasing market for high-friction surfaces, alternative systems have come onto the market, some of which use different resins. The binders used in currently available systems are based on either epoxy-resin, rosin-ester, polyurethane-resin or acrylic-resin. These developments have been assessed by TRL for the Highways Agency to allow the current specification to be widened to include other systems that can prove to be fit for purpose.

This report describes a series of trials laid at different times with a range of types of high-friction surface systems. Whilst only epoxy-resin systems have been in-service for the required service life of these surfaces, an order of ranking between the systems in terms of (maintained) skid resistance, texture depth and longevity has emerged. This overall ranking order is that the epoxy-resin and polyurethane-resin systems maintained their properties most consistently, followed by the acrylic-resin system just ahead of the rosin-ester system. However, the polyurethane-resin system has been found to be more prone to premature deterioration if not handled carefully prior to application.

Consideration of the different laying techniques employed for different resins indicates that the choice of resin type may be influenced by constraints imposed while laying as well as the performance requirements in service. The thermoplastic rosin-ester systems can be used in situations where traffic-control requirements do not allow sufficient time for the traditional chemically-curing epoxy-resin systems to cure before the section of road needs to be re-opened. The newer chemically-curing polyurethane and acrylic-resin systems have shorter curing times than the epoxy-resin systems, although not as short as the cooling time for the rosin-ester systems, which again allows the road to be opened to traffic earlier.

The results from a limited programme of laboratory testing are also described. These tests have shown that it is possible to differentiate between the different materials and that the ranking is generally consistent with that found from the road trials. Therefore, these tests have been refined as part of a more complete suite of tests to develop a performance-related scheme to classify high-friction surface systems. The use of these laboratory tests will allow alternative, as yet not marketed, systems to be assessed relatively quickly in the laboratory and hence encourage innovation in this field. A certification procedure has been developed by a specialist group representing the British Board of Agrément, the Highways Agency, the CSS, other specifying bodies, the industry and TRL as the first product area under the *Highway Authorities Product Approval Scheme* (HAPAS).

1 Introduction

The concept of using epoxy-resin as the binder in a surface treatment was first investigated in the USA in the mid-1950s. A development of that system, in which calcined bauxite chippings in the size range 1.2 to 2.8 mm are held in a bitumen-extended epoxy-resin binder (James, 1963; Hatherly & Lamb, 1970; James 1971), was introduced into the UK in the 1960s to provide enhanced skid resistance for accident black-spots. The system proved successful (Denning, 1978) and, since 1986, has been called up in Clause 924 to the *Specification for Highway Works* (MCHW 1).

With the introduction of a national Departmental Standard for skid resistance in 1988 on motorways and trunk roads, currently as set out in HD 28/94 (DMRB 7.3.1), and a similar policy being adopted by the counties (ACC et al, 1989), the market for high-friction surface systems has grown substantially. As a result, a number of alternative binders are being offered in high-friction surface systems and the number of commercial organisations that offer resin-based systems is increasing.

Clause 924 in the *Specification for Highway Works* (MCHW 1), *Resin-Based High Skid Resistant Surface Treatment*, gave a recipe for the constituent materials and the method for applying them based on bitumen-extended epoxy-resin rather than a performance requirement against which any system can be judged. For this reason, the Highways Agency commissioned TRL to carry out a review of the road performance of products being offered as resin-based high-friction surface systems.

This report provides information on a series of full-scale road trials, together with details from a limited laboratory test programme. The efficiency of the laboratory tests on the various systems are compared by reference to the performance of those systems as measured on the road trials.

2 Binder system

There are several resins that are used as the binders in high-friction surface systems. The binder systems known to be used at this time are:

- Epoxy-resin;
- Rosin-ester;
- Polyurethane-resin; and
- Acrylic-resin.

The main features and their differences are described below.

2.1 Epoxy-resin

Epoxy-resin has been used as the binder for some time; it comes as a two component system. One part contains the resin together with a proportion of oil which reduces the viscosity of the resin and acts as an extender; the other part contains the curing agent together with bitumen and oil extenders and accelerators. (Systems are now being offered with variations on the extenders used traditionally, but none of these have been included in the trials.) The two parts are added in approximately equal quantities by weight on site and mixed thoroughly together. Once mixed, the two parts react chemically so that there is then a finite time to complete the surface dressing work. The precise properties of the binder in-situ can be adjusted by varying the proportions of the two components.

The binder is spread by a metered pressure sprayer, which accurately and continuously proportions the two components, intimately mixing them before spraying. The calcined bauxite is then spread over the binder by mechanical metering equipment before the binder has cured. The aggregate should uniformly cover the binder with a slight excess, which is removed by sweeping after the binder has cured. The system has to be left for several hours after application for the reaction to be complete, and should not be opened to traffic until after sweeping (usually 3 to 4 hours). The time taken for the binder to cure is dependent on the ambient temperature, with the cure time being greatly extended at temperatures below 10°C.

2.2 Rosin-ester

The use of rosin-ester to hold calcined bauxite chippings is relatively new compared with the use of epoxy-resin. Unlike epoxy-resin where two components are mixed and the aggregate is applied afterwards, the resin and chippings are pre-blended and bagged as a dry powder for transporting to site. On site, the operatives have only to heat the material to the required temperature and then spread it, usually in hand-held box-screeds, on the road surface. The finished thickness is about 5 mm. The pre-blending means that the calcined bauxite is initially completely covered by binder, unlike the epoxy-resin surface treatments. The material requires little or no sweeping and, being thermoplastic rather than chemically curing, stiffens quickly (less than a quarter of an hour if the surface is cooled with water), allowing the road to be opened to traffic with minimum delay. However, because the rosin-ester surface treatment is hand applied, the overall time taken between starting to apply the material to opening the road to traffic may, in practice, not differ much from applying an epoxy-resin surface treatment. The system may be applied at any time of year provided that the road is dry.

In the original formulations as tested in this project, it was claimed that calcined bauxite made up over 36 per cent of the total aggregate but not 100 per cent, as would be the case when it is broadcast across the surface as with epoxy-resin. An alternative with 100 per cent calcined bauxite aggregate (other than filler) is now being offered. This alternative reflects more closely with the Department of Transport’s policy for its roads.

2.3 Polyurethane-resin

The polyurethane-resin system being used in the trials is a multiple-component chemically curing system which is generally hand applied with the aggregate being scattered over the binder. The polyurethane-resins were developed in order to try to achieve a quicker curing time than epoxy-resin, particularly at low temperatures. The relevant curing times of different resins have not been compared in this research, and in any case there is a temperature below which the road surface is liable to be contaminated due to precautionary salting.

The system tested in the trials consisted of three components, two liquid and one powder, which are stored in different shaped receptacles, with one of each being required per batch. The components are mixed together in a container with a hand-held beater and laid by hand; the aggregate is dispensed separately after the binder is in place, also being spread by hand. Other systems currently on the market consist of two packs, with the extender pre-dispersed.

2.4 Acrylic-resin

Acrylic-resin is used in a two-component system similar to epoxy-resin. However, acrylic-resin has a much faster cure time than epoxy-resin. Consequently, the curing agent is put onto the aggregate so that the chemically curing process is not initiated until the aggregate is in position. The consistency of the binder prior to contact with the curing agent is designed to wet sufficient of the aggregate to provide adequate bond without the binder totally submerging the chippings in areas. Also, the need for an even application of the aggregate is greater than with a mixed-binder/curing agent system in order to avoid local accumulations of the aggregate. Nevertheless, the process is completed quicker, allowing earlier opening of the road.

As yet, only one acrylic-resin based system is known to be marketed. The supplier has developed a machine which includes storage and distribution systems for both the binder and aggregate (Figure 1); however, on larger jobs the calcined bauxite can be distributed from a separate lorry because the storage on the combined machine is relatively limited. When using a separate lorry for the chippings, the binder will not cure until the aggregate and curing agent is placed. However, if the delay is extended, there is the possibility of loss of monomers from the relatively thin layer of uncured binder.

Figure 1 Laying equipment for acrylic-resin system

The acrylic-resin system can also be laid by hand, but it is understood that the result is less uniform.

3 Road trial sites

3.1 Rosin-ester/epoxy-resin comparisons

3.1.1 M4/A329(M) interchange, Reading

In the early 1990s, Berkshire County Council, as agents for the Department of Transport, were concerned at the number of accidents on the junction of the M4 and A329(M) near Reading, particularly at four locations, two each on the M4 eastbound to A329(M) southbound (Theale to Bracknell) slip road and on the M4 westbound to A329(M) northbound (Maidenhead to Reading) slip road. Three of these sites were on concrete and one on rolled asphalt. Conventional epoxy-resin high-friction surface systems are not normally considered suitable for application to concrete surfacing without additional preparatory works because there is a significant chance that they will not adhere. However, one manufacturer offered an epoxy-resin system which included an additional primer which was claimed to make it suitable for use on concrete surfacings. Another manufacturer supplied a rosin-ester system which they considered suitable for use on concrete. These materials were tested on this high-stress site, as given in Table 1 (together with details of later sections, see Section 3.3.2), the area of each section being approximately 1,000 m^2.

Prior to application of the rosin-ester system, the road was heated with lances to remove any dirt and grease. All joints were masked with tape, removed soon after the material was applied. The material was supplied in 25 kg plastic bags. Thirty bags per batch were emptied into a boiler (either with or without the plastic bag), heated to about 200°C and kept at that temperature whilst being stirred for 20 to 30 minutes. The material was then discharged into a bucket for transfer to a screed box. The screed boxes were drawn manually across the surface to leave a layer about 6 mm thick. The screed boxes were either of 1000 mm or 610 mm width, depending on the preference of the crew. The material was laid in transverse strips except for two preliminary strips laid along the wheel-tracks applied to increase the texture where it is most needed. The material could be trafficked in less than half an hour.

The preparation for the epoxy-resin system also included heating the surface to remove dirt and grease. The primer was then applied by hand-held long-handled rollers (similar in principal to those used for internal decoration of buildings) prior to the resin. The resin was applied by hand using rubber squeegee brushes. Calcined bauxite chippings were then applied, again by hand, before the resin was left to cure (about 2 hours). Once the resin was cured, the loose chippings were removed by brushing with a mechanical sweeper prior to the site being re-opened.

Major maintenance was carried out on the junction in 1996 involving replacing most of the high-friction surfacing, so no monitoring was undertaken after then.

3.1.2 A5 roundabouts, Warwickshire

A series of roundabout approaches on the A5 in Warwickshire required treatment for skid resistance.

