Porous Asphalt Trials in the United Kingdom

DOUGLAS M. COLWILL, GRAHAM J. BOWSKILL, J. CLIFFORD NICHOLLS, AND MAURICE E. DAINES

In the United Kingdom, trial sections of porous asphalt were laid on the A38 at Burton in 1984 and 1987. A range of binders, binder contents, and modifiers was used. The performance of the surfaces has been monitored regularly; some are still in good condition, whereas others show signs of distress. The parameters measured were skidding resistance, surface texture, hydraulic conductivity, and deformation. A more recent trial was laid on the M1 motorway near Wakefield in 1991. At this site, aggregate gradings from specifications used in the United Kingdom and other European countries were laid to compare their properties, including ranking their hydraulic conductivities. In addition, a section with rolled-in high polished-stone value (PSV) chippings was placed to assess the feasibility of achieving the skid resistance without requiring high PSV aggregate throughout the layer of porous asphalt. Together with other evidence from trials that have not been monitored in such detail, the indications are that durable porous asphalt can be designed for long-term spray and noise reduction, even for heavily trafficked motorways.

Porous asphalts are bituminous bound mixes with carefully selected gradings so as to have about 20 percent void contents when fully compacted. The reasons for using porous asphalt are to improve safety and to enhance the driving environment. These effects can be achieved because the principal advantages of using porous asphalt as the wearing course are the reduction of (a) noise in both wet and dry conditions, (b) spray caused by vehicle tires in wet conditions, and (c) glare at night in wet conditions.

Safety is also enhanced by less water on the road surface, allowing better tire-road grip, and road capacity may be increased in wet conditions.

The disadvantages of porous asphalt are its relatively low structural strength, due to its high void content, and possible shorter service life. In addition, being relatively weak in shear, the material is particularly vulnerable at high stress sites. Furthermore, careful consideration needs to be given to providing the drainage path to allow water passing through the layer to escape.

Currently there are two major sites in the United Kingdom where trial lengths of porous asphalt with various grades of binder, binder contents, modifiers, and aggregate gradings have been placed. These sites are on the A38 Burton bypass, where trial sections were placed in both 1984 (*1*) and 1987 (*2*), and on the M1 motorway near Wakefield, which was placed in 1991. In addition, there are two extant older lengths of the material, which are not being monitored in such detail: one on the M6 near Manchester, placed in 1981, and the other on the A38 at Burton, placed in 1983. Since 1988, some local authorities have placed relatively long lengths of porous asphalt using British Standard BS 4987: Parts 1 and 2: 1988 (*3*), which includes specifications for 20 mm and 10 mm porous asphalts.

The Transport Research Laboratory (TRL), on behalf of the U.K. Department of Transport (DOT), has been monitoring the performance of the various trial sections. TRL has found that the standard material can last at least 8 years; improved materials are expected to be more durable. On the basis of the experience gained, DOT has prepared an advice note and specification (*4*) so as to allow the material to be used for certain situations in commercial quantities on DOT trunk roads and motorways.

MATERIALS EXAMINED

All the trial sections placed at Burton from 1984 and at Wakefield were designed using the binder drainage test (*1,2,4*) to determine a target binder content in order to eliminate binder drainage while maximizing the binder content and hence optimize durability. The two sections that had been placed earlier were based on recipe mixes, as had been all trials placed before 1984.

1984 Burton Trial

In the summer of 1984, 15 sections of porous asphalt with a total length of about 1.5 km containing proprietary and nonproprietary binders were placed on both lanes of the southbound two-lane highway of the A38 Burton bypass to allow comparison of different binders and binder contents on the effectiveness and durability of the material. Details of the laying and subsequent performance are reported elsewhere (*1,2,5*). The grading for Section 2A was out of specification and closed up early; it has not been included in the assessments. Brief details of their composition are given in Tables 1 and 2.

The commercial vehicle traffic (>1.5 tonnes) in 1990 was about 3,600 and 500 vehicles per day for the nearside and offside lanes, respectively. From 1984 to 1990 the commercial traffic increased by 8 percent, whereas the increase in cars was 42 percent. A speed survey carried out September 27, 1990, showed the average speed of commercial vehicles was

D. M. Colwill, J. C. Nicholls, and M. E. Daines, Transport Research Laboratory, Old Wokingham Road, Crowthorne, Berks RG11 6AU, United Kingdom. G. J. Bowskill, Highways Engineering Division, Department of Transport, St. Christopher House, Southwark Street, London SE1 0TE, United Kingdom.

