The design of porous asphalt mixtures to performance-related criteria

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

J C Nicholls and I G Carswell
This report has been produced by TRL Limited, under/as part of a Contract placed by the Highways Agency. Any views expressed are not necessarily those of the Agency.

TRL is committed to optimising energy efficiency, reducing waste and promoting recycling and re-use. In support of these environmental goals, this report has been printed on recycled paper, comprising 100% post-consumer waste, manufactured using a TCF (totally chlorine free) process.
CONTENTS

Executive Summary 1

1 Introduction 3

2 Laboratory testing 3
   2.1 Test programme 3
   2.2 Permeability tests 3
       2.2.1 Vertical permeability 3
       2.2.2 Horizontal permeability 4
       2.2.3 Site samples 6
       2.2.4 Laboratory samples 6
   2.3 Particle loss test 7
   2.4 Scuffing test 8
   2.5 Affinity between binder and aggregate test 9

3 Design procedure for porous asphalt mixtures 9
   3.1 Suitability of test methods 9
       3.1.1 Permeability 9
       3.1.2 Durability 10
       3.1.3 Affinity between binder and aggregate 11
       3.1.4 Binder drainage 11
   3.2 Proposed procedure 11

4 Advice 12
   4.1 General 12
   4.2 Aggregate selection 12
   4.3 Binder selection 12
   4.4 Fillers and adhesion agents 14
   4.5 Aggregate grading 14
   4.6 Twin-layer porous asphalt 14
   4.7 Durability 14
       4.7.1 Binder durability 14
       4.7.2 Mixture durability 15
   4.8 Permeability 15

5 Conclusions 15

6 Acknowledgements 15

7 References 16

Abstract 17

Related publications 17
Executive Summary

Since 1994, porous asphalt has been available in the United Kingdom as a surfacing material on motorways and other trunk roads but its use has been limited because of the high costs quoted in returned tenders. There are several reasons for the high cost, some of which may be due to the way porous asphalt is specified. There is concern about being able to comply with all the requirements of the specification, which has been exacerbated by problems encountered with porous asphalt mixtures that comply with the compositional requirements of the specification but do not comply with the performance-related aspects; in particular, the relative hydraulic conductivity.

Four laboratory tests (vertical and horizontal permeability, particle loss, scuffing and affinity between binder and aggregate) have been carried out on samples of porous asphalt taken from site and manufactured in the laboratory with the objective of identifying a design procedure for porous asphalt using performance-related tests.

Testing samples from site showed that the horizontal permeability correlated reasonably well with relative hydraulic conductivity whereas the vertical permeability did not. However, the results from site samples were biased by the probable loss of detritus during the coring process that affected the relationship between in-situ relative hydraulic conductivity and laboratory permeability measurements. Therefore, the relationship found had to be modified by comparison of laboratory-made samples and earlier in-situ results from similar mixtures.

The scuffing test and the particle loss test showed only minor damage, because all the mixtures tested were durable, and so it is not possible to indicate a preferred test. However, it should be noted that the particle loss test was selected because it is being standardised by the Comité Européen de Normalisation and it may be useful in identifying less durable mixtures.

The affinity between binder and aggregate test was found to be too severe for aggregates having high polished-stone values but, if the stresses are reduced, it should prove a useful means of identifying mixtures that do not require hydrated lime, the addition of which complicates the mixing procedure.

The results have been used to develop a procedure for checking the suitability of a particular porous asphalt mixture in terms of hydraulic conductivity, durability and binder drainage. This procedure could be used by Contractors to provide them with some degree of assurance that they can comply with all the requirements of the present specification. However, feedback on the use of the procedure would allow the factors to be updated as experience of the procedure is gained.

