Development of Spray-Reducing Macadam Road Surfacings in the United Kingdom, 1967–1987

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Increases in traffic speeds and intensities, associated with the development of the motorway system in the United Kingdom since the late 1950s, have accentuated the problem of vehicle-generated spray. Although some reduction in spray dispersion can be achieved by improved mudguard design, a more effective solution is to use a permeable wearing course that acts both as a sponge and as a draining layer. Pervious macadam with 20-mm aggregate was developed for roads from the 10-mm nominal size "friction course" that was developed in the 1950s to minimize aquaplaning on airfield runways. The evolution of pervious macadam has been primarily the result of a number of road trials that have led to specification trials by the Department of Transport. The resulting specification for pervious macadam is included in the latest revision of British Standard 4987. The material can be expected to have effective spray-reducing properties for 3 years for a traffic flow of 7,000 commercial vehicles per day (cvd) per lane or for 6 years for 2,500 cvd. To improve the long-term durability of the material and its economic viability, a road trial was started in 1984 to study the performance of pervious macadams with polymer-modified binders.

The introduction of higher speed aircraft in the 1950s gave rise to the need for runway surfacings that were free from standing water capable of inducing aquaplaning and subsequent loss of control of aircraft during braking. The solution to this problem was found in a material, known as "airfield friction course," that provided a free-draining surfacing. The maximum size aggregate used in this application was 10 mm so that damage to jet engines by any loose chippings was minimized. This concept was subsequently adapted for roads because increasing traffic flows and speeds gave rise to the hazard of reduced visibility from spray.

In the United Kingdom roads are wet for between one-quarter and one-half of the year, depending on location. Estimates of accidents in which spray is a contributory factor vary from 1.3 to 10 percent of all wet-road accidents *(1, 2)*. Szatkowski and Brown *(3)* have estimated the cost of accidents caused by spray to be about one-third of that of accidents caused by skidding on wet roads. There are other detrimental aspects of spray that are less easily quantifiable; these include stress on drivers on high-speed roads, particularly when overtaking, and nuisance to cyclists and pedestrians in urban areas.

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Limited spray reduction can be achieved by improved design of mudguards on commercial vehicles, but a more effective solution is to use a water-permeable, pervious wearing course that acts as a sponge and a draining layer. To be effective, a pervious wearing course must retain a free-draining structure. In general, this is more difficult to achieve on roads than on aircraft runways because of the heavily channelized nature of most road traffic and accumulations of dust and detritus. General factors that contribute to these properties in a material are a stable, mostly single-sized aggregate matrix and a stiff but flexible durable binder. In the application of pervious materials as road surfacings it is possible to use larger aggregate particles than the 10-mm aggregate used in the airfield application with the consequent potential of larger sized voids that are less likely to become blocked. The viscosity of the binder has to be increased to make the mixture more resistant to rutting, but, because the surfacing is permeable, the binder is subjected to weathering throughout its depth; this renders it susceptible to hardening and subsequent embrittlement. When the binder has hardened to a viscosity of about 20 pen, surface fretting followed by disintegration occurs. To reduce these effects of weathering, present research is aimed at modifying the binder so that the film thickness can be increased without the risk of binder drainage and the onset of embrittlement can be delayed by improving the low-temperature rheology.

The evolution of this type of surfacing has been primarily the result of a number of road trials because it has not been possible to simulate accurately in the laboratory the long-term effects of traffic on the effective spray reduction of the materials and of natural weathering of the binder on the durability of the surfacing.

The greatest benefits from a spray-reducing surfacing will be realized on the most heavily trafficked sites, but, of course, these provide the most difficult environment in which to obtain acceptable performance from this type of material. Spray measurements determined from a vehicle-mounted optical backscatter measuring device suggest that, when the road is very wet, pervious macadam generates only about 10 percent of the spray level that is generated from the hot-rolled asphalt surfacing used in the United Kingdom. An additional benefit of pervious macadam is that it generates about 6 to 8 dB(A) less noise under wet conditions than rolled asphalt *(4, 5)*. In noise-sensitive areas the quieter surfacing may be a more acceptable solution than the suppression of noise in dwellings or compensation payments. Structurally, 40 mm of pervious macadam is equivalent to about 16 mm of rolled asphalt or 20 mm of dense bitumen macadam *(6)*.