TABLE 1 Materials Placed at Burton and on M6

Year/ section number	Binder	Target binder content (per cent)	Aggregate grading (see Table 2)	Filler*
84/ 1	70 pen bitumen	3.7 ± 0.3	1	Hyd. lime
84/ 2B	100 pen bitumen	3.7 ± 0.3	1	No hyd. lime, 4.5% limest'e filler
84/ 3	Bitumen + epoxy resin (Shell Int'nal)	3.7 ± 0.3	1	No hydrated lime
84/ 4	100 pen bitumen plus Inorphil fibres (9% of binder)	5.0 ± 0.3	1	No hydrated lime
84/ 5	100 pen bitumen + 5% 18-150 EVA†	4.2 ± 0.3	1	Hyd. lime
84/ 6	100 pen bitumen + 5% 18-150 EVA†	3.7 ± 0.3	1	Hyd. lime
84/ 7	Mobilplast grade C1 (Mobil Oil Co Ltd)	4.2 ± 0.3	1	Hyd. lime
84/ 8	200 pen bitumen + 5% 18-150 EVA†	3.7 ± 0.3	1	Hyd. lime
84/ 9	100 pen bitumen + EVA (Esso Chem. Ltd)	4.2 ± 0.3	1	Hyd. lime
84/10	200 pen bitumen + SBS‡ (Philmac Oils)	4.2 ± 0.3	1	Hyd. lime
84/11	200 pen bitumen + SBS‡ (Shell Int'nal)	4.2 ± 0.3	1	Hyd. lime
84/12	100 pen bitumen + SR‡‡ (BP Ltd)	5.0 ± 0.3	1	Hyd. lime
84/13	100 pen bitumen	3.7 ± 0.3	2	Hyd. lime
84/14	100 pen bitumen + Pulvatex natural rubber crumb (8.3% of binder#)	5.0 ± 0.3	1	Hyd. lime
84/15	100 pen bitumen - CONTROL	3.7 ± 0.3	1	Hyd. lime
87/ 1	200 pen bitumen + 5% UL02133 EVA†† (Exxon Chemicals)	4.2 ± 0.3	1	Hyd. lime
87/ 2	70 pen bitumen + SR‡‡ (Tarmac Oils)	4.7 ± 0.3	1	Hyd. lime
87/ 3	100 pen bitumen + Arbocel zz 8/1 cellulose fibres (0.35% in mix)	4.7 ± 0.3	1	Hyd. lime
87/ 4	Bitumen + epoxy resin (Shell Int'nal)	4.5 ± 0.3	3	Hyd. lime
87/ 5	SB2/100 (BP)	5.0 ± 0.3	1	Hyd. lime
87/ 6	200 pen bitumen + 7.4% Revertex LCS natural rubber latex#	4.7 ± 0.3	1	Hyd. lime
87/ 7	100 pen bitumen - CONTROL	3.7 ± 0.3	1	Hyd. lime
87/ 7A	100 pen bitumen	3.4 ± 0.3	1	No hyd. lime, 6.5% filler
83	200 pen bitumen + 5% 18-150 EVA	4.2 ± 0.5	4	Hyd. lime
81/M1	100 pen bitumen	4.2 ± 0.5	4	Hyd. lime

Notes: * Includes 2 per cent hydrated lime in all mixes unless otherwise noted
† EVA: Ethylene-vinyl acetate co-polymer (18 to 19 per cent vinyl acetate, 150 melt flow index)
†† EVA: Ethylene-vinyl acetate co-polymer (33 per cent vinyl acetate, 21 melt flow index)
‡ SBS: Styrene-butadiene-styrene block co-polymer
‡‡ SR: Synthetic rubber
# equivalent to 5 per cent natural rubber in the binder

TABLE 2 Aggregate Gradings at Burton and on M6

BS Sieve	Per cent by mass passing Grading 1	Grading 2	Grading 3	Grading 4
28 mm				100
20 mm	100 - 5	100 - 5	100 - 5	95 ± 5
14 mm	65 ±10	60 ±10	80 ±10	65 ±15
10 mm	-	-	-	-
6.3 mm	25 ± 5	20 ± 5	30 ± 5	25 ± 5
3.35 mm	10 ± 3	10 ± 3	15 ± 3	10 ± 3
75 μm	4.5± 1	4.5± 1.5	6.5± 1.5	4.5± 1.5

90.6 km/hr (56.3 mph) in the nearside lane and 97.8 km/hr (60.8 mph) in the offside lane.