Table 1 Sites with high-friction surface systems on M4/A329(M)

Site No.	*Slip road*	*Resin*	*Substrate*	*Date laid*
R1	Theale to Bracknell	Rosin-ester	Rolled asphalt	April 1991
NX		None	Concrete	
R2		Rosin-ester	Concrete	April 1991
NX		None	Concrete	
R6		Acrylic-resin	Concrete	October 1993
R3	Maidenhead to Reading	Rosin-ester	Concrete	April 1991
NX		None	Concrete	
R4		Epoxy-resin	Concrete	April 1991
R5	Reading to Maidenhead	Acrylic-resin	Concrete	October 1993

Warwickshire County Council agreed to allow these sections to be used for a trial, the length to be treated for each approach being increased to 100 m from the conventional 50 m in order to make it easier to get representative SCRIM coefficients. Alternate roundabout approaches were treated with an epoxy-resin system and a rosin-ester system, as shown in Table 2. Although the roundabouts all had slightly different features and traffic flows, it was considered that any undue influence of roundabout design or location could be identified in the results as outliers.

The crews working on both materials were of about the same number. Typically, the crew using the rosin-ester system were able to complete one lane of one approach each day, while the crew applying the epoxy-resin system were able to do one lane of two approaches per day (i.e. the epoxy-resin system was twice as ‘productive’ as the rosin-ester system). The rosin-ester system was applied continuously throughout the working day, subject only to refilling the boiler (see Section 3.1.1), and, once work had been finished, traffic could be allowed over the material; in one case, fifteen minutes after laying. The epoxy-resin system was applied to a timetable, with much of the time waiting for the resin to cure.

In 1994, construction work was undertaken on the southbound entry to the roundabout with the M42 (W1) to connect in the Tamworth bypass. This work removed part of the trial surfacings and made monitoring difficult. In 1996, the Holly Lane roundabout (W4) was resurfaced due to the poor state of the surfacing, including the high-friction surface system, by that time.

3.2 Polyurethane-resin/epoxy-resin comparisons

3.2.1 A1(M)/A167, Durham

A series of sites consisting of approaches to roundabouts, traffic lights (on roundabouts) and pedestrian crossings on the A1(M) and A167 in County Durham were treated with high-friction surface systems in late 1992 and early 1993. Some of the sites were treated with a polyurethane-resin system whilst the remainder were treated with a conventional epoxy-resin system. Details of the sites are given in Table 3.

In addition to comparing two different binders, polyurethane-resin and epoxy-resin, the trial also incorporated a comparison of two different high Polished Stone Value (PSV) artificial aggregates, Guyanese calcined bauxite and aluminium oxide. The latter was used on two sites with the polyurethane-resin whilst the former was used elsewhere.

The two systems were laid by different contractors; the epoxy-resin system was laid by a contractor experienced in applying the system while the polyurethane-resin system was laid by a contractor for whom it was their first experience with this material, although they did receive assistance from the supplier. Although most of the work with the polyurethane-resin system was completed successfully, the contractor had to carry out remedial work on two of the sites (nearside lane of southbound off slip at D5 and the southbound approach to D2). Work on another site (southbound approach to D7) had not been completed when monitoring started but, when this section was extended a year after the main length, this extension was also found to be defective.

The main defect observed was that some areas had a yellow appearance in which the aggregate was not retained properly. It was understood from the supplier that this weakness was probably the result of a reaction between the curing agent and moisture, causing gassing and a breakdown of the system’s adhesive and cohesive strengths. The most likely source of the moisture was from the filler component, which it was assumed had become contaminated.

Repair work was carried out on two sites (northbound exit from A1(M) to D6 and southbound approach to D7) by overlaying completely during 1996. The resulting thick layering caused delamination and cracking, presumably

Table 2 Sites with high-friction surface systems on A5, Warwickshire

Site No.	*Junction*	*Resin*	*Substrate*	*Date laid*
W1	M42, junction 10	Epoxy-resin	Rolled asphalt	August 1991
W2	Dordon roundabout	Rosin-ester	Rolled asphalt	August 1991
W3	Boot Hill roundabout	Epoxy-resin	Rolled asphalt	August 1991
W4	Holly Lane roundabout	Rosin-ester	Rolled asphalt	August/Sept 1991
W5	Higham Lane roundabout	Epoxy-resin	Rolled asphalt	August/Sept 1991
W6	Gibbet Hill roundabout	Rosin-ester	Rolled asphalt	August/Sept 1991

Table 3 Sites with high-friction surface systems in Durham

Site No.	*Road No.*	*Location*		*Length (m)*	*System*	*Date treated*
D1	A167	Hermitage	N/bnd approach	100	Polyurethane*	August 1992
		roundabout	S/bnd approach	100	Epoxy-resin	October 1992
D2	A167	Picktree	N/bnd approach	100	Epoxy-resin	October 1992
		roundabout	S/bnd approach	100	Polyurethane	August 1992
D3	A167	Blind Lane	N/bnd approach	50	Epoxy-resin	October 1992
D4	A1(M)/A167	interchange	App to A1(M) N/bnd on	50	Epoxy-resin	October 1992
		roundabout	App to A1(M) S/bnd off	50	Polyurethane	August 1992
			App to A1(M) N/bnd off	50	Epoxy-resin	October 1992
			App to A167 off	50	Epoxy-resin	October 1992
D5	A1(M)	Blind Lane	N/bnd off slip	50	Epoxy-resin	March 1993
		interchange	S/bnd off, o/s lane	100	Epoxy-resin	March 1993
			S/bnd off, n/s lane	100	Polyurethane	August 1992
D6	A1(M)	Bradbury	N/bnd off slip	100	Polyurethane	August 1992
		interchange	S/bnd off slip	100	Epoxy-resin	March 1993
D7	A167	Aycliffe	N/bnd approach	50	Epoxy-resin	March 1993
		pel. X'ing	S/bnd approach†	50	Polyurethane*	August 1992 June 1993

** Polyurethane-resin with aluminium oxide rather than Guyanese calcined bauxite.*
† Full length not laid on first visit.

because the surfacing was able to act independently of the substrate. This explanation is supported by the delamination having not occurred over the extension to D7, where the original material had already been extensively removed by trafficking. However, the delamination did occur over the original length, which was still intact prior to repair.

3.2.2 A46, Stratford

The approaches to two pairs of roundabouts on the A46 in Warwickshire were laid with polyurethane-resin and epoxy-resin based systems in late 1992 and early 1993, with details given in Table 4. Both materials were laid by their respective suppliers. No problems were reported despite the work being carried out outside the normal season for laying high-friction surface systems. It should be noted that the polyurethane-resin system, for which the suppliers claim that there is no restriction for cold, only damp, was laid in February.

Unfortunately, the construction of a new road connecting into the roundabout at site S3, which initially only had a service garage entry/exit, was started in 1994, and involved removing the trial surfacing.

3.3 Acrylic-resin/epoxy-resin comparisons

3.3.1 A453, Nottingham

The approaches to a pair of pelican crossings on the A453 near Nottingham were laid with acrylic-resin and epoxy-resin based systems in July and August 1993 (Table 5), both systems being laid by one company which supplied both products.

The laying was not observed by TRL. However, a joint TRL/Highways Agency inspection was carried out approximately two months after the Glapton Lane site (and three other sites with the acrylic-resin system in Nottingham) and one month after the Clifton roundabout site had been treated. Although the weather was dry and overcast during the inspection, the road was still wet from earlier rain.

The epoxy-resin system and one of the non-trial acrylic-resin system sites in Nottingham looked in reasonable condition, although not as good as one might have expected after only two months on the road. The acrylic-resin system on the trial site showed signs of revealing the underlying material in places (Figure 2). In other places, there were ridges of material, presumably at joints where there is more than one layer, and in some places small 'craters' could be seen (Figure 3). It was considered that, because the curing agent was on the aggregate and the binder had a quick cure once in contact, the unevenness could have resulted from imprecision in spreading. Nevertheless, overall the surface was generally rough, as would be expected of high-friction surface systems.

Of the acrylic-resin based system on the three non-trial sites, one was similar to the trial site except that there were more ridges (Figure 4); ridges reportedly occur where the high-friction surface system has been hand-applied, which was the method employed at that site. Another non-trial site was variable, but was on a hill which may have exacerbated problems of uniform laying (the adjacent surface dressing was in very poor condition). The remaining non-trial site looked in the best condition of all the acrylic-resin based system sites, including the trial site.

Table 4 Sites with high-friction surface systems near Stratford

Site No.	*Intersection*	*Resin*	*Substrate*	*Date laid*
S1	A3400, Stratford	Polyurethane	Rolled asphalt	February 1993
S2	A422, Stratford	Epoxy-resin	Rolled asphalt	October 1992
S3	Garage, Alcester	Polyurethane	Rolled asphalt	February 1993
S4	A46, Alcester	Epoxy-resin	Rolled asphalt	October 1992

Table 5 Sites with high-friction surface systems at Nottingham

Site No.	*Location*	*Resin*	*Substrate*	*Date laid*
N1	Glapton Lane pelican crossing	Acrylic-resin	Rolled asphalt	July 1993
N2	Clifton roundabout pelican crossing	Epoxy-resin	Rolled asphalt	August 1993

Figure 2 Underlying material showing through acrylic-resin system

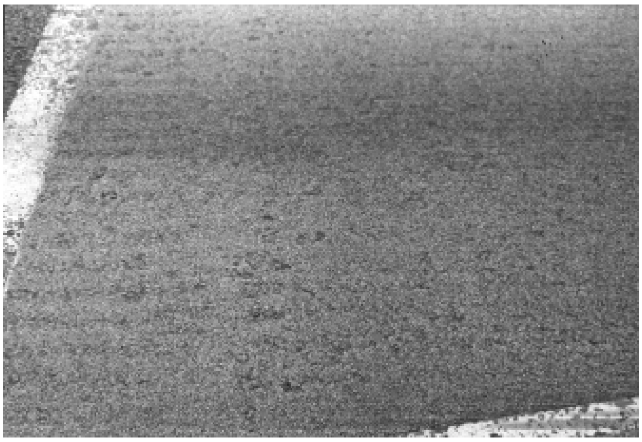

Figure 3 Pockmarked appearance of acrylic-resin system

Figure 4 Ridges on acrylic-resin system

3.3.2 M4/A329(M), Reading

In 1993, two additional areas on the concrete slip-roads to the M4/A329(M) interchange were required to have high-friction surface systems applied. These areas, sections R5 and R6 in Table 1, were treated with the acrylic-resin based system with no concurrent epoxy-resin based system alongside as control; comparison had to be made with the control from the previous trial at the interchange (Section 3.1.1).