In addition, the current Highways Agency specification clause has been reviewed and proposals put forward for a performance-related specification clause for porous asphalt. The laboratory design procedure is considered to assist in achieving compliance with both the existing clause and, to a greater extent, future performance-related specification clauses. Advice is given on the proposed design procedure in order to help material engineers to design porous asphalt in future and, therefore, assist in the implementation of the current policy of providing quieter road surfaces. This advice on the laboratory design of porous asphalt should facilitate this aim and might encourage Contractors to supply porous asphalt at a lower cost than at present.
1 Introduction

Porous asphalt is an environmentally-advantageous surfacing material that was included in the British Standard in 1988 (BSI, 1988) and has been included in the Specification for Highway Works (MCHW 1), the Notes for Guidance on the Specification for Highway Works (MCHW 2) and the Design Manual for Roads and Bridges (DMRB 7.2.4) since 1994. The porous asphalt defined in the specification is based on a 20 mm nominal maximum aggregate size and is defined by compositional limits and a performance-related requirement for hydraulic conductivity. Prior to its adoption as a surfacing material for trunk roads, TRL had carried out extensive research on the material for the Highways Agency in order to ensure that the surface could routinely provide adequate durability (Nicholls, 1997a).

However, since the material has been specified for use on the trunk road network, some problems have been encountered with mixtures complying with the compositional aspects of the specification but not with the performance-related aspects, in particular the relative hydraulic conductivity. Also, tenders for porous asphalt as the surfacing have been at a cost that is significantly higher than was anticipated, with the result that only limited quantities of porous asphalt have been laid. There are several reasons why the cost of porous asphalt in the United Kingdom is currently higher than that for other surfacing materials, both in terms of the material costs and the scheme costs (Fabb, 1998). Some of the extra costs may be due to lack of familiarity with the material, but there are other contributory factors. The higher material cost is principally due to:

- the need for high PSV aggregate of 20 mm nominal size, which has been a premium size because of its use, at least until thin surfacings became widely available, for pre-coated chippings in hot rolled asphalt;
- the need for the premium aggregate throughout the 50 mm layer;
- the requirement to lay in echelon, necessitating providing more equipment;
- the tighter tolerances applied in order to achieve the required porosity; and
- the mixture of compositional and performance-related requirements in the specification, requiring the supplier to design the mixture to achieve the latter without the ability to control the properties of the completed surfacing.

The reasons for the higher scheme costs include:

- the higher material cost;
- the need to provide positive drainage; and
- the need for extra total pavement thickness because of the relatively low structural strength.

Therefore, the Highways Agency (HA) commissioned the TRL Limited to investigate laboratory tests that could be used in a design procedure for porous asphalt. The programme investigated four laboratory test methods for assessing porous asphalt [permeability (CEN, 1998), particle loss (CEN, 1997a), scuffing (Nicholls, 1997b) and affinity between binder and aggregate (CEN, 1997b)] and led to a proposed design protocol employing the permeability, particle loss and affinity between binder and aggregate tests in addition to the currently used binder drainage test.

It was intended that the proposed design protocol should be particularly suited to provide the supplier with the confidence that the product he is offering will comply with the performance-related aspects of any future performance-related specification clause.

2 Laboratory testing

2.1 Test programme

The test programme investigated three methods of assessing laboratory mixtures and site samples of porous asphalt. These were permeability, particle loss and scuffing. In addition, results became available of laboratory tests for assessing the affinity between binder and aggregate for a porous asphalt mixture. The permeability, particle loss and affinity between binder and aggregate tests were generally carried out in accordance with the current drafts of the procedures being developed as harmonised European Standards prEN 12697-19 (CEN, 1998), prEN 12697-17 (CEN, 1997a) and prEN 12697-11 (CEN, 1997b), respectively, and the scuffing test to a TRL protocol originally developed for high-friction surfacings (Nicholls, 1997b).

In order to be able to relate results to in-service performance, particularly the relative hydraulic conductivity, cores were extracted from the porous asphalt laid on the M1 near Wakefield and on the M4 near Cardiff for testing as follows:

- a 100 mm diameter cores for particle loss;
- b 150 mm diameter cores for permeability; and
- c 200 mm diameter cores for scuffing.