1987 Burton Trial

Subsequently, a length of highway immediately north of the 1984 trial sections was reconstructed and the opportunity taken to extend the work by laying a further c.800 m of porous asphalt in seven trial sections during November and December 1987 (*2*). Brief details of the composition of the porous asphalt sections are given in Tables 1 and 2.

1991 Wakefield Trial

Another trial was conducted on the M1 near Wakefield during July and August 1991. The trial was designed to compare the performance of the 20 mm nominal sized porous asphalt developed in the United Kingdom with examples of the smaller materials generally used elsewhere. Three sections were placed to the U.K. specifications of BS 4987 (*3*) but with slightly tighter tolerances, using both the standard 20 mm and the 10 mm size, together with sections using the gradings and binder grades taken from Belgium (*6*), The Netherlands (*7*), and Sweden (*8*). Unmodified bitumen was used as the binder except in one of the U.K. 20 mm gradings, which included bitumen modified by natural rubber, because the material had performed well at Burton. Therefore, the U.K. 20 mm porous asphalts will allow results from this trial to be related with those from the Burton trials. Details of the mixes are given in Tables 3 and 4.

In addition, a section of U.K. 10 mm grading porous asphalt was placed with 14 mm precoated chippings with a high polished-stone value (PSV) rolled in. This is to assess the viability of producing porous asphalt with relatively high skid resistance

TABLE 3 Materials Placed at Wakefield

Section Number	Binder	Target binder content (per cent)	Aggregate grading (see Table 4)	Filler	Thickness (mm)
1	100 pen bitumen + 5% natural rubber	4.5±0.3	A	2% hydrated lime	50
2 (UK)	100 pen bitumen	3.4±0.3	A	2% hydrated lime	50
3 (UK)	100 pen bitumen	5.2±0.3	B	2% hydrated lime	50
4 (Bel)	100 pen bitumen	4.3±0.3	C		40
5 (NL)	100 pen bitumen	4.3±0.3	D		40
6 (Sw)	80 pen bitumen	4.3±0.3	E		40
7	100 pen bitumen	5.2±0.3	B*	2% hydrated lime	50

Note: * 14 mm chippings pre-coated with 1.8 per cent of 100 pen bitumen applied prior to rolling

TABLE 4 Aggregate Gradings at Wakefield

BS Sieve	Per cent by mass passing Grading A	Grading B	Grading C	Grading D	Grading E
28 mm	100				100
20 mm	100 - 5		100	100	100 - 5
14 mm	65 ±10	100	-	90 ± 5	70 ±20
10 mm	-	95 ± 5	Max 65	67.5±7.5	45 ±10
6.3 mm	25 ± 5	47.5±7.5	Max 32	27.5±7.5	29 ± 7
3.35 mm	10 ± 3	25 ± 3	19 ± 3	17 ± 5	19 ± 7
75 μm	4.5±1.0	4.5±1.5	5.0±1.5	4.5±1.0	3.5±1.5

without having to use aggregate of high PSV throughout the depth of the material. The details of this section are also given in Tables 3 and 4.

The daily traffic flow for southbound Lanes 1, 2, and 3, measured in October 1991, was 9,960, 13,660 and 6,920, respectively, of which 4,570, 1,320 and 40, respectively, were commercial vehicles exceeding 1.5 tonnes.

Other Sections

A year before laying the first of the trials on the southbound highway of the A38 Burton bypass, a 550 m length of 20 mm porous asphalt was placed on the northbound highway using a 200 pen bitumen modified with ethylene-vinyl acetate copolymer (EVA). Details of the mix are given in Tables 1 and 2.

In the early 1980s, a series of six specification trial lengths of porous asphalt were placed at various locations in the United Kingdom. Although not monitored closely throughout its life, one of these trials is now being studied because it lasted for 11 years before requiring maintenance on a heavily trafficked section of the M6 motorway near Manchester. The standard 20 mm grading was used, and the binder was 100 pen bitumen. Details of the material are given in Tables 1 and 2.