Due to the length of the site (approximately 450 m on the Reading to Maidenhead slip-road), a separate lorry was used initially to spread the calcined bauxite. Minor problems occurred with the lorry on section 5 and the delivery method changed from lorry to integral supply and back to the lorry along the site. It was noticed that the binder was not covered at the edges and calcined bauxite had to be swept onto it by broom. Nevertheless, the overall appearance was good and sweeping up of any loose chippings was able to take place less than half an hour after application.

Major maintenance was carried out on the junction in 1996 involving replacing most of the high-friction surfacing, so no monitoring was undertaken after then.

4 Road trial results

4.1 Initial properties

Measurements of texture depth, both by the sand-patch method and by mini-texture meter (MTM) (BSI, 1994), and the skid resistance, by the portable skid resistance tester (RRL, 1960), were carried out on the surfacings at Reading before and after treatment. The tests were generally carried out in the wheel-track nearest the carriageway edge (nearside wheel-track in nearside lane, offside wheel-track in offside lane) together with the oil-lane (midway between wheel-tracks). The mean values across all locations are given in Table 6, those from the portable skid resistance tester having been corrected for temperature (RRL, 1964).

The relationship between sand-patch and sensor-measured texture depth is noticeably different between the existing rolled asphalt and concrete surfaces (the ‘before’ measurements’), with an average ratio between sand-patch and sensor-measured readings of 1.2, and that of the high-friction surface systems (the ‘after’ measurements), with an average ratio of 2.25.

4.2 Regular monitoring

Regular monitoring on the various sites has been carried out using the Sideway-force Coefficient Routine Investigation Machine (SCRIM) (Hosking & Woodford,

Table 6 Initial results from M4/A329(M)

Site No. (Table 1)	*R1*	*R2*	*R3*	*R4*	*R6*
Sand patch (mm)					
Before	1.4	0.8	0.6	1.0	-
After	2.3	2.1	2.6	1.9	3.1
MTM (mm)					
Before	0.99	0.64	0.80	0.71	-
After	0.96	1.06	1.09	0.82	-
1 week later	-	-	0.91	0.83	-
Ratio (Sand-patch/MTM)					
Before	1.41	1.25	0.75	1.41	-
After	2.40	1.98	2.39	2.32	-
Pendulum					
Before	62	54	61	67	-
After	81	80	83	108	112
1 week later	-	-	78	101	-

1976) by either TRL or the relevant Highway Authority. It was intended to obtain three readings during each summer season, but this was not always possible, particularly in the first year if the material was laid late in the season or access was restricted due to construction work, such as on the M4 during 1994. The Mean Summer SCRIM Coefficients (MSSC), or mean annual result if less than two results, are given in Appendix A, Section A.1.

When the monitoring was carried by TRL, the sensor-measured texture depth was also measured using SCRIMtex provided it was not raining at the time. The mean annual results are given in Appendix A, Section A.2.

Each year, the sites were assessed by an Inspection Panel using a marking system (Nicholls, 1997) based on one developed by Lees (1957). The results are given in Appendix A, Section A.3 with the marking system being reproduced in Appendix B.

5 Laboratory tests

Five different proprietary high-friction surface systems were investigated. The materials were an epoxy-resin (control), an acrylic-resin, a polyurethane-resin and two rosin-ester systems. Each material was applied to prepared chipped rolled asphalt slabs. The asphalt slabs with pre-coated chippings (305 mm x 305 mm x 50 mm nominal) were made at TRL with the finished surface grit blasted to simulate a worn asphalt surface with a texture depth (sand patch) in the range 1.0 to 1.4 mm. These slabs were then sent to each manufacturer for applying their respective products. When returned, the materials were tested using the scuffing test and wear test at TRL.

The scuffing test is designed to simulate the turning action of traffic and record any changes in the mechanical properties of the surfacings, with the equipment used described in Appendix C. The tests were carried out at 5°C and 45°C to give an indication of behaviour toward the temperature extremes experienced in the UK. Two samples of each material were tested at 45°C and one at 5°C for a total of 500 wheel passes each (approximately 8 minutes duration). At the end of each test, the material was visually assessed and photographed. Texture measurements were made on all the samples tested at 5°C, but it was not possible to carry out the measurements on one of the rosin-ester system materials tested at 45°C because the ‘scuffed’ area was uneven.

The wear test is designed to simulate the wear of extended trafficking using a circular test-track applying loads through vehicle wheels (designated as Road Machine No. 1 and described in Appendix D). Two samples of each material were arranged around the circular table of Road Machine No. 1, the test temperature set to 5°C and the table rotational speed to 10 revolutions per minute. The condition of the various materials was then monitored before and after the test run, which was curtailed after 100,000 wheel-passes when the tyres became shredded by the high-friction surface systems.

Texture depth was measured by the sand-patch test to BS 598: Part 105 (BSI, 1994) on the slabs in both tests, together with the skid resistance value using the portable skid resistance tester (RRL, 1960) and visual condition (Appendix B). The results from both the scuffing tests and the wear test are given in Appendix E.

The tests have been developed further into test protocols (Nicholls, 1997) for use in the *Highway Authorities Product Approvals Scheme* (HAPAS) for high-friction surface systems operated by the British Board of Agrément. With this certification scheme, requirements for appropriately certified high-friction surfacing systems can be incorporated into specifications by specifying bodies such as the Highways Agency and members of the CSS.

6 Discussion

6.1 Site performance

6.1.1 Site application

The rosin-ester based high-friction surface systems are applied by a hand-held shoe, although there have been (unsuccessful) attempts to apply it by machine. Each pass is visible on the finished surfacing, so that the resultant appearance is ‘striped’. They are quick to apply in small areas and require no curing time once the material has cooled to ambient temperature, so that such areas can be quickly reopened to traffic. However, this advantage over the more traditional epoxy-resin based systems is lost on more extensive sites because there are limited advantages of scale. Rosin-ester based systems are also able to be applied in difficult areas, such as relatively steep gradients. Overall, in terms of application, they appear to have advantages for relatively small or difficult jobs when the road needs to be reopened as soon as possible.

Polyurethane-resin based high-friction surface systems need careful storage prior to mixing, but the finished products appear robust. Polyurethane systems are currently hand-applied, which allows them to be easily used for small jobs and repair work but restricts the speed of operation relative to machine-application, whilst the final appearance is pleasing and the cure time is less than for conventional epoxy-resin based systems.

The acrylic-resin system appears to be similar to the conventional epoxy-resin systems except that it has a much shorter cure time and is applied by a self-contained machine, including the aggregate.

6.1.2 Skid resistance

6.1.2.1 Epoxy-resin

Epoxy-resin was used as the control for each of the other systems, and so its performance is reported in each of the following sections.

6.1.2.2 Rosin-ester

The SCRIM coefficients recorded on the A329(M)/M4 intersection show that initially the epoxy-resin system had the highest skid resistance of the surfacings with an average value of 0.81 in 1991 whilst the rosin-ester system, at 0.69, was also greater than the untreated concrete, at 0.49. This ranking and the differences between them was maintained, with the relevant average values being 0.75 (epoxy-resin), 0.68 (rosin-ester) and 0.45 (concrete) in 1994 and 0.63 (epoxy-resin), 0.58 (rosin-ester) and no record (concrete) in 1996. Hence, the rosin-ester system had a SCRIM coefficient approximately 0.2 greater than the untreated concrete and the epoxy-resin system had one 0.3 higher. The substrate type appeared to be of little significance, with the rosin-ester on rolled asphalt (R1) starting with an average SCRIM coefficient of 0.71 compared to 0.68 on concrete (R2 and R3) but with the minor difference being reversed in the following years. By 1995, after 4 years in service, the skid resistance drops significantly but erratically, presumably because the system was wearing thin and the substrate was exposed over part of the area, as observed during the visual condition inspection.

Berkshire County Council has monitored the accidents on the M4/A329(M) slip roads since the high-friction surface systems were applied. Although the data are limited and have not been analysed statistically, their view is that the number of accidents has reduced substantially. This may be due to the higher SCRIM coefficients or the visual effect of a section of ‘special material’. The latter effect is enhanced by the black tyre-marks left on the rosin-ester materials.

The SCRIM coefficients from the A5 for both resins on each date are shown graphically in Figure 5, with separate lines through the mean of the points on a date for each resin. As at Reading, the sections with the epoxy-resin system have a greater SCRIM coefficients than those with the rosin-ester system. This difference starts at about 0.2 but reduces to about 0.1 after a year, presumably because the resin is worn off the calcined bauxite. Given that this ranking order is consistent at all the sites, the difference in performance is considered to be significant.

The results from these two rosin-ester trials indicate that the SCRIM coefficient rises initially as the resin is worn off the aggregate, but remains about 0.1 units lower than the value achieved with the epoxy-resin system. Neither of these findings is surprising because the aggregate is totally embedded in the rosin-ester system, while it is scattered

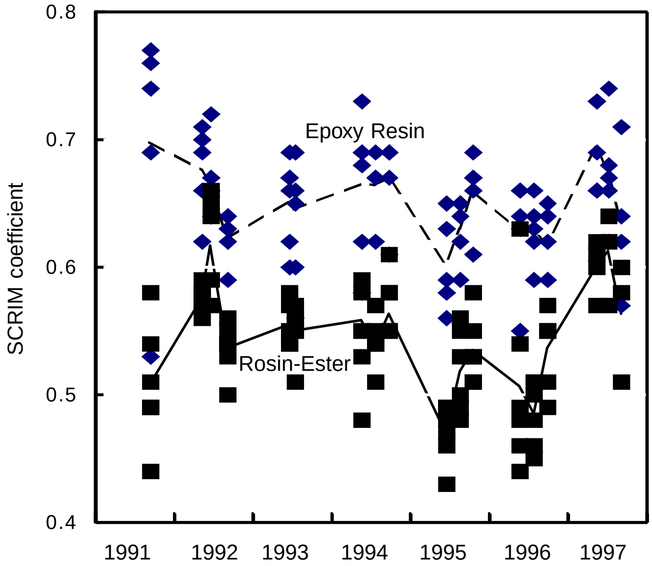

Figure 5 SCRIM results from A5, Warwickshire

over the sprayed binder in the epoxy-resin system. Also, the aggregate in the rosin-ester system used in the trials is not all calcined bauxite; no trials have been monitored with an embedded system containing 100 per cent calcined bauxite to assess the effect of using a mixed aggregate. Nevertheless, the performance of the rosin-ester system is better than that of the untreated areas and it has the advantage of being able to be applied at locations and in situations where a epoxy-resin system cannot be used.