EARLY ROAD TRIALS

The first pervious macadam wearing course was laid on Motorway M40 in 1967 *(7)*. The material used was a 19-mm nominal size wearing course with a grading that complied with the then current British Standard 1621 for an "open-textured" bitumen macadam, and a 100-pen bitumen that contained 4 percent natural rubber as binder. The performance of this material was carefully monitored for more than 10 years during which time the traffic increased from 600 cvd to 1,900 cvd. Jacobs *(8)* reported that the initial surface texture was well over 2 mm and that it subsequently dropped and remained reasonably constant at about 2 mm. The draining properties were markedly reduced after 2 years, but in all other respects the material remained quite effective as a road surfacing and produced less tire noise than other surfacings with a similar surface macrotexture.

Warwickshire County Council experimented with the 10-mm friction course at about the same time on a similarly trafficked site, and its conclusions about the performance of this material were similar to those reported by Jacobs for the 20-mm materials.

Brown *(9)* carried out an experiment with a 10-mm friction course and a 20-mm pervious macadam using two bitumens of 100 pen and 200 pen from different crude oil sources, as well as a 100-pen bitumen modified by the addition of natural rubber. On this much more heavily trafficked site, which carried 4,500 cvd for the first 16 months and 2,300 cvd subsequently, it was found that the coarser 20-mm material with the harder bitumen (100 pen) retained its spray-reducing properties for more than 6 years. A surprising finding was the difference in the reduction of permeability measured in similar materials containing bitumen from different crude sources. The 20-mm macadam made with a 100-pen bitumen from a Venezuelan crude source showed a reduction of 80 percent in 2 years whereas that made using a similar grade bitumen from a Middle Eastern source showed a reduction of only 33 percent.

In 1973 the opportunity was taken to lay pervious macadam (20-mm nominal size aggregates and 100-pen bitumen) on the southbound carriageway of Motorway M1, which carried about 7,000 cvd in the nearside lane *(10)*. Effective spray reduction was achieved for 3 years under the heaviest motorway traffic. It was also observed at this site that after 2½ years the permanent deformation in the nearside wheeltrack was about 1 mm for the pervious macadam; the conventional surfacing for this site, rolled asphalt, had deformed by 3 mm *(3)*.

TABLE 1 SPECIFIED AGGREGATE GRADINGS FOR A38 BURTON BYPASS

British Standard Sieve (mm)	Percent by Mass Passing	
	Grading 1	Grading 2
20	100 – 5	100 – 5
14	65 ± 15	60 ± 10
6.3	25 ± 5	20 ± 5
3.35	10 ± 5	10 ± 5
75 μm	4.5 ± 1.5	4.5 ± 1.5

As a result of these experiments, the most suitable composition of pervious macadam was found to be 20-mm nominal size aggregate with a grading similar to Grading 1 in Table 1 using 100-pen bitumen binder; subsequently the Department of Transport carried out a number of specification trials to prove the material, and this specification is included in the latest revision of British Standard 4987. The surfacing is expected to have effective spray-reducing properties for 3 years under a traffic flow of 7,000 cvd and for 6 years with a traffic flow of 2,500 cvd.

It was thought that there should be benefits from the use of elastomeric additives even though the trials using natural rubber had not produced conclusive results.

In 1975 an experiment was started at Buckden, Cambridgeshire, on Trunk Road A1, which carried 2,300 cvd, to provide information on the performance of a range of wearing-course materials including open-textured and pervious macadams. The results after 7 years of traffic have been summarized in Table 2 *(5)* in terms of the relative performance of the materials with respect to a number of properties.