PROPERTIES

Durability

A regular regime of monitoring has been carried out for both Burton trials, which is also being followed for the Wakefield trial. Site measurements, including skidding resistance, surface texture, hydraulic conductivity, deformation, and visual inspection, were carried out initially and have been repeated regularly. Similar measurements have also been made at the 1981 and 1983 sites during the last year.

Skidding Resistance

U.K. DOT has been developing a policy of improving the skid resistance of its major road network in order to reduce accidents. As part of this policy, a standard for skidding resistance of in-service trunk roads was introduced in 1988 (*9*). This standard requires all trunk roads and motorways to be monitored every 3 years using a sideway-force coefficient routine investigation machine (SCRIM) (*10*). The results from the SCRIM surveys are then assessed against the criteria set for 13 categories of site to identify where treatment to improve skidding resistance is required.

The sideway-force coefficient of a road is not a constant. It depends on factors such as the traffic flow, the season of the year, and the properties of the aggregate. The seasonal effect can be minimized by taking the mean of at least three sets of readings spread between May and September of the same year. The relevant aggregate property is the PSV (*11*). Relationships have been derived to give the PSV necessary to achieve the required mean summer SCRIM coefficient (MSSC) for various commercial traffic flows.

Skidding resistance has been measured using SCRIM at 50 km/hr, generally three times during the spring, summer, and autumn of each year. From these values, the MSSC and equilibrium SCRIM coefficient (ESC) were derived. The ESC is the average MSSC value over a number of years once conditions have reached equilibrium; this state takes at least 3 years to be reached. In the United Kingdom, the values obtained on trunk roads are compared with investigatory levels set by DOT (*9*).

For the 1984 Burton trial, the skidding resistances appear to have reached equilibrium in 1987. The ESC values for the years 1987 to 1990 show an average difference of 0.07 between the offside and nearside lanes, both for the porous asphalts and adjacent lengths of nonexperimental rolled asphalt. The range of values between individual porous asphalts is 0.06 for both lanes and their MSSC values are, on average, 0.07 higher than the nonexperimental rolled asphalts.

For the 1987 Burton trial, it is uncertain whether equilibrium conditions had been reached by 1990. The average MSSC between 1988 and 1990 was 0.50 for the nearside lane and 0.55 for the offside lane, with the range for individual porous asphalts being 0.07.

The Wakefield trial is far too new for the sections to have reached equilibrium. The initial results give MSSC values for the nearside lane above 0.50 for all sections except that with rolled-in chippings, which is slightly lower at 0.47 and similar to a control section of rolled asphalt having precoated chippings from the same source. Thus, after 1 year, the porous asphalts are maintaining a slightly higher skidding resistance than rolled asphalt. There was 60 percent cover with high PSV chippings in the porous asphalt, but the lower PSV in the main body of the mat, exposed for about 40 percent of the area, marginally reduced the average. If the procedure is adopted, the appropriate PSV of the chippings will need to be assessed, and the PSV of the aggregate used in the porous asphalt and the area that will be exposed will have to be taken into account.

The skidding resistance of the length of M6 placed in 1981 was 0.43 after 11 years of service. This is on a heavily trafficked stretch of motorway, one of the busiest in the United Kingdom. However, the result is significantly greater than the investigatory level of 0.35 for this category of road.

The result from the northbound section of the A38 after 9 years, at a lower trafficked level than the M6, was 0.49, which shows that good skid resistance can be maintained.

Overall, the evidence is that porous asphalt provides skid resistance at least as good as that of rolled asphalt when the same PSV aggregate is used for the porous asphalt and the pre-coated chippings in rolled asphalt.

Surface Texture

Surface texture has been determined using three methods during a period of developing technology:

- Sand patch (SP). Texture depths were measured annually or biannually at 10 locations along the wheelpath of each section. The test was generally performed to BS 598: Part 105: 1990 (*12*) or its predecessor, except that more recently a direct-reading cursor calibrated in millimeter texture depth has been used, enabling results to be obtained more rapidly.

• Mini-texture meter (MTM) (*13*). This is a laser sensor-measured texture depth (SMTD) device that is pushed by an operative and measures the root-mean square (rms) of the variation in texture depth. The equipment was used along the wheelpaths of each section on the same occasions as the SP method.