6.1.2.3 Polyurethane-resin

At Durham, the initial average SCRIM coefficients for the polyurethane-resin, both using calcined bauxite and aluminium oxide aggregate, and epoxy-resin systems were all between 0.69 and 0.72, with no significant change between 1993 and 1994 results. There was a noticeable drop in some readings thereafter, although some of them then appear to recover. The two aluminium oxide sites had readings below the average for the calcined bauxite sites, but still well within the range of values obtained for the latter until 1995, when the values for sites with aluminium oxide dropped significantly. By 1997, the sites with polyurethane and epoxy-resin binders and calcined bauxite had dropped on average between 0.3 and 0.4 whilst the sites with polyurethane-resin and aluminium oxide had dropped on average by 0.10.

At Stratford, measurements were only made from 1994 (year 2) when, unfortunately, the second polyurethane-resin site was unavailable for testing. The average SCRIM coefficient for the polyurethane-resin system was higher than for the epoxy-resin system in year 2, but the difference was small and reduced to zero after four years before returning with a 0.3 difference in 1997. Nevertheless, the SCRIM coefficients for the polyurethane-resin system were very similar to those for the standard epoxy-resin system, as would be expected because, in both systems, the aggregate is broadcast over the pre-spread binder.

6.1.2.4 Acrylic-resin

The results from Nottingham show marginally higher SCRIM coefficients for the acrylic-resin system than for the epoxy-resin system, exaggerated in 1996 by a particularly low value. At Reading, the SCRIM coefficient for the acrylic-resin system during its first summer was lower than that of the epoxy-resin system in its first summer, being equivalent to the MSSC in its second and subsequent summers. However, the epoxy-resin had been laid in the spring whilst the acrylic-resin had been laid in the autumn; consequently, the acrylic-resin system had carried traffic for six months longer than the epoxy-resin system when tested. Hence, as with the polyurethane-resin system, the initial results indicate that the skid resistances will be very similar but with acrylic-resin systems having, if anything, marginally higher values than epoxy-resin systems.

6.1.2.5 Relative ranking

Combining all the data on SCRIM coefficients by taking averages for each binder type (and separating the polyurethane-resins between those with calcined bauxite as aggregate and those with aluminium oxide) and relating them to the number of summer seasons that the surfacing had been in service gives an overall performance as shown in Figure 6. In deriving the number of summer seasons during which a surfacing was in service, it was assumed that any system laid in or before September had experienced at least part of the summer, whilst those laid in October or later had not. Therefore, the base year for the various trial sites are as given in Table 7, with some having different dates for different resins due to the materials being laid in different months.

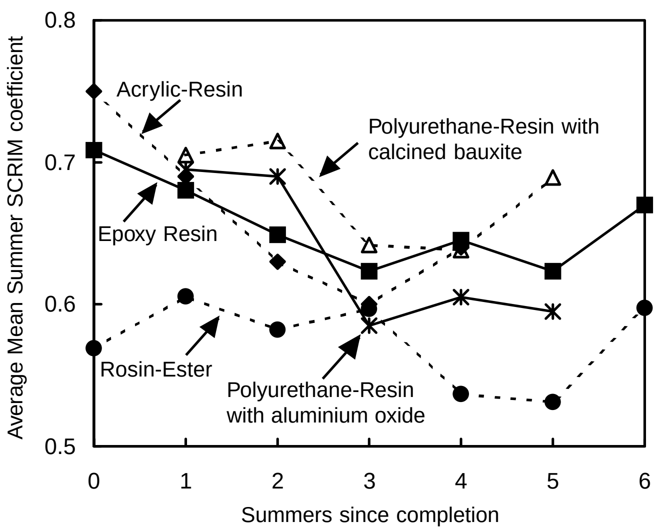

Figure 6 Mean summer SCRIM coefficients

The SCRIM coefficients are primarily dependant on the properties of the aggregate used, the traffic level on the site and the stress imposed at the site. Therefore, the MSSC levels should be independent of the system. Further, the weather can affect the result (hence the need for a testing season) and, because different sites were applied in

Table 7 Base year for trial sites

Site	*Resin*	*Base year*
M4/A329(M) Reading	Epoxy-resin and rosin-ester	1991
	Acrylic-resin	1994
A5 Warwickshire	Epoxy-resin and rosin-ester	1991
A1(M)/A167 Durham	Polyurethane-resin	1992
	Epoxy-resin	1993
A46 Stratford	Polyurethane-resin and epoxy-resin	1993
A453 Nottingham	Acrylic-resin and epoxy-resin	1993

different years, any overall shift in weather pattern could influence the relative performances. Nevertheless, Figure 6 gives some indication of an overall ranking for the binders and demonstrates the following points:

- the acrylic-resin started off with the highest values but dropped off more quickly to fall marginally below the epoxy-resin after two years, falling further below after three years, but recovering to be similar to epoxy-resin four years;
- the polyurethane-resin has a higher value than the epoxy-resin until the third year, when the two types give very similar results with calcined bauxite before the polyurethane-resin increased after 5 years;
- the aluminium oxide aggregate starts with similar SCRIM coefficients to the calcined bauxite in the same-resin type, but then drops off more quickly in year 3 before stabilising in years 4 and 5;
- the rosin-ester has the lowest SCRIM coefficient, initially about 0.2 lower with the difference reducing to about 0.1 units within a year; and
- all high-friction surfaces are significantly better than the untreated concrete on the Reading site, with only the rosin-ester not exceeding the 0.55 investigatory level (DMRB 7.3.1) required of the most difficult sites.

With the exception of the difference between the encapsulated rosin-ester system and the exposed aggregate of the other systems, these differences could be explained by differences in the aggregate rather than any inherent differences in the resins. Nevertheless, the ranking of the binder systems with calcined bauxite aggregate in descending order of MSSC values is polyurethane-resin, epoxy-resin, acrylic-resin and rosin-ester.

6.1.3 Texture depth

6.1.3.1 Epoxy-resin

Epoxy-resin was used as the control for each of the other systems, and so its performance is reported in each of the following sections.

6.1.3.2 Rosin-ester

The average texture depths for the different surrfacings on the Reading site show that the concrete which had not been treated with high-friction surfacing had the deepest sensor-measured texture depth with 0.68 mm in 1992 rising to 0.80 mm in 1994 (although that on the two different slip roads were quite different with 0.72 mm and 0.87 mm in

1994), the section with the epoxy-resin system had texture depths of 0.63 mm to 0.68 mm and the sections with the rosin-ester system had about 0.55 mm in each year (except for an unexplained high value in 1995). On the A5, there was a similar ranking order but the difference was more marked with the mean sensor-measured texture depth for the epoxy-resin system being about 0.7 mm whilst that for the rosin-ester system was about 0.45 mm. The 'traditional' epoxy-resin system are known to have relatively low texture depths, but the results indicate that the texture depth of rosin-ester systems could be substantially lower than those of epoxy-resin systems.

6.1.3.3 Polyurethane-resin

At Durham, the initial average sensor-measured texture depths were 0.66 mm for the polyurethane-resin/calcined bauxite system, 0.75 mm for the polyurethane-resin/aluminium oxide system and 0.67 mm for the epoxy-resin/calcined bauxite system. This gives a reverse ranking to that found for SCRIM coefficients. Thereafter, the values for calcined bauxite with both resins remained essentially constant (although with some variation) whilst the texture depth for the polyurethane with aluminum oxide tended to drop more noticeably (although still with marginally the highest value in 1997). At Stratford, the epoxy-resin system again had marginally better sensor-measured texture depths, averaging 0.62 mm compared to 0.56 mm for the polyurethane-resin system in year 2 and very similar values after 4 years. However, in 1997 the value for the epoxy-resin system dropped noticeably, believed to have been due to mud on the road at one roundabout.

6.1.3.4 Acrylic-resin

Of the four initial sensor-measured texture depth results from Nottingham, three were very similar and one, from the acrylic-resin site, was significantly lower. Thereafter, the results for the epoxy-resin system tended to drift down slightly whilst those for the acrylic-resin system varied widely. However, the texture depth from the sites at Reading with the acrylic-resin system were greater than the equivalent values from the epoxy-resin system. Therefore, it is possible that this low result is untypical and that the acrylic-resin system generally has very similar texture depths to epoxy-resin systems.

6.1.3.5 Relative ranking

Combining all the data on sensor-measured texture depths by taking averages for each binder type (and separating the polyurethane-resins between those with calcined bauxite as aggregate and those with aluminium oxide) and relating them to the number of summer seasons during which they were in service (Table 7) gives an overall performance as shown in Figure 7.

Figure 7 shows that the epoxy-resin and polyurethane-resin systems with calcined bauxite are relatively consistent, whilst the acrylic-resin system with calcined bauxite and the polyurethane-resin with aluminium oxide systems start somewhat higher but then dropped below before recovering, in the case of the acrylic-resin to a higher value than initially. The rosin-ester starts and ends lower than the other systems and consistently drops further. Overall, the higher texture is achieved with the systems where the aggregate is scattered over the binder compared with the rosin-ester systems, where it is encased; of binders employing the scatter approach, the epoxy-resin and the polyurethane-resin systems are the more consistent. In terms of ranking for sensor-measured texture depth, the epoxy-resin and polyurethane-resin systems are best because they are consistently high, the acrylic-resin system is dropped to third because of its variability and the rosin-ester systems are last because of their relatively low and declining values.

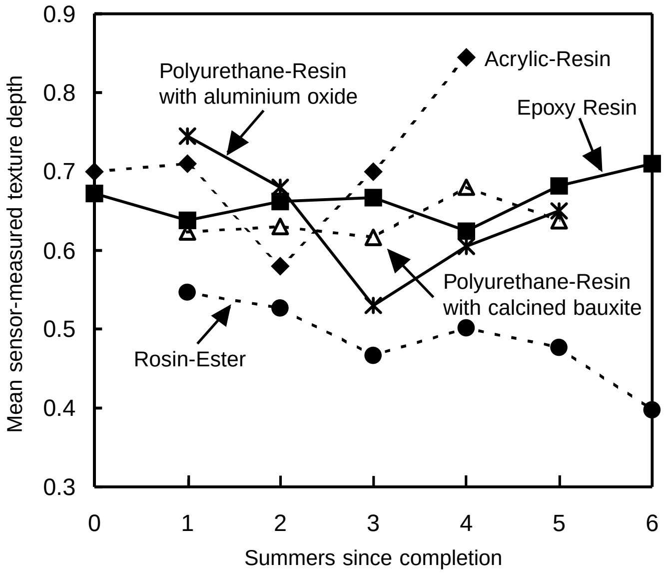

Figure 7 Mean sensor-measured texture depths

6.1.4 Durability

6.1.4.1 Debonding

Debonding (also known as 'delamination') has also been found on various sites throughout the UK with several of the binder systems, especially rosin-ester and polyurethane-resin. Debonding appears to be a particular problem when the systems are laid sufficiently thickly for the layers to have the strength to act independently from the underlying substrate. Therefore, a compromise is needed during application between applying sufficient material to resist wear from trafficking and restricting the thickness in order to allow the layer to move thermally with the substrate.