Prior to the extraction of the 150 mm diameter specimens for permeability testing, in-situ relative hydraulic conductivity (RHC) measurements were undertaken at the location of each of the cores in accordance with DD 229 (BSI, 1996a).

Laboratory samples were prepared from porous asphalt slabs to BS 4987: Part 1 (BSI, 1993) with 20 mm and 10 mm nominal aggregate sizes using the TRL roller compactor and then cored to provide samples for the permeability and particle loss tests. A porous asphalt mixture with 14 mm nominal size aggregate was also manufactured using a grading estimated between those given for 20 mm and 10 mm mixtures in BS 4987: Part 1 (BSI, 1993).

2.2 Permeability tests

2.2.1 Vertical permeability

The test procedure for measuring the vertical permeability, \( k_v \) (CEN, 1998), involves adjusting the water supply to a cylindrical specimen, or core, of porous asphalt fixed in a tube of the same diameter so that a constant head is
maintained (Figure 1). The supply of water collected for a given head is used to calculate the vertical permeability of the specimen, in m³/s, using the Darcy formula.

The test apparatus, which was used for measuring the horizontal as well as the vertical permeability, was manufactured in-house at TRL and is shown in Figure 2. The equipment was intended to be used to assess:

- the practicality of the draft CEN test method; and
- the potential of the test equipment to evaluate various porous asphalt mixtures in the laboratory.

### 2.2.2 Horizontal permeability

The test procedure for the measurement of horizontal permeability, $k_h$ (CEN, 1998) uses the same apparatus as for the vertical permeability except that the tube stops at the top face of the specimen rather than continuing down the sides and the bottom face of the specimen is blocked by a plate (Figure 3). Therefore, the supply of water collected for a given head is used to calculate the horizontal permeability, in m³/s, of the specimen using a modified version of the Darcy formula.

![Figure 1 Apparatus set up to measure vertical permeability](image)
Figure 2 View of permeameter

Figure 3 Apparatus set up to measure horizontal permeability
To prepare a sample for the test, perspex tubing of about 150 mm outside diameter was attached to the top of the porous asphalt cores by taping the tube to the sample around the outside and then applying glue between the tube and porous asphalt sample on the inside. After gluing the sample and removing the tape, it was necessary to check the joint between tube and sample for any unsealed gaps at the interface and apply further glue as necessary.

Gluing a perspex tube to the top of a porous asphalt sample effectively reduced its diameter for testing purposes because water could only pass through the area within the inside diameter of the perspex tubing. Therefore, the latter diameter was used as the sample diameter for calculating the horizontal permeability. The thickness of the samples was also reduced slightly as a result of the application of glue filling some voids at the top surface. However, because this reduction was difficult to measure easily, the actual sample thickness was used in the calculations.

2.2.3 Site samples

Initially, tests were undertaken for vertical permeability using samples retrieved from site. Three sets of tests were undertaken on cores extracted from the M4 Cardiff in order to assess the potential repeatability of the test and to identify the effect, if any, of detritus being washed from the samples during the course of the testing. However, it is probable that some, if not most, of the detritus would have been removed from the samples at the time of coring.

A summary of the results for site samples and the in-situ measurement of relative hydraulic conductivity at the location of the cores, prior to core extraction, are given in Table 1. The comparison of results for relative hydraulic conductivity on site and vertical permeability and horizontal permeability of cores from the M1 near Wakefield are shown in Figure 4 and those from the M4 near Cardiff in Figure 5.

The samples retrieved from the M4 Cardiff in September 1997 from the hard-shoulder were considered to be effectively clogged from the in-situ relative hydraulic conductivity readings taken at locations of cores, prior to extraction. Nevertheless, the repeatability of the test was good for the three sets of tests for vertical permeability that were undertaken on five of the samples. The results showed no trend of increasing permeability with repeat tests, with the separate values for each specimen within ± 0.000 015 m³/s except of one sample, for which they were within ± 0.000 035 m³/s.