The pervious macadam showed advantages in retention of skid resistance at high speed, spray suppression, and noise reduction and disadvantages in durability and cost.

1984 ROAD TRIAL

This trial was laid on Trunk Road A38, Burton Bypass, in Staffordshire with the objective of comparing the performance of pervious macadams made with a range of conventional and polymer-modified bitumens. The performance of the materials may be improved by

1. Reducing binder drainage in the interval between mixing and laying to enable a higher binder content to be used; the

TABLE 2 RELATIVE PERFORMANCE OF SURFACINGS AT BUCKDEN AFTER 6 YEARS

Aspect of Performance	Open-Textured Macadam	Pervious Macadam	Dense Bitumen Macadam	Rolled Asphalt	Surface Dressing
Rutting	* * *	* * *	* * * *	* * * *	NA
Durability	* * *	* *	* *	* * * *	* * *
Skid resistance					
Low speed	* * * * *	* * * * *	* * * * *	* * * *	* * * * *
High speed	* * * *	* * * * *	* * * *	* * * *	* * * * *
Riding quality	* * * *	* * *	* * * * *	* * *	*
Spray suppression	* * *	* * * * *	*	* *	* * *
Noise reduction	* * * *	* * * *	* * *	* *	*
Ease of application	* * *	* * *	* * *	* *	* * * *
Area/unit cost	* *	* *	* *	*	* * * * *

NOTE: Ratings range from * * * * * (very good) to * (poor).

TABLE 3 A38 BURTON BYPASS: DESIGNATION OF SECTIONS

Section	Aggregate Grading	Binder	Target Binder Content (percent ± 0.3)
1	1	70-pen bitumen	3.7
2	1	100-pen bitumen[a]	3.7
3	1	Shell bitumen + epoxy resin[a]	3.7
4	1	100-pen bitumen + Inorphil[b]	5.0
5	1	100-pen bitumen + 5.0% 18-150 EVA[c]	4.2
6	1	100-pen bitumen + 5.0% 18-150 EVA[c]	3.7
7	1	Mobil Mobilplast grade C1	4.2
8	1	200-pen bitumen + 5.0% 18-150 EVA[c]	3.7
9	1	100-pen Esso bitumen + 5.0% modified EVA	4.2
10	1	200-pen Philmac bitumen + SBS[d]	4.2
11	1	200-pen Shell bitumen + SBS[d]	4.2
12	1	100-pen BP bitumen + SR[e]	5.0
13	2	100-pen bitumen	3.7
14	1	100-pen bitumen + Pulvatex NR[f]	5.0
15	1	100-pen bitumen (control)	3.7

[a]4.5 percent limestone filler (no hydrated lime).
[b]Inorphil fibers (alumino magnesium silicate) added at 9 percent of binder percentage (no hydrated lime).
[c]Ethylene vinyl acetate, 18 percent vinyl acetate content, 150 melt flow index (ICI).
[d]Styrene-butadiene-styrene block copolymer.
[e]Synthetic rubber.
[f]Pulvatex NR (natural rubber) added at 8.3 percent of binder percentage; equivalent to 5.0 percent of natural rubber in binder.

resulting thicker binder film should delay the onset of embrittlement; and

2. Rendering the macadam more resistant to deformation and closing-up by adjusting the aggregate grading and by improving the rheological properties of the binder.

Fifteen trial surfacings were laid in August and September 1984; the traffic flow is about 3,500 cvd in the nearside lane and about 400 cvd in the offside lane.