6.1.4.2 Epoxy-resin

The durability of epoxy-resin is generally regarded as good. However, when Hereford and Worcester County Council carried out a survey of sites in Herefordshire on which epoxy-resin based surface treatments had been used, it found a generally high standard of work but with exceptions that, at the relatively high cost of the process, were worth noting. The faults found included:

- ‘transverse ribbing’, primarily a visual defect caused by a worn chipping bar producing line-type depositions of aggregate or, possibly, by the spray-bar skirt dragging the sprayed binder;
- ‘lumping’, an unsightly defect of random ridges, bulges and other surface irregularities caused by brushing or disturbing the aggregate before the binder has cured - the aggregate is ‘rolled’ in lumps which cure en-masse; and
- ‘grinning’, the general mode of wear failure with part of the old surface showing through, which may be exacerbated by rigid or inflexible material flaking off hard (i.e. aggregate) surfaces where there is little or no bond to the applied material.

At the Reading site where an epoxy-resin system was applied over concrete, this was assessed by the Inspection Panel as being significantly the best in 1992 but only similar to the other sections the following year. The marking for this section was reduced because of local debonding at the edge of three bays near the middle. The debonding probably started there because the pre-heating of the existing surface prior to laying had to be restrained to avoid damaging the jointing material. The epoxy-resin system was then marked higher following local repairs although it subsequently dropped again.

These comments are included to show that even the control material is not perfect: similar results could be expected from surveys of high-friction surface systems with other resins.

6.1.4.3 Rosin-ester

A joint inspection by representatives of the county, Highway Agency and TRL was carried out on several sites in Worcestershire on which the rosin-ester based surface treatment had been used. As with the epoxy-resin sites, the material was performing effectively on most of the sites but there were some defects. These defects included:

- ‘stripes’, a visual defect caused by strips wearing differentially, presumably because the shoe is filled to a different extent on each application;
- ‘laminating’, a major fault caused by thick layers of the material not adequately adhering to the underlying layer; and
- ‘patches’, a visual defect where different batches of the material, usually applied at different times, are of a different colour.

The section at Reading with the rosin-ester system sites only started with ‘Moderate’ ratings on average, which slipped to an average of ‘Acceptable’ in 1994 and 1995 and to ‘Acceptable to Suspect’ in 1996 due to the material wearing thin with the trafficking. On the A5, the rosin-ester sites obtained similar ratings, but here they were always inferior by at least one grade to the epoxy-resin systems, rising to two grades after five to six years. The difference between the performance of the system at both sites indicates that the rosin-ester system is not as durable as the ‘traditional’ epoxy-resin system.

The relatively poor durability of rosin-ester high-friction surface systems, indicated by the visual assessments by the Inspection Panel and the results of laboratory tests (Section 6.2), is supported by observation of sites that are not part of this trial. An example is at the junction of the M42 and A38 near Bromsgrove (Figure 8) where the material was laid in November 1989 and the photograph taken in early 1993, 3½ years later. This section has since been replaced.

Figure 8 Worn rosin-ester system, after 3½ years

6.1.4.4 Polyurethane-resin

The polyurethane-resin system gave a very good initial appearance, particularly at the Stratford sites. The average Inspection Panel assessments at Durham indicate that the polyurethane-resin/ calcined bauxite system was not as good as the other two initially or subsequently, whilst the polyurethane-resin/aluminium oxide system started equal to the epoxy-resin but thereafter was not quite as good. All three systems degenerated gradually with time in service. However, the polyurethane-resin/calcined bauxite combination was heavily biased by the problems on two sections where the component materials were damp (see Section 3.2.1).

At Stratford, all the sites were in either ‘Good’ or ‘Excellent’ condition up to 1994, with all the polyurethane-resin system sites being marked as ‘Excellent’. However, the average for the polyurethane-resin system was down to ‘Moderate to Acceptable’ in 1996 compared to ‘Good to Moderate’ for the epoxy-resin system, this ranking being reversed in 1997. The results demonstrate that the relatively poor initial results by the Inspection Panel for the sites with the polyurethane-resin/ calcined bauxite system at Durham may not necessarily be indicative of poor durability but lack of care in application, but that in the longer term the epoxy-resin system performs better.

6.1.4.5 Acrylic-resin

The ‘Acceptable’ assessment for the acrylic-resin system site at Nottingham after less than a year, dropping to ‘Suspect to Poor’ after four years, is primarily due to the fairly extensive areas where the aggregate on the underlying surface is visible or showing through, whilst the epoxy-resin system was ‘Good to Moderate’ for three years and still ‘Moderate’ the following year. Similarly, the acrylic-resin system was ‘Good to Moderate’ at Reading compared to ‘Excellent’ dropping to ‘Good’ for the epoxy-resin system at the same stages. These results indicate that there is some uncertainty about the durability of the acrylic-resin system.

6.1.4.6 Relative ranking

Combining all the data on visual assessments by taking averages for each binder type (and separating the polyurethane-resins between those with calcined bauxite as aggregate and those with aluminium oxide) and relating them to the number of summer seasons in service (Table 7) gives an overall performance as shown in Figure 9.

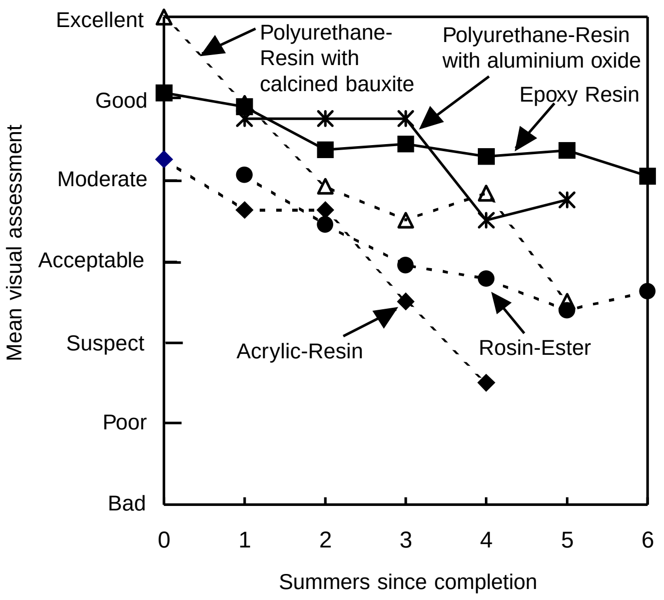

Figure 9 Mean visual assessment categories

Figure 9 allows an overall ranking of systems to be made from the observations to date in terms of durability. This ranking, ignoring the polyurethane-resin with aluminium oxide as aggregate, is that the epoxy-resin system is best, then the polyurethane-resin system, the rosin-ester system and finally the acrylic-resin system. The polyurethane-resin with aluminium oxide appears to be best of all until the fourth year, but the result is derived from only two sites.

6.1.5 Overall ranking

The overall rankings for the various resins trialled with calcined bauxite as the aggregate is as follows:

	SCRIM coefficient	*Texture depth*	*Visual assessment*	*Overall*
Epoxy-resin	2	1 =	1	1 =
Polyurethane-resin	1	1 =	2	1 =
Acrylic-resin	3	3	4	3
Rosin-ester	4	4	3	4

Combining the rankings for the individual properties gives the overall ranking, with the systems that were tested in descending order of performance being epoxy-resin and polyurethane-resin, acrylic-resin and rosin-ester. This overall ranking might be affected by the addition of other factors, such as the susceptibility to dampness of the component materials.

6.2 Laboratory tests

6.2.1 Performance

From the scuffing test at 5°C, all the materials behaved similarly and thus no comparative ranking could be made. It was concluded that the test regime was not sufficiently severe to differentiate between the different materials. At the higher test temperature, differences do emerge, with the rosin-ester systems showing the greater wear, probably due to the thermoplastic nature of the systems. This was particularly noticeable in the case of the samples with one of the systems, where material started sticking to the test wheel. If this was reflected in practice at severely stressed road sites, then wear is likely to be rather rapid at high road temperatures.

A further problem observed during the higher temperature test was the tendency for some of the materials to debond from the underlying asphalt. The reasons for this are difficult to determine from this test alone. However, with the asphalt being relatively soft and the high-friction surface systems being relatively stiff at this temperature, large shear stresses can be induced at the interface layer which may have caused debonding to take place. The scuffing regime itself with localised stressed areas (especially at the end of the wheel travel) may have exacerbated the problem.

Earlier work carried out on epoxy-resin based systems, containing different amounts of epoxy-resin (Denning & Carswell, 1983), also showed this debonding effect at the higher test temperatures. In some formulations, the whole treatment was removed after relatively few passes. In practice, evidence of debonding has been reported from a number of road sites where high-friction surface systems have been used. Some of these treatments have debonded because of water ingress and, to a lesser extent, the presence of dirt and grease. At this stage, it is not possible to say whether the debonding observed in the scuffing test relates to the debonding observed at some of the road sites. A more rigorous laboratory test programme would need to be carried out to investigate this aspect further.

From the single test run using Road Machine No. 1 carried out at 5°C and 10 revolutions per minute, differences emerged between the systems tested. All the systems showed a reduction in texture, caused through the dislodgment of loosely held chippings. The pendulum values remained high, with the rosin-ester systems (which contain the calcined bauxite within the mixture) showing an increase in skid resistance value. This was most probably due to exposure of the aggregate, which also indicates material wear. Visually, some of the materials were wearing thin, although this may have been exacerbated by the exposed metal reinforcement of the shredded tyres. However, given that all the samples were subjected to the same severity of tracking, it would indicate that some systems are likely to wear at a more rapid rate than others.

Using consistent test parameters will allow these tests to be standardised to compare different systems, which has already been done on a limited scale (Liles, 1994). The tests, as part of a more extensive suite of tests, could be included in the development of performance-related specifications. However, they are being prepared for the *Highway Authorities Product Approval Scheme* (HAPAS) run by the British Board of Agrément on behalf of highway specifying authorities as a certification scheme for high-friction surface systems which itself is to be called up in the *Specification for Highway Works* (MCHW 1).

6.2.2 Comparison with site performance

From the scuffing test at 5°C, no difference was found between the resins whilst, from the scuffing test at 45°C, a ranking was found from the visual assessments with the polyurethane-resin system being best, followed by the epoxy-resin system just ahead of the acrylic-resin system and the rosin-ester systems last. The wear test produced similar rankings using either the visual assessment or the final skid resistance values, these being:

	Skid resistant value	*Visual assessment*	*Overall*
Epoxy-resin	1	1 =	1
Polyurethane-resin	3 =	1 =	2
Acrylic-resin	2	3	3
Rosin-ester	3 =	4	4

The visual assessment is considered to be more representative because the skid resistance value is partially dependant on the polished stone value of the aggregate (although the polyurethane-resin, which finished with nearly the lowest SRV, did start with the highest value). Overall, the rosin-ester systems did not perform as well as the other three resin types, between which the differences in performance were less distinct.