2.2.4 Laboratory samples

Inspection of the cores cut from the laboratory manufactured slabs showed that the 20 mm porous asphalt mixture had a reasonably open matrix whilst the 14 mm and 10 mm porous asphalt mixtures appeared to be more dense, particularly the 10 mm mixture. Therefore, only the 20 mm mixture was tested fully for vertical and horizontal permeability. Two sets of tests were undertaken for evaluation of vertical permeability for the 20 mm mixture to give an indication of repeatability. A single set of vertical permeability tests was undertaken on the 14 mm porous asphalt mixture that confirmed the visual observation of relatively low permeability with low values being measured. Therefore, the 10 mm porous asphalt laboratory mixture was not assessed for permeability.

The bulk densities of the laboratory-prepared specimens were measured using the dimensional method and mean values of 2.07 Mg/m³, 2.17 Mg/m³, and 2.24 Mg/m³ for the 20 mm, 14 mm and 10 mm porous asphalt mixtures, respectively, were recorded. These measurements were made on the 100 mm diameter cores cut for particle loss measurement.

### Table 1 Summary of permeability results from site samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Test 1</th>
<th>k_v (m³/s)</th>
<th>Test 2</th>
<th>k_v (m³/s)</th>
<th>Test 3</th>
<th>RHC (s^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 Wakefield</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S 2</td>
<td>0.000 451</td>
<td>–</td>
<td>–</td>
<td>0.000 424</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>S 3</td>
<td>0.000 933</td>
<td>–</td>
<td>–</td>
<td>0.000 242</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>S 4</td>
<td>0.000 013</td>
<td>–</td>
<td>–</td>
<td>0.000 156</td>
<td>0.051</td>
<td></td>
</tr>
<tr>
<td>S 5</td>
<td>0.000 051</td>
<td>–</td>
<td>–</td>
<td>0.000 160</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>S 7</td>
<td>*</td>
<td>–</td>
<td>–</td>
<td>0.000 182</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.000 362</td>
<td></td>
<td></td>
<td>0.000 233</td>
<td>0.033</td>
<td></td>
</tr>
<tr>
<td>M4 Cardiff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MP 248/0</td>
<td>0.000 271</td>
<td>0.000 245</td>
<td>0.000 202</td>
<td>–</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>MP 248/5</td>
<td>0.000 311</td>
<td>0.000 322</td>
<td>0.000 316</td>
<td>0.000 034</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>MP 249/5</td>
<td>0.000 600</td>
<td>0.000 572</td>
<td>0.000 602</td>
<td>0.000 157</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>MP 251/5</td>
<td>0.000 504</td>
<td>0.000 497</td>
<td>0.000 487</td>
<td>0.000 120</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>MP 252/5</td>
<td>0.000 485</td>
<td>0.000 505</td>
<td>0.000 504</td>
<td>0.000 043</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>MP 253/3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.000 054</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.000 434</td>
<td>0.000 428</td>
<td>0.000 422</td>
<td>0.000 082</td>
<td>0.009</td>
<td></td>
</tr>
</tbody>
</table>

* Very low flow, sample may not have been fully separated from base course.
The permeability results from laboratory prepared samples are summarised in Table 2. No relative hydraulic conductivity measurements were made because that test has to be carried out in-situ on a porous pavement.