Aggregate

The coarse aggregate was specified to have a minimum polished stone value of 60, a maximum aggregate crushing value of 16, a maximum aggregate abrasion value of 12, and a flakiness index not exceeding 20. The main aggregate grading used was Grading 1 (Table 1), which is similar to that used in the earlier trials *(3)*. One section of the slightly coarser Grading 2 (Table 1) was laid; this grading was the result of cooperative

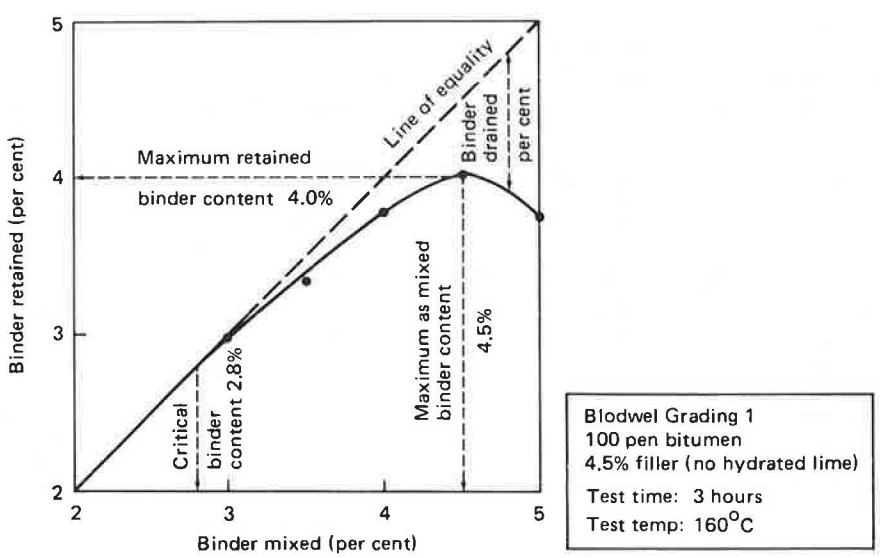

FIGURE 1 Typical binder drainage test result.

work involving the British Aggregate Construction Materials Industries, the Refined Bitumen Association, and the Transport and Road Research Laboratory.

For all except three of the materials used in the trial (Sections 2–4), the filler was specified to contain 2 percent (by mass of the aggregate) hydrated lime to act as an antistripping agent and as a binder stiffener.

Binders and Binder Contents

The control binder was 100-pen bitumen; the full list of the materials used in the experiment is given in Table 3. Hitherto the binder contents for pervious macadams in the United Kingdom have been based on experience; in the United States some qualitative and semiquantitative approaches have been used to assist in the specification of binder contents *(11–13)*.

The design binder contents in this work were determined by a recently developed quantitative binder drainage test on the total mix. In this test *(14)* a sample of pervious macadam is placed in a perforated basket and then put in an oven over a preweighed tray. The weight of material draining onto the tray is determined at the end of the test period. This drained material is essentially a mixture of binder and filler, and it is assumed that the ratio of filler to binder in the drained material is the same as that in the original mixture. The amount of binder draining and hence the binder content remaining in the mixture can then be calculated. By carrying out the test over a range of binder contents, a curve relating binder content retained to initial binder content can be drawn, as shown in Figure 1. Surprisingly, a peak is reached beyond which the binder content retained in a mix actually reduces rapidly with increasing initial binder content. From Figure 1, the highest practical binder content consistent with a minimum of drainage

TABLE 4 RESULTS OF BINDER DRAINAGE TESTS

Section No.	Binder type	Binder content per cent			
		Critical (approx)	Max. retained	Max. as-mixed	Trial target ±0.3
1	70 pen bitumen	3.5	3.5	3.5	3.7
2	100 pen bitumen (no hydrated lime)	2.8	4.0	4.5	3.7
3	Shell bitumen + epoxy resin††	4.0	>5.0	>5.0	3.7
4	100 pen bitumen + Inorphil	>7.0	>7.0	>7.0	5.0
5	100 pen bitumen+5.0% 18-150 EVA	4.0†	4.2†	4.5†	4.2
6	100 pen bitumen+5.0% 18-150 EVA	4.0†	4.2†	4.5†	3.7
7	Mobil Mobilplast C1	3.5	3.8	4.0	4.2
8	200 pen bitumen+5.0% 18-150 EVA	3.5	3.9	4.0	3.7
9	100 pen bitumen**+5.0% Esso modified EVA	3.5	3.8	4.2	4.2
10	200 pen Philmac bitumen+SBS	4.0	4.3	4.5	4.2
11	200 pen Shell bitumen+SBS	4.5	>5.0	>5.0	4.2
12	100 pen BP bitumen+SR	>5.0	>5.0	>5.0	5.0
13	100 pen bitumen (grading 2)	3.4	3.4	3.5	3.7
14	100 pen bitumen +Pulvatex	>5.5	>6.0	>7.0	5.0
15	100 pen bitumen	3.0	3.6	4.0	3.7