The results from the road trials are also discriminating between the different types of high-friction surface system (Section 6.1.5). The relative rankings for site : laboratory measurements are as follows:

	Skid resistance	*Texture*	*Visual*	*Overall*
Epoxy-resin	2 : 1	1 = : -	1 : 1 =	1 = : 1
Polyurethane-resin	1 : 3 =	1 = : -	2 : 1 =	1 = : 2
Acrylic-resin	3 : 2	3 : -	4 : 3	3 : 3
Rosin-ester	4 : 3 =	4 : -	3 : 4	4 : 4

This comparison shows a real but imperfect correlation between the results of the laboratory tests and observation from site.

7 Conclusions

Although the study was based on measurements at a restricted number of test sites, and only epoxy-resin systems were laid on all of those sites, the following conclusions can be drawn:

1 The performance of resins in the trials has been assessed by visual assessment and by measuring SCRIM coefficient and texture depth; the overall ranking order of resins that is beginning to emerge is that the ‘traditional’ epoxy-resin system and the polyurethane-resin systems have performed the best, then the acrylic-resin system and finally the rosin-ester system.

2 After six years in service, a rosin-ester high-friction surface system can still be effective, but not as effective as a surface with a standard epoxy-resin and is likely to need replacement.

3 Initially, a polyurethane-resin system appears to be as good as a conventional epoxy-resin system, even though the former was hand laid. However, after four years in service there is evidence that the durability of polyurethane-resin systems is less effective than that of epoxy-resin systems. It has also been found to be very important to store the components of the polyurethane-resin system carefully.

4 After four years in service, the performance of an acrylic-resin system performed only marginally better than that of a rosin-ester system. Fairly extensive areas where the high-friction surface system had worn sufficiently to expose aggregate from the underlying surface during the first year has raised concerns about the durability of the system.

5 Debonding from the asphalt layer is a potential problem with all high-friction surface systems. In some cases, the rosin-ester systems showed signs of debonding in the scuffing test. The over-thick application of high-friction surface systems can cause debonding.

6 From very limited comparisons, aluminium oxide initially appears to be at least as good as calcined bauxite for the aggregate in these systems, but its longer-term performance appears less promising.

7 Laboratory assessment of the materials has been found to be feasible. The scuffing test at 45°C is able to identify those materials which are likely to suffer debonding from the substrate at high road temperatures; the wear test using Road Machine No. 1 is able to provide an indication whether a product will be as durable as a high-friction surface system. The results are reasonably consistent with the observed relative performances on the road.

8 Acknowledgements

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Appendix A: Road trial results

A.1 Mean summer SCRIM Coefficients

Site	*Section*	*Resin*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
M4/A329(M)	R1	Rosin-ester	0.71	0.65	0.62*	0.68*	0.71	0.59	-
Reading	NX	None	0.51	0.47	0.43*	0.46*	-	-	-
	R2	Rosin-ester	0.68	0.66	0.63*	0.68*	0.41	0.56	-
	R3	Rosin-ester	0.68	0.71	0.65*	0.69*	0.66	0.59	-
	NX	None	0.47	0.45	0.43*	0.44*	-	-	-
	R4	Epoxy-resin	0.81	0.76	0.72*	0.75*	0.66	0.63	-
	R5	Acrylic-resin	-	-	-	0.75*	0.61	0.64	-
	R6	Acrylic-resin	-	-	-	0.75*	0.78	0.62	-
	Mean	None	0.49	0.46	0.43	0.45	-	-	
		Epoxy-resin	0.81	0.76	0.72	0.75	0.66	0.63	
		Rosin-ester	0.69	0.67	0.63	0.68	0.59	0.58	
		Acrylic-resin				0.75	0.70	0.63	
A5	W1, n/b	Epoxy-resin	0.53†	0.67	0.68*	0.58†	0.61	0.62	0.62
Warwickshire	W1, s/b	Epoxy-resin	-	-	0.58*	0.67	-	-	-
	W2, n/b	Rosin-ester	0.44†	0.57	0.58*	0.56	0.55	0.53	0.62
	W2, s/b	Rosin-ester	0.49†	0.58	0.56*	0.57	0.53	0.54	0.60
	W3, n/b	Epoxy-resin	0.74†	0.64	0.69*	0.64	0.65	0.62	0.73
	W3, s/b	Epoxy-resin	0.69†	0.65	0.62*	0.69	0.63	0.60	0.65
	W4, n/b	Rosin-ester	0.54†	0.57	0.56*	0.55	0.50	0.48	-
	W4, s/b	Rosin-ester	0.49†	0.56	0.55*	0.57	0.47	0.50	-
	W5, n/b	Epoxy-resin	0.76†	0.65	0.66*	0.68	0.66	0.64	0.67
	W5, s/b	Epoxy-resin	0.77†	0.66	0.67*	0.68	0.66	0.63	0.68
	W6, n/b	Rosin-ester	0.51†	0.58	0.55*	0.51	0.51	0.51	0.60
	W6, s/b	Rosin-ester	0.58†	0.57	0.54*	0.56	0.49	0.48	0.57
	Mean	Epoxy-resin	0.70	0.65	0.67	0.66	0.64	0.62	0.67
		Rosin-ester	0.51	0.57	0.56	0.55	0.51	0.51	0.60
A1(M)/A167	D1, n/b	Polyurethane‡	-	-	0.71*	0.68	0.60	0.59	0.61
Durham	D1, s/b	Epoxy-resin	-	-	0.69*	0.72	0.57	0.56	0.65
	D2, n/b	Epoxy-resin	-	-	0.70*	0.71	0.68	0.63	0.69
	D2, s/b	Polyurethane	-	-	0.73*	0.73	0.64	0.60	0.68
	D3, n/b	Epoxy-resin	-	-	0.64*	0.65	0.62	-	0.67
	D4, to A1(M)								
	n/b on	Epoxy-resin	-	-	0.69*	0.73	0.70	0.69	0.68
	s/b off	Polyurethane	-	-	0.77*	0.78	0.69	0.66	0.72
	n/b off	Epoxy-resin	-	-	0.72*	0.75	0.70	0.66	0.67
	D4, to A167	Epoxy-resin	-	-	0.74*	0.77	0.68	0.63	0.69
	D5, n/b	Epoxy-resin	-	-	-	-	-	0.58	0.61
	D5, s/b, o/s	Epoxy-resin	-	-	0.65*	0.71	-	-	-
	D5, s/b, n/s	Polyurethane	-	-	0.68*	0.66	0.65	0.66	0.67
	D6, n/b	Polyurethane	-	-	0.70*	0.71	0.67	0.62	0.68
	D6, s/b	Epoxy-resin	-	-	0.72*	0.70	0.68	0.59	0.65
	D7, n/b	Epoxy-resin	-	-	0.78*	0.66	0.68	0.59	0.66
	D7, s/b	Polyurethane‡	-	-	0.68*	0.70	0.57	0.62	0.58
	Mean	Epoxy-resin			0.70	0.71	0.66	0.62	0.66
		Polyurethane			0.72	0.72	0.66	0.64	0.69
		Polyurethane‡			0.70	0.69	0.59	0.61	0.60
A46	S1, w/b	Polyurethane	-	-	#	0.63	0.71	0.58	0.64
Stratford	S1, e/b	Polyurethane	-	-	#	0.72	0.70	0.62	0.65
	S2, w/b	Epoxy-resin	-	-	#	0.63	0.62	0.58	0.63
	S2, e/b	Epoxy-resin	-	-	#	0.63	0.65	0.58	0.61
	S4, w/b	Epoxy-resin	-	-	#	0.67	0.61	0.65	0.64
	S4, e/b	Epoxy-resin	-	-	#	0.62	0.59	0.57	0.61
	Mean	Epoxy-resin				0.64	0.62	0.60	0.62
		Polyurethane				0.68	0.71	0.60	0.65
A453	N1, s/b	Acrylic-resin	-	-	-	0.69	0.65	0.60	0.62
Nottingham	N1, n/b	Acrylic-resin	-	-	-	0.68	0.61	0.60	0.66
	N2, s/b	Epoxy-resin	-	-	-	0.63	0.58	0.47	0.59
	N2, n/b	Epoxy-resin	-	-	-	0.68	0.65	0.62	0.63
	Mean	Epoxy-resin				0.66	0.62	0.55	0.61
		Acrylic-resin				0.69	0.63	0.60	0.64

** Mean of measurements on only two dates*
 # Data missing because no surveys carried out
† Measurement on single date
‡ Aluminium oxide used as aggregate rather than calcined bauxite

n/b = north bound
s/b = south bound
e/b = east bound
w/b = west bound

A.2 Annual mean sensor-measured texture depths (SCRIMtex)