• High-speed texture meter (HSTM) (*14*). This is a vehicle-mounted SMTD that was generally used three times each year during spring, summer, and autumn.

All of these methods were developed for impervious materials and do not necessarily give a precisely equivalent measure on porous asphalt. In particular, the loss of sand into the open pores could bias the result from SP, as well as contribute to the build up of detritus, whereas the effect of the different shape of the surfacing on the beams from the laser device is uncertain for MTM and HSTM. However, suitable alternatives have yet to be developed.

For the trials, high values of surface texture were obtained on the newly placed porous asphalt using the SP test (1.7 mm to 5.5 mm at Burton, depending on the material), whereas values of the order of 1 mm rms were obtained using HSTM. The high SP values are due to the sand flowing into the large voids in the porous asphalt and illustrate the importance of taking account of how texture is measured. After about 2 years at Burton, SP values dropped to about 2.2 mm and remained essentially constant. HSTM values showed a smaller drop during the first year and have since generally increased slightly, with levels generally in excess of 1 mm rms after 5 years for the 1984 trial. During the hot summers of 1990 and, to a lesser extent, 1989, levels dropped noticeably, with the offside lane generally maintaining a slightly higher texture than the nearside lane. Those sections with the highest binder contents generally had the lowest texture depths—about 1.8 mm (SP) in the nearside lane after 6 years for Sections 4, 12, and 14 of the 1984 Burton trial. Overall, it appears unlikely that any 20 mm grading porous asphalt will have an unacceptably low value of texture depth, even after many years and irrespective of binder type and content.

Hydraulic Conductivity

Hydraulic conductivity has been determined annually or biannually using a falling-head permeameter (*1,2*). Measurements are made at 5 locations in the wheelpaths of each section. The design of this instrument has improved since 1984, and the latest version is specified in the DOT draft specification (*4*).

For the 1984 Burton trial, the hydraulic conductivity fell substantially to, on average, 16 percent and 22 percent of the "as placed" values for the nearside and offside lanes, respectively, after 3 years (*5*). After 6 years, the corresponding values were 10 percent and 15 percent (*2*). However, significant differences exist between sections, with Sections 3, 13, and 15 (control) performing better than average and Sections 4, 12, and 14 performing worse than average. The latter group had the highest binder contents and showed a lower hydraulic conductivity from new. For these sections, the hydraulic conductivity is now contributing little to spray suppression, although drainage through gaps between aggregate particles in the surface still ensures a useful spray reduction when compared with rolled asphalt.

For the 1987 Burton trial, trends similar to those from the 1984 trial are evident, but marked reductions occurred during the hot summers of 1989 and, more particularly, 1990. In 1990, the reduction in 3 months was about what was expected in 1 year, with presumably a similar reduction in the ultimate spray-reducing life. The higher binder contents of Sections 3 and 6 are reflected in lower initial hydraulic conductivities, whereas the lower initial value for Section 4 reflects the finer grading used.

The Wakefield trial demonstrated that the U.K. 20 mm grading produces hydraulic conductivity values up to an order of magnitude better than those using smaller aggregate. This was particularly noticeable when compared with the value achieved by the U.K. 10 mm porous asphalt, which was worse after 1 year than that achieved by many sections of the 1984 Burton trial after 6 years. The use of 14 mm chippings rolled into the 10 mm porous asphalt improved the situation; however, much improved performance should be possible if a more hydraulically conductive porous asphalt were used. A better option may be to roll 14 mm precoated chippings into 20 mm porous asphalt. Laboratory testing has shown that this is possible. A 100 m section of this material has been placed on the A38 at Burton recently, replacing Section 1 of the 1984 trial.

Deformation

Deformation has been measured regularly using a 2.0 m straightedge beam and calibrated wedge, bridging the nearside wheelpath in Lane 1 and the offside path in other lanes. Measurements are taken at 6 equidistant points along the beam at 10 locations in each section. From these data, the mean and standard deviation peak-to-valley height for each section is calculated (*2*). The mean value from the first set of measurements carried out on a section provides a baseline for subsequent determinations of the deformation. A difference of more than 0.6 mm in the means determined from two sets of measurements was generally found to be statistically significant. By comparing measurements in spring and autumn of the first year, it was possible to identify surfaces likely to deform excessively in the longer term.