Note: 3 hours at 160°C

** BP bitumen used in drainage test. Esso bitumen used in trial

† 2 hours at 160°C

†† 2 hours at 120°C

TABLE 5 A38 BURTON BYPASS: INITIAL SURFACE MEASUREMENTS

Section no.	Texture depth (mm)*	Relative hydraulic conductivity≠ s^{-1}		Skid resistance s.f.c.**
		n.s. lane	o.s. lane	
1	2.5	0.38	0.38	0.66
2A	3.1	0.21	0.18	) 0.62
2B	5.5	0.72	0.62	)
3	3.1	0.50	0.41	0.66
4	3.6	0.24	0.16	0.63
5	3.3	0.33	0.23	0.63
6	3.1	0.32	0.28	0.64
7	3.0	0.23	0.31	0.57
8	2.6	0.24	0.44	0.62
9	2.5	0.25	0.41	0.62
10	3.2	0.40	0.47	0.62
11	3.7	0.41	0.44	0.62
12	3.4	0.19	0.19	0.58
13	3.1	0.41	0.58	0.62
14	2.7	0.17	0.26	0.63
15	2.9	0.42	0.37	0.62

* Nearside lane September 1984

** November 1984 nearside lane

≠ Reciprocal for outflow time of 0.00125 m^3, corrected for apparatus constants.

can be deduced. The binder drainage test, mostly performed at 160°C for 3 hr, was carried out on all the binders used in this trial; the values for the critical binder content (the lowest level at which binder drainage appears), the maximum retained binder content, and the maximum binder content of the as-mixed material are given in Table 4.

The relationship between the laboratory test and practice was investigated in a practical trial that was carried out before the test sections were laid. In this trial, lorry loads of pervious macadam traveled 80 km and stood for an additional 2 ± ½ hr. Samples were taken from the tops of the lorry loads for analysis both at the mixing plant and after the journey and standing time. Although there was no visible drainage, analysis results showed reductions of binder content of up to 0.9 percent that confirmed the trend of the binder drainage test result, although the trial results showed greater drainage than the test predicted *(14)*.

Nevertheless, this test formed a rational basis for the specification of the binder contents used in the test sections. In specifying a binder content, it would be inappropriate to set a level greater than the maximum as-mixed value, which would indicate appreciable drainage, or below the critical binder content, which would reduce durability. Because of such factors as specification tolerance on target binder content, the precision of the drainage test, and the desirability of reducing the number of variables in a full-scale trial, small differences in the binder drainage test results were ignored. These factors and, in some cases, the proprietor's option supported the selection of three groups with target contents of 3.7, 4.2, and 5.0 percent.

Observations on Laying the Trial Sections

The materials were laid by two pavers operating in echelon (except for the epoxy resin material); this made possible a well-compacted permeable and invisible longitudinal joint. In general, there was a 3- to 5-hr delay between mixing and laying; however, this did not result in load temperatures being appreciably lower than the target mixing temperatures. With the epoxy resin material, laying took place as soon as the lorries arrived on site, and in this case a satisfactory but visible longitudinal joint resulted.