### Table 2 Summary of permeability results from laboratory samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Test 1 (m/s)</th>
<th>Test 2 (m/s)</th>
<th>Sample ID</th>
<th>Porous Asphalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/1</td>
<td>0.001 224</td>
<td>0.001 112</td>
<td>14/1</td>
<td>0.000 256</td>
</tr>
<tr>
<td>20/2</td>
<td>0.000 961</td>
<td>0.000 923</td>
<td>14/2</td>
<td>0.000 330</td>
</tr>
<tr>
<td>20/3</td>
<td>0.001 523</td>
<td>0.001 421</td>
<td>14/3</td>
<td>0.000 112</td>
</tr>
<tr>
<td>20/4</td>
<td>0.001 218</td>
<td>0.001 125</td>
<td>14/4</td>
<td>0.000 403</td>
</tr>
<tr>
<td>20/5</td>
<td>0.001 157</td>
<td>0.001 025</td>
<td>14/5</td>
<td>0.000 286</td>
</tr>
<tr>
<td>20/6</td>
<td>0.000 704</td>
<td>0.000 625</td>
<td>14/6</td>
<td>0.000 430</td>
</tr>
<tr>
<td>Mean</td>
<td>0.001 131</td>
<td>0.001 039</td>
<td>Mean</td>
<td>0.000 303</td>
</tr>
</tbody>
</table>

#### 2.3 Particle loss test

The procedure for the particle loss test (CEN, 1997a) uses the Los Angeles Abrasion equipment, with the steel balls removed, to abrade compacted asphalt samples. The proportional loss of material after a fixed period is calculated from the initial and final mass of the sample. According to the draft CEN Standard, the method evaluates the resistance to disintegration of a porous asphalt mixture under traffic, except that by studded tyres.

The draft CEN standard was followed with the exception that the sample dimensions differed from the

---

**Figure 4** Permeability of site samples from M1 near Wakefield

**Figure 5** Permeability of site samples from M4 near Cardiff
stated requirement of 101.6 mm (4 inches) diameter by 63.5 mm (2.5 inches) height and, due to an oversight, the bar which disturbs the samples was left off the Los Angeles equipment, thereby reducing the severity of the test. The samples cut from site were dependent upon the layer thickness retrievable from the porous asphalt whilst the laboratory prepared sample thickness were 55 ± 5 mm. The latter was dependent upon the depth of the metal moulds used for slab manufacture.

The test method states that the sample should be rotated in the test chamber for a total of 300 revolutions (approximately 10 minutes). In order to establish the degree of failure with time over the test period, the test was halted after 60, 120, 180 and 240 revolutions and the samples weighed. These intermediate measurements were made on all the samples retrieved from site and at least one sample from each of the laboratory prepared mixtures. A summary of the results from the particle loss testing is given in Table 3.

Table 3 Summary of particle loss test results

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Particle loss (per cent) M1 Wakefield</th>
<th>Particle loss (per cent) M4 Cardiff</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>9.5 MP 247/5</td>
<td>1.7 MP 248/5</td>
</tr>
<tr>
<td>S2</td>
<td>4.6 MP 249/5</td>
<td>8.1 MP 250/0</td>
</tr>
<tr>
<td>S4</td>
<td>1.3 MP 251/5</td>
<td>3.1 MP 252/0</td>
</tr>
<tr>
<td>S5</td>
<td>2.1 MP 253/3</td>
<td>12.7 MP 254/0</td>
</tr>
<tr>
<td>S7</td>
<td>5.2 MP 255/3</td>
<td>3.9 MP 256/0</td>
</tr>
<tr>
<td>Mean</td>
<td>4.5 Mean</td>
<td>5.3 Mean</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Particle loss (per cent) Laboratory 20 mm</th>
<th>Particle loss (per cent) Laboratory 14 mm</th>
<th>Particle loss (per cent) Laboratory 10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/1</td>
<td>3.4 14/1</td>
<td>2.9 14/2</td>
<td>1.3 10/1</td>
</tr>
<tr>
<td>20/2</td>
<td>2.6 14/2</td>
<td>1.1 14/3</td>
<td>5.1 10/2</td>
</tr>
<tr>
<td>20/3</td>
<td>3.7 14/3</td>
<td>3.2 14/4</td>
<td>1.0 10/3</td>
</tr>
<tr>
<td>20/4</td>
<td>2.9 14/4</td>
<td>2.6 14/5</td>
<td>1.2 10/5</td>
</tr>
<tr>
<td>20/5</td>
<td>1.8 14/5</td>
<td>2.3 14/6</td>
<td>2.0 10/6</td>
</tr>
<tr>
<td>20/6</td>
<td>3.1 14/6</td>
<td>4.2 10/6</td>
<td>3.0 10/6</td>
</tr>
<tr>
<td>Mean</td>
<td>2.9 Mean</td>
<td>2.7 Mean</td>
<td>2.3 Mean</td>
</tr>
</tbody>
</table>