For the 1984 Burton trial, the first measurements were made in 1986, forming the baseline for subsequent tests. The annual deformation rates fell from their initial values in successive years. Two mechanisms are likely: initially some secondary compaction will occur, which locks the aggregate skeleton; subsequently the binder will harden, which stiffens the porous asphalt. Porous asphalt is not expected to deform excessively, and the total deformation values confirm this. All the surfaces deformed at overall rates of less than 0.5 mm/year, and many did not deform significantly in the offside lane during this period. Those sections with the highest binder contents tended to show the greatest deformation, but these rates of deformation were still acceptable.

The measurements at other sites showed similar behavior.

Visual Inspection

Visual inspections have been carried out annually by a panel of industry representatives, with each section being rated on a scale of Very Good, Good, Fairly Good, Fair, Poor, or Bad. However, the assessments are relatively subjective, and the ratings allocated to specific sections can vary slightly, even apparently improving slightly on occasion.

For the 1984 Burton trial, 10 of the 15 sections showed some deterioration after 1 year but were still rated as Good. By 1992, the control section (Section 15) was still rated as Fairly Good to Fair. Sections 5 to 9, which incorporate EVA, had not performed as well as the control, which does not confirm the good performance of the 1983 Burton section, which also contained EVA. The preblended EVA polymers selected produced only marginal improvements in binder retained in the binder drainage test (*2*). Also, analysis of EVA contents of the mixed materials showed low and variable results. EVA stiffens the binder at temperatures below the crystalline melting point of the polymer, but in general, harder binders are less durable in porous asphalt than softer binders. This is supported by the poor result for Section 1 containing 70 pen bitumen.

Section 2B (similar to the control but without hydrated lime) is also inferior to the control section. The two sections containing preblended styrene-butadiene-styrene block copolymer (SBS) performed marginally better than the control section, but one of them, Section 11, might have performed even better had a higher binder content been used, which appears possible from the binder drainage test (*2*).

Sections with the highest binder contents in the 1984 Burton trial, made possible by the use of either a polymer or mineral fiber (Sections 4, 12, and 14), were the most durable (as indicated by the inspection panel assessments) but had the lowest hydraulic conductivities and consequently the shortest spray-reducing lives. Section 14, incorporating natural rubber, could have used an even higher binder content as indicated by the binder drainage test (2), although this would reduce the hydraulic conductivity even further and hence the spray-reducing life. However, Section 12, incorporating a premixed binder containing a proprietary synthetic rubber, suffered some binder drainage at the mixing and placement stages, which resulted in a few binder-rich patches on the road.

For the 1987 Burton trial, the inspection panel rating after 3 years did not show much change from the original condition. Section 1, incorporating a 200 pen bitumen with a premixed 33/21 EVA, showed a few binder-rich patches, indicating some binder drainage. The porous asphalt for Section 5 suffered considerable binder drainage at the time of laying, resulting in low and variable binder contents in the mat and some "fat" areas because the polymer had not been homogeneously preblended with the bitumen. With premixed polymer modified binders, it is important to ensure that a stable, homogeneous blend is used to avoid problems of binder drainage.

The visual condition of all sections of the Wakefield trial were, as expected, Good to Very Good after the first year.

Performance Summary

Table 5 presents a summary of the performance of the surfaces in the various trials for five parameters. The criteria for the star ratings given were derived primarily for the 1984 and 1987 Burton trials, but the same criteria have been applied to the results from the other trials. Nevertheless, it must be taken into account that, when the measurements were taken, the surfaces at different sites had different ages.

The ** rating represents approximately expected typical performance; the *** and * represent performances better or worse than this rating, respectively. An additional **** rating has been added for hydraulic conductivity because of the wide range in values after 1 year from the Wakefield trial, with two sections being significantly more conductive than others, even though the latter are better than typical after 1 year than the average for the 1984 and 1987 Burton trials after 6 and 3 years of trafficking, respectively.

For skidding resistance, the range over the Burton trials is quite small. For both trials, the porous asphalts with epoxy-resin binders are slightly better than typical, whereas a marginally low value was provided by 100 pen plus EVA at the higher binder content (Section 5, 1984 trial).