Because the target binder contents were set at values only slightly higher than the critical binder contents given in Table 4, a small reduction in measured binder contents for site samples would be expected. Only 3 of the 15 sections showed some evidence of binder drainage; in those 3 cases average binder contents for site samples were more than 0.3 percent below the target values.

Before the road was opened to traffic, measurements of texture depth and relative hydraulic conductivity were made in the nearside wheelpath of the nearside lane. Measurements of

TABLE 6 RESULTS OF TESTS ON CORES OF WEARING COURSE

Section no.	Binder	Specific gravity	Voids open to water (%)	Rate of tracking (mm/h)
1	70 pen bitumen	2.404 2.378	24.4 18.6	* 0.6
2	100 pen bitumen (no hydrated lime)	2.414 2.370	24.4 20.3	0.9 1.1
3	Shell bitumen + epoxy resin	2.400 2.400	26.3 24.5	0.3 0.2
4	100 pen bitumen + Inorphil	2.335 2.344	18.3 22.0	* *
5	100 pen bitumen +5.0% 18-150 EVA	2.362	21.0	2.4
6	100 pen bitumen +5.0% 18-150 EVA	2.371 2.333	19.2 19.2	0.8 0.3
7	Mobil Mobilplast C1	2.325 2.265 2.365 2.327	19.1 17.9 19.8 16.6	0.5 0.2 0.7 0.6
8	200 pen bitumen +5.0% 18-150 EVA	2.320 2.347 2.366 2.356	23.1 18.5 24.1 19.1	* 1.9 1.0 0.2
9	100 pen Esso bitumen +5.0% Esso EVA	2.342 2.382	17.1 19.0	0.9 0.3
10	200 pen Philmac bitumen+SBS	2.412 2.307	18.3 19.6	1.4 0.8
11	200 pen Shell bitumen+SBS	2.351 2.352	20.7 17.1	0.3 0.3
12	100 pen BP bitumen+SR	2.282 2.317	16.8 17.3	0.3 1.4
13	100 pen bitumen (grading 2)	2.336 2.404	19.9 *	5.2 *
14	100 pen bitumen+ Pulvatex	2.268 2.280	18.9 14.7	2.2 0.4
15	100 pen bitumen	2.370 2.388	18.2 24.4	0.4 1.0

Note: Cores taken from nearside wheel track of nearside lane
* Core disintegrated

skid resistance [sideway force coefficient (sfc)] were made after 6 weeks of trafficking. Results are given in Table 5. Cores were removed from both lanes of each section and various parameters, including voids open to water and resistance to permanent deformation, were measured. These results are given in Table 6; details of the methods of measurement used have been given by Daines *(14)*.

The compositions of the polymer-modified binder could not be checked against the specifications because standard procedures are not available for the analyses. Infrared spectroscopy can be used with some polymers, but this method cannot be used with all of the polymers used in this trial. The contributors assured the compositions of their proprietary binders and the laboratory's staff supervised the blending of the other polymers. Work is continuing to develop methods of measuring the polymer content of binders.

Future Measurements

Regular measurements are being made of surface texture, hydraulic conductivity, profile, skid resistance, and visual condition. Spray suppression and noise levels are also included in the program. Surface texture and profile are measured using infrared lasers as sensors *(15)*; skid resistance is measured by the long-established sideway-force method; and spray suppression is measured by the more recently developed optical backscatter device *(16)*.

After 2 years of trafficking there are some signs of differences in the performance of the various materials, but it is too early to draw any conclusions about the relative merits of the additives used.

GENERAL CONCLUSIONS

Pervious macadam surfacings have been shown to have advantages over other types of surfacing, in particular suppression of spray, lower noise levels, and maintenance of high-speed skid resistance. The major disadvantage is the relatively short life of the material on heavily trafficked sites where the advantages are most apparent to the road user.

Efforts have been made to improve the durability of the material by using polymers and mineral fibers that make it possible to use higher binder contents. If the life of the surfacing can be increased without significant loss in other properties, this type of material will become more economically attractive and may be more widely used.

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