Site	*Section*	*Resin*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
M4/A329(M)	R1	Rosin-ester	-	0.52	0.48	0.53	1.97*	0.57	-
Reading	NX	None	-	0.60	0.65	0.72	-	-	-
	R2	Rosin-ester	-	0.57	0.54	0.53	0.66	0.48	-
	R3	Rosin-ester	-	0.55	0.56	0.57	0.53	0.58	-
	NX	None	-	0.75	0.79	0.87	-	-	-
	R4	Epoxy-resin	-	0.64	0.63	0.68	0.66	0.63	-
	R5	Acrylic-resin	-	-	-	0.72	0.61	0.62	-
	R6	Acrylic-resin	-	-	-	0.68	0.78	0.62	-
	Mean	None		0.68	0.72	0.80	-	-	
		Epoxy-resin		0.64	0.63	0.68	0.66	0.63	
		Rosin-ester		0.55	0.53	0.54	0.65	0.54	
		Acrylic-resin				0.70	0.70	0.62	
A5	W1, n/b	Epoxy-resin	-	-	-	0.89	0.64	0.72	0.87
Warwickshire	W1, s/b	Epoxy-resin	-	-	-	0.70	-	-	-
	W2, n/b	Rosin-ester	-	-	-	0.33	0.41	0.47	0.56
	W2, s/b	Rosin-ester	-	-	-	0.41	0.33	0.38	0.34
	W3, n/b	Epoxy-resin	-	-	-	0.62	0.69	0.64	0.64
	W3, s/b	Epoxy-resin	-	-	-	0.64	0.64	0.58	0.61
	W4, n/b	Rosin-ester	-	-	-	0.48	0.41	0.43	-
	W4, s/b	Rosin-ester	-	-	-	0.48	0.59	0.60	-
	W5, n/b	Epoxy-resin	-	-	-	0.71	0.70	0.67	0.69
	W5, s/b	Epoxy-resin	-	-	-	0.70	0.78	0.85	0.74
	W6, n/b	Rosin-ester	-	-	-	0.45	0.72	0.34	0.34
	W6, s/b	Rosin-ester	-	-	-	0.42	0.36	0.44	0.35
	Mean	Epoxy-resin				0.71	0.69	0.69	0.71
		Rosin-ester				0.43	0.47	0.44	0.40
A1(M)/A167	D1, n/b	Polyurethane‡	-	-	0.77	0.65	0.44	0.57	0.64
Durham	D1, s/b	Epoxy-resin	-	-	0.55	0.53	0.49	0.47	0.50
	D2, n/b	Epoxy-resin	-	-	0.55	0.50	0.57	0.47	0.48
	D2, s/b	Polyurethane	-	-	0.64	0.56	0.55	0.63	0.57
	D3, n/b	Epoxy-resin	-	-	0.69	0.61	0.50	-	0.65
	D4, to A1(M)								
	n/b on	Epoxy-resin	-	-	0.50	0.53	1.23*	0.72	0.59
	s/b off	Polyurethane	-	-	0.55	0.62	0.53	0.63	0.64
	n/b off	Epoxy-resin	-	-	0.68	0.65	0.75	0.90	0.71
	D4, to A167	Epoxy-resin	-	-	0.72	0.67	0.69	0.64	0.66
	D5, n/b	Epoxy-resin	-	-	-	-	-	0.53	0.58
	D5, s/b, o/s	Epoxy-resin	-	-	0.76	0.66	-	-	-
	D5, s/b, n/s	Polyurethane	-	-	0.60	0.62	0.65	0.63	0.56
	D6, n/b	Polyurethane	-	-	0.83	0.78	0.85	1.04	0.78
	D6, s/b	Epoxy-resin	-	-	0.80	0.70	0.71	0.69	0.66
	D7, n/b	Epoxy-resin	-	-	0.80	0.67	0.74	0.75	0.72
	D7, s/b	Polyurethane‡	-	-	0.72	0.71	0.62	0.70	0.68
	Mean	Epoxy-resin			0.67	0.61	0.64	0.65	0.62
		Polyurethane			0.66	0.65	0.65	0.73	0.64
		Polyurethane‡			0.75	0.68	0.53	0.64	0.66
A46	S1, w/b	Polyurethane	-	-	#	0.51	0.64	0.58	0.54
Stratford	S1, e/b	Polyurethane	-	-	#	0.61	0.56	0.54	0.61
	S2, w/b	Epoxy-resin	-	-	#	0.64	0.73	0.66	0.57
	S2, e/b	Epoxy-resin	-	-	#	0.54	0.64	0.58	0.51
	S4, w/b	Epoxy-resin	-	-	#	0.70	0.61	0.71	0.53
	S4, e/b	Epoxy-resin	-	-	#	0.58	0.61	0.55	0.50
	Mean	Epoxy-resin				0.62	0.65	0.63	0.53
		Polyurethane				0.56	0.60	0.56	0.58
A453	N1, s/b	Acrylic-resin	-	-	-	0.66	0.56	0.79	0.63
Nottingham	N1, n/b	Acrylic-resin	-	-	-	0.79	0.52	0.61	1.06
	N2, s/b	Epoxy-resin	-	-	-	0.80	0.78	0.74	0.74
	N2, n/b	Epoxy-resin	-	-	-	0.79	0.82	0.71	0.60
	Mean	Epoxy-resin				0.80	0.80	0.73	0.67
		Acrylic-resin				0.73	0.54	0.70	0.82

** Not included in calculation of mean because it is an outlier, possible due to intermittent loss of surfacing*
 # Data missing because no surveys carried out
‡ Aluminium oxide used as aggregate rather than calcined bauxite

A.3 Visual assessment

Site	*Section*	*Resin*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
M4/A329(M)	R1	Rosin-ester	-	M_{v}	M_{v}	MA_{-}	$A_{v,d,w}$	$A_{v,d,w}$	-
Reading	R2	Rosin-ester	-	M	MA_{v}	$AS_{-,d}$	$AS_{v,d,w}$	$S_{t,d,w}$	-
	R3	Rosin-ester	-	M_{v}	GM_{v}	$MA_{d,v}$	$A_{v,d,w}$	$AS_{v,d,w}$	-
	R4	Epoxy-resin	-	E	M_{d}	G	G	GM_{d}	-
	R5	Acrylic-resin	-	-	-	GM_{-}	$M_{v,w}$	$M_{v,t,w}$	-
	R6	Acrylic-resin	-	$\underline{-}$	$\underline{-}$	$\underline{M_{v}}$	$\underline{G_{w}}$	$\underline{GM_{w}}$	-
	Mean	Epoxy-resin		E	M	G	G	GM	
		Rosin-ester		M	M	A	A	AS	
		Acrylic-resin				GM	GM	GM	
A5	W1, n/b	Epoxy-resin	-	$M_{t,c}$	GM	G	GM_{w}	M_{w}	M_{w}
Warwickshire	W1, s/b n/s	Epoxy-resin	-	EG	MA_{c}	$A_{d,c}$	$MA_{c,w}$	$M_{d,c}$	$MA_{d,c,w}$
	o/s			G	G	G	E	G	
	W2, n/b	Rosin-ester	-	G	$MA_{t,c}$	A_{c}	M_{c}	$A_{d,c,w}$	$S_{d,c,w}$
	W2, s/b	Rosin-ester	-	G	$MA_{t,c}$	A_{c}	$MA_{d,c,w}$	$A_{d,c,w}$	$A_{t,d,c,w}$
	W3, n/b	Epoxy-resin	-	$M_{v,c}$	MA_{c}	M_{c}	M_{c}	M_{c}	$M_{c,w}$
	W3, s/b	Epoxy-resin	-	G	MA_{c}	$M_{v,c}$	$M_{c,w}$	$M_{c,w}$	M_{c}
	W4, n/b	Rosin-ester	-	MA_{c}	$S_{v,d,c}$	$S_{v,d,c}$	$S_{d,c}$	$SP_{v,d,c,w}$	†
	W4, s/b	Rosin-ester	-	M_{v}	$AS_{v,d,c}$	$SP_{v,d,c}$	$SP_{d,c}$	$P_{v,d,c,w}$	†
	W5, n/b	Epoxy-resin	-	MA	G	G	G	G_{c}	GM_{c}
	W5, s/b	Epoxy-resin	-	EG	M_{c}	$M_{t,c}$	$M_{t,c,w}$	$M_{c,w}$	$MA_{c,w}$
	W6, n/b	Rosin-ester	-	MA_{c}	M_{c}	M_{c}	MA_{c}	$A_{v,c,w}$	$AS_{t,c,w}$
	W6, s/b	Rosin-ester	-	$\underline{MA_{c}}$	$\underline{MA_{c}}$	$\underline{MA_{c}}$	$\underline{S_{d,c,w}}$	$\underline{AS_{v,d,c,w}}$	$\underline{A_{t,d,c,w}}$
	Mean	Epoxy-resin		GM	M	M	GM	GM	M
		Rosin-ester		M	A	A	A	AS	AS
A1(M)/A167	D1, n/b	Polyurethane‡	-	-	GM	GM	G	G	GM_{w}
Durham	D1, s/b	Epoxy-resin	-	-	G	G	G	EG	EG
	D2, n/b	Epoxy-resin	-	-	G	$GM_{-,c}$	MA_{w}	$M_{c,w}$	$MA_{c,w}$
	D2, s/b	Polyurethane	-	-	$MA_{v,d}$	$A_{-,t}$	$AS_{c,w}$	$M_{c,w}$	$AS_{d,c,w}$
	D3, n/b	Epoxy-resin	-	-	M_{d}	MA_{-}	GM_{w}	M_{w}	MA_{w}
	D4, to A1(M)								
	n/b on	Epoxy-resin	-	-	M	M_{-}	G	GM_{w}	M_{w}
	s/b off	Polyurethane	-	-	G	GM_{d}	G	G	GM_{d}
	n/b off	Epoxy-resin	-	-	G	G	MA_{w}	GM_{w}	M_{w}
	D4, to A167	Epoxy-resin	-	-	EG	G	GM_{w}	GM_{w}	M_{w}
	D5, n/b	Epoxy-resin	-	-	G	GM	M_{w}	M_{w}	MA_{w}
	D5, s/b, o/s	Epoxy-resin	-	-	G	GM	M_{w}	GM_{w}	M_{w}
	D5, s/b, n/s	Polyurethane	-	-	$AS_{v,d}$	$SP_{d,c}$	$SP_{v,d,c}$	$S_{d,c}$	$SP_{d,c,w}$
	D6, n/b	Polyurethane	-	-	GM	GM_{c}	$GM_{c,w}$	G	$SP_{v,c,w}$
	D6, s/b	Epoxy-resin	-	-	EG	EG	M_{c}	AS_{d}	$M_{v,c,w}$
	D7, n/b	Epoxy-resin	-	-	EG	EG	GM_{w}	G	G
	D7, s/b, 1st	Polyurethane‡	-	-	G	G	GM_{c}	S_{d}	SP_{d}
	extra					$\underline{PB}$	$\underline{PB_{v,d}}$		$\underline{GM}$
	Mean	Epoxy-resin			G	G	M	GM	M
		Polyurethane			M	A	MA	M	AS
		Polyurethane‡			G	M	M	M	MA
A46	S1, w/b	Polyurethane	-	-	E	E	EG	$MA_{d,c,w}$	$MA_{d,c,w}$
Stratford	S1, e/b	Polyurethane	-	-	E	E	GM_{w}	$M_{d,c}$	$MA_{d,c}$
	S2, w/b	Epoxy-resin	-	-	G	G	G	G	G
	S2, e/b	Epoxy-resin	-	-	E	E	GM_{w}	G	G
	S3, w/b	Polyurethane	-	-	E	E	*	*	*
	S3, e/b	Polyurethane	-	-	E	E	*	*	*
	S4, w/b	Epoxy-resin	-	-	G	G	G	GM_{w}	GM_{w}
	S4, n/b	Epoxy-resin	-	-	G	E	G	G	$M_{c,w}$
	S4, e/b	Epoxy-resin	-	-	$\underline{EG}$	$\underline{E}$	$\underline{G}$	$\underline{M_{c,w}}$	$\underline{GM_{w}}$
	Mean	Epoxy-resin			EG	EG	G	GM	MA
		Polyurethane			E	E	G	MA	GM
A453	N1, w/b	Acrylic-resin	-	-	-	AS_{s}	$A_{v,w}$	S_{w}	$SP_{c,w}$
Nottingham	N1, e/b	Acrylic-resin	-	-	-	A_{s}	$A_{v,w}$	A_{w}	$SP_{v,c,w}$
	N2, w/b	Epoxy-resin	-	-	-	M_{s}	$M_{t,w}$	M_{w}	$M_{t,c,w}$
	N2, e/b	Epoxy-resin	-	-	-	$\underline{G}$	$\underline{G}$	$\underline{G}$	$\underline{M_{w}}$
	Mean	Epoxy-resin				GM	GM	GM	M
		Acrylic-resin				A	A	AS	SP