For texture depth (HSTM), the range of results is quite small, and most of the sections are rated typical. Sections that had higher binder contents, and so are more durable, yielded slightly lower results.

A wide range of hydraulic conductivity is apparent after 6 years with the two SBS porous asphalts in the 1984 Burton trial (Sections 10 and 11) retaining better than typical values, greater than some sections in the 1987 trial after 3 years. Those rated as below typical are virtually closed up; this includes the 10-year-old section on the M6 near Manchester, as would be expected, and Section 6 of the 1987 Burton trial (200 pen plus natural rubber) after only 3 years. The early closing up of the latter section was probably accelerated by the effects of two hot summers and the soft base binder.

On the Wakefield trial, only Sections 1 and 2 (U.K. 20 mm grading) had good hydraulic conductivities from new, demonstrating the advantages of using a larger aggregate grading.

For annual deformation rate, the majority of the 1984 sections at Burton are better than typical, whereas some of the 1987 sections are worse than typical. It is expected that the annual rate for the 1987 materials will be reduced in future years.

Regarding durability as assessed by visual conditions, a wide range is evident for the 1984 materials at Burton. Table 6 provides the frequency of sections ranked by their binder contents and latest visual condition assessments. This shows a trend of better visual condition at higher binder contents. Table 7 presents the frequency of sections ranked by their binder contents and 1990 hydraulic conductivity rating, which indicate the highest hydraulic conductivity after 6 years was achieved with 4.2 percent binder; sections with the poorest hydraulic conductivities had the highest binder contents. If the hydraulic conductivity and visual condition classes are compared (see Table 8), the compromise between durability and hydraulic conductivity that appears most balanced will result in a ** rating for both.

Hence, to aim for improved durability without sacrificing too much hydraulic conductivity will be provided by a binder content of about 4.5 percent; this can be achieved without binder drainage using natural or synthetic rubbers, mineral, or organic fibers for a mix with 20 mm nominal aggregate.

Noise Reduction

Although the Burton and Wakefield trials were originally set up to monitor the changes in physical properties such as texture depth, skid resistance, hydraulic conductivity, and du-

TABLE 5 Performance Summary of Trials (Nearside Lane)

Section	Skidding resistance (MSSC)	Texture depth (mm rms)	Relative hydraulic conductivity (s^{-1})	Deformation rate (mm/year)	Visual condition
1981 M6 M'ch'ter section	(after 11 years) ★	(after 11 years) ★★	(after 10 years) ★★	(after 10 years) ★★	(after 10 years) ★★
1983 A38 Burton section	(after 9 years) ★★	not available	(after 7 years) ★	not available	(after 9 years) ★★
1984 A38 Burton trial: Section	(after 6 years)	(after 6 years)	(after 6 years)	(after 6 years)	(after 8 years)
1	★★	★★★	★	★★	★
2B	★★	★★	★	★★★	★
3	★★★	★★★	★★	★★★	★★
4	★★	★★	★	★★★	★★★
5	★	★★★	★★	★★★	★★
6	★★	★★★	★★	★★★	★
7	★★	★★	★	★★★	★
8	★★	★★★	★★	★★★	★★
9	★★	★★★	★★	★★★	★
10	★★	★★	★★★	★★★	★
11	★★	★★★	★★★	★★★	★★
12	★★	★★	★	★★★	★★
13	★★	★★	★★	★★★	★
14	★★	★★	★	★★	★★
15	★★	★★	★★	★★★	★★
1987 A38 Burton trial: Section	(after 3 years)	(after 3 years)	(after 3 years)	(after 3 years)	(after 5 years)
1	★★	★★★	★★	★★★	★★★
2	★★	★★★	★★	★★★	★★★
3	★★	★★	★★	★★	★★★
4	★★★	★★	★★★	★★★	★★★
5	★★	★★	★★	★	★★★
6	★★	★★	★	★	★★★
7	★★	★★	★★★	★	★★★
7A	★★	★★	★★★	★	★★★
1991 M1 Wakef'ld trial: Section	(after 1 year)	(after 1 year)	(after 1 year)	(after 1 year)	(after 1 year)
1	★★★	★★	★★★★	★★	★★★
2	★★★	★★	★★★★	★	★★★
3	★★★	★	★★	★	★★★
4	★★★	★★	★★★	★★	★★★
5	★★★	★	★★★	★★	★★★
6	★★★	★	★★★	★	★★★
7	★★	★★	★★★	★	★★★
Key:					
★★★★			>0.20		
★★★	>0.50	>0.9	0.06-0.20	<0.3	G to VG
★★	0.47-0.50	0.7-0.9	0.03-0.06	0.3-0.5	<G to >F
★	<0.47	<0.7	<0.03	>0.5	F to B