† Section replaced

‡ Aluminium oxide used as aggregate rather than calcined bauxite

** Section removed with construction of new connecting road*

Appendix B: Inspection panel marking system

B.1 Basic 7-point scale

Mark	*Description*	
E	(excellent)	no discernable fault
G	(good)	no significant fault
M	(moderate)	some faults but insufficient for serious problem
A	(acceptable)	several faults but would usually be just acceptable
S	(suspect)	seriously faulted but still serviceable in the short term
P	(poor)	requires remedial treatment
B	(bad)	requires immediate remedial treatment

B.2 Fault suffixes applicable to high-friction surfaces

Suffix	*Description*
-	Loss of aggregate
v	Variable, with random variations from point to point within the section only, not 'traffic laning' or of obvious variations from load to load.
t	Variability with traffic intensity, showing marked transverse differences caused by variations in traffic intensity between lanes.
d	De-lamination from substrate
c	Cracking
w	Wear, with underlying substrate showing through

B.3 Inspection panel members

J Mercer/J T Williams	Pavement Engineering Group, Highways Agency
M White	Quarry Products Association
D J Williams/J Harris	Redland Aggregates Limited
J N Preston	Shell Bitumen
C R Curtis	ARC Group Head Office
C V Underwood OBE/E Bracewell	Road Surface Dressing Association
J Carswell	BP International
J C Nicholls	Transport Road Laboratory

Local representatives

D S Rieley	Babtie Shaw and Morton
C A Catt/C E Whittaker	Warwickshire County Council
G Race	Durham County Council
J Colebrooke	East Midlands Regional Office, Highways Agency

Appendix C: Scuffing wheel-tracking test machine

C.1 Equipment

The Scuffing Wheel-Tracking Test Machine was developed at TRL by modifying the equipment used to measure the resistance to permanent deformation of bituminous mixes, as standardised in BS 598: Part 110 (BSI, 1996). The solid rubber tyre of the deformation resistance test is replaced by a pneumatic tyre of a similar diameter and is mounted at an angle of 20° to the rolling direction. The tyre is inflated to 45 psi. A photograph of the apparatus is shown in Figure C.1 and the test procedure is fully described in Appendix G of TRL Report TRL176 (Nicholls, 1997).

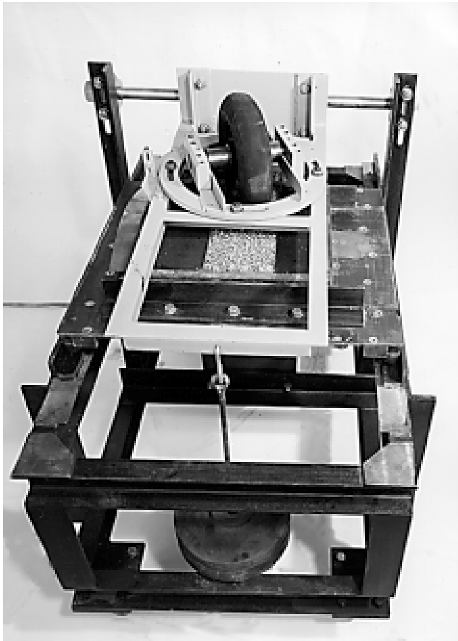

Figure C1 The scuffing wheel-tracking test machine

C.2 References

British Standards Institution (1996). *Sampling and examination of bituminous mixtures for roads and other paved areas, Part 1, Methods of test for the determination of wheel-tracking rate.* BS 598: Part 110: 1996, British Standards Institution, London.

Nicholls J C (1997). *Laboratory tests on high-friction surfaces for highways.* TRL Report TRL176. Transport Research Laboratory, Crowthorne.

Appendix D: TRL road machine No. 1

D.1 Apparatus

Road Machine No. 1 was originally built in the 1930s for experiments on surfacing materials and comprises a 2.3 m diameter table which is driven by an external motor and a separate gear motor. Up to ten samples of 305 mm x 305 mm x 50 mm (nominal) can be accommodated on the circular table. Two standard car wheels with Michelin XDX, 195/70 VR 14 tyres are mounted over the table so as to be able to run freely on the driven table whilst applying a dead load under each wheel of c.5 kN. The table speed is infinitely variable between 0 and 25 revolutions per minute which, with the wheels set at 0.9 m from the centre, equates to a linear speed of up to 8.5 km/h. The number of revolutions are automatically logged.

The wheels can be set in one of four positions with respect to the vertical plane. The set angles are 0, 7°, 14° and 21°. The lesser the angle, the greater amount of lateral stress is induced on the test specimens. A separate tracking-motor is incorporated which allows the wheels to transversely track the width of the test specimens for speeds up to 10 rev/min. Initially, this facility was not used for these trials, but the wheels were set at slightly different radii so that the central portion was tracked by both wheels whilst that each side was only tracked by a single wheel.

The machine has been enclosed in a temperature controlled chamber in which tests can be carried out at any set temperature within the range 0°C to 40°C. The machine, without its environmental chamber, is shown in Figure D.1 and the test procedure is fully described in Appendix H of TRL Report TRL176 (Nicholls, 1997).

D.2 Reference

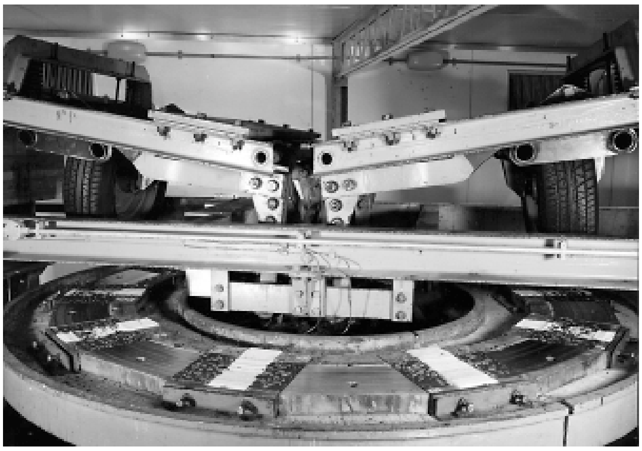

Figure D1 TRL road machine No. 1

Nicholls J C (1997). *Laboratory tests on high-friction surfaces for highways.* TRL Report TRL176. Transport Research Laboratory, Crowthorne.

Appendix E: Laboratory test results

Table E1

	Before testing		*After testing*		
	Textire depth (mm)	*Skid resistance value*	*Texture depth (mm)*	*Skid resistance value*	*Visual # assessment*
Scuffing test (500 passes @ 5°C)					
Epoxy-resin A	2.25	97	2.1	-	E
Rosin-ester B	1.35	64	1.3	-	E
Rosin-ester C	1.8	77	1.6	-	E
Polyurethane-resin D	2.0	102	1.95	-	E
Acrylic-resin E	2.25	88	1.9	-	E
Scuffing tests (500 passes @ 45°C)					
Epoxy-resin A	2.4	92	1.7	-	M/A
	2.5	99	2.0	-	M/A
Rosin-ester B	1.35	63	1.3	-	S
	1.4	57	1.5	-	S
Rosin-ester C	1.8	77	-	-	P/B
	2.65	87	-	-	B
Rosin-ester X†	1.6	-	1.3	-	G
Polyurethane-resin D	1.8	99	1.6	-	G
	1.8	100	1.6	-	G
Polyurethane-resin Y†	2.5	-	2.0	-	E
Acrylic-resin E	2.55	89	2.0	-	M/A
	2.7	93	2.2	-	S
Wear test (100,000 wheel-passes @ 5°C / 50,000 wheel-passes @ 10°C‡)					
Epoxy-resin A	2.4	95	1.3	80	M/A
	2.3	94	1.25	85	M/A
Epoxy-resin V	2.6	96	1.4	69	M
	2.6	88	1.5	70	M
Epoxy-resin W	2.2	85	1.4	67	G
	2.3	89	1.5	70	G
Rosin-ester B	1.4	64	0.9	80*	S
	1.6	61	0.9	74*	S
Rosin-ester C	3.0	81	-	-	P
	2.0	70	1.0	73*	S
Rosin-ester X	1.5	62	1.1	69*	M
	1.7	57	1.4	65*	M
Polyurethane-resin D	1.95	101	1.2	73	M/A
	1.75	98	1.2	76	M/A
Polyurethane-resin Y	2.2	93	1.6	67	E
	2.3	91	1.6	65	E
Polyurethane-resin Z	2.2	95	1.4	67	E
	2.1	92	1.4	65	E
Acrylic-resin E	2.55	88	1.3	82	M/A
	2.55	87	1.3	77	S

#Visual assessment values described in Appendix B.
**The test run exposed further aggregate, thus increasing skid resistance.*
†Additional 500 wheel-passes resulted in no further change in visual appearance.
‡100,000 wheel-passes @ 5°C for systems A to E in initial set of tests; 50,000 wheel-passes @ 10°C for systems V to Z in later set of tests.
Note: Epoxy-resin V and polyurethane-resin Y identical to epoxy-resin W and polyurethane-resin Z, respectively, except using calcined bauxite from a different source.

Abstract

With the increasing number of systems available which provide high-friction surfaces, the ‘recipe/method’ specifications based on the original bitumen-extended epoxy-resin system have become inadequate. Therefore, a series of road trials in various parts of England, mostly on approaches to roundabouts, have been set up to compare the performance of three alternative resin systems with those of epoxy-resin systems. The trials were laid between 1991 and 1993, giving between four and six years of in-service performance. From the results, the overall ranking order of resins trialled that is beginning to emerge is the epoxy-resin system first, then the polyurethane-resin system, followed by the acrylic-resin system just ahead of the rosin-ester system. Laboratory tests have been devised to simulate accelerated wear under trafficking and a limited programme has been carried out which appears to give a similar ranking. The results have been used to develop performance-related criteria for a *Highway Authorities Product Approval Scheme* (HAPAS) certification procedure which can be used to assess existing systems and systems that may be developed in future.

Related publications

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

SR798 High-performance surface dressing: 3. Properties of thermosetting binders related to road performance by J H Denning and J Carswell. 1983 (price code AA, £10)

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