TABLE 6 Visual Condition and Binder Content of 1984 Burton Trial Sections After 6 Years

Visual condition (see key to Table 5)	Binder Content 3.7%	4.2%	5.0%
★	4	3	-
★★	3	2	2
★★★	-	-	1

TABLE 7 Hydraulic Conductivity and Binder Content of 1984 Burton Trial Sections After 6 Years

Hydraulic conductivity (see key to Table 5)	Binder Content 3.7%	4.2%	5.0%
★	2	1	3
★★	5	2	-
★★★	-	2	-

TABLE 8 Visual Condition and Hydraulic Conductivity of 1984 Burton Trial Sections After 6 Years

Visual condition (see key to Table 5)	Hydraulic conductivity (see key to Table 5)		
	★	★★	★★★
★	3	3	1
★★	2	4	1
★★★	1	-	-

rability, the acoustic performance of the surfaces over a period of exposure to trafficking and weathering was also monitored. Acoustical measurements from the Burton trials have been taken at regular intervals spanning almost 6 years using the statistical pass-by method (SPB) to determine whether differences in the material properties affect the acoustical performance both initially and over a period of exposure to trafficking.

From these observations, the noise from vehicles running freely on porous asphalt has been found to be significantly less than the noise generated on conventional nonporous surfaces (*15*). The average reductions obtained when comparing new (untrafficked) porous asphalt surfaces with conventional rolled asphalt surfaces having equivalent skidding resistance were found to range between 5.5 and 4 dB(A) in dry conditions. After 4 years, the reductions still averaged 4 dB(A), and after nearly 6 years, this benefit had reduced to approximately 3 dB(A). The difference is greater in wet conditions.

Variation in the binder contents within the range of 3.7 to 5.0 percent or the use of binder modifiers and additives to improve the durability of porous asphalt do not appear to systematically affect noise emission performance. However, the noise levels for different surface types do vary over significant ranges.

Measurements on the Wakefield trial using the SPB method revealed that surfaces made using aggregate gradings with a high proportion of small stone sizes gave poorer overall acoustical absorption at normal incidence than surfaces made with larger particles. When new, the U.K. 20 mm porous asphalt gave the best overall acoustical performance, with reductions in the noise generated from light vehicles of 5.2 dB(A) and from heavy vehicles of 4.5 dB(A), when compared with that from equivalent rolled asphalt surfaces.

However, the 11-year-old porous asphalt on the M6 had a noise reduction of 0.9 dB(A) compared with adjacent rolled asphalt based on direct measurement of traffic noise. The reduction on the 9-year-old A38 northbound porous asphalt was 0.7 dB(A). These findings still have to be confirmed using SPB measurements.

CONCLUSIONS

1. With careful choice of aggregate grading, binder type, and content, 20 mm nominal size porous asphalt can have a life in excess of 10 years on heavily trafficked roads, although the spray- and noise-reducing properties will be significantly less than when first placed.
2. A reasonable compromise between durability and hydraulic conductivity will be provided by a binder content of about 4.5 percent; this can be achieved without binder drainage by adding natural or synthetic rubbers, mineral or organic fibers for a mix with 20 mm nominal size aggregate.
3. Porous asphalt containing 20 mm nominal size aggregate appears to have significantly higher values of hydraulic conductivity and hence spray-reducing life than mixes with smaller aggregate.
4. Twenty mm porous asphalt reduces spray, compared with conventional impermeable surfaces, by about 95 percent when first placed, which declines to about 50 percent when the surface is fully clogged by detritus.
5. When placed, 20 mm porous asphalt reduces noise, compared with conventional impermeable surfaces, by between 5.5 and 4 dB(A) in dry conditions. Surfaces made using aggregate gradings with a high proportion of smaller particle sizes gave poorer overall acoustical absorption at normal incidence than surfaces made with larger sizes.

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