The particle loss was generally less than 5 per cent. The losses incurred were as a result of a ‘rounding’ of the sample edges during the test. The loss was gradual over the test period. Therefore, it was difficult to assess the suitability of the test for assessing design mixtures because no ‘failures’ were observed, probably due to the reduced severity of the conditions.

2.4 Scuffing test

The procedure for the scuffing test (Nicholls, 1997b) involves a loaded pneumatic-tyred wheel, with its axle set at an angle to the direction of motion, repeatedly passing over the surfacing of a specimen at an elevated temperature (Figure 6). The standard test (developed for high-friction surfacings) scuffs the sample for a period of 12 minutes and an assessment of the erosion index is made upon completion of the test. The erosion index gives an indication of the resistance of the sample to wear by scuffing. The erosion index is the sum of assessments of each 50 mm x 50 mm square in a 2 x 5 grid as 0 (less than 25 per cent damage), 1 (25 to 50 per cent), 2 (50 to 75 per cent) or 3 (over 75 per cent damage). Hence, an erosion index of zero indicates no erosion whilst an erosion index of 30 indicates less than 25 per cent of the surfacing remains intact over the area covered by the whole grid.

Scuffing was undertaken on 200 mm diameter cored samples retrieved from site. Three samples were tested from the M1 Wakefield and six from the M4 Cardiff. Scuffing the cores taken from the M1 Wakefield together with one from the M4 Cardiff for the standard period of 12 minutes resulted in no loss of aggregate. Therefore, the testing period for the remaining five M4 samples was extended to 24 minutes. The loss of aggregate was still minimal after this extended period and the assessment of erosion index was considered to be 3 or less for all of the samples. A summary of the results is given in Table 4.

Theoretically, this test is more suitable than the particle loss test because it more closely replicates the type of mechanism that can cause failure of the surfacing. However, it is difficult to assess the suitability of either test (although the particle loss test as carried out was not as severe as it should have been) for assessing design mixtures because no ‘failures’ were observed during the tests (an erosion index of 3, being the sum of markings between 0 and 3 from ten squares, is not considered to identify a ‘failure’).
2.5 Affinity between binder and aggregate test

An aggregate and bitumen combination that was proposed for a trial of porous asphalt to a draft performance-related specification clause was tested for affinity between and aggregate and binder, in accordance with prEN 12697-11 (CEN, 1997b), by Babtie Engineering Laboratories to establish if hydrated lime is not needed (see Section 3.1.3). The test was carried out at (40 ± 1) rev/min instead of the specified speed of (60 ± 1) rev/min because of availability of suitable equipment. (The test method requires the higher speed unless ‘the purpose of the test performance is to compare mixes without adhesion agents of aggregate/bitumen compositions which are expected to show low resistance to binder stripping’).

The material failed to reach the target value set, so the test was repeated without hydrated lime and then again with 2.0 % hydrated lime incorporated into the mixture. The results of all three tests are given in Table 5 and shown in Figure 7.

Table 5 Results from affinity between aggregate and binder tests

<table>
<thead>
<tr>
<th>Test period (min)</th>
<th>Site</th>
<th>Sample ID</th>
<th>Erosion index</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>M1 Wakefield</td>
<td>S2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>M4 Cardiff</td>
<td>MP 252/5</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>M4 Cardiff</td>
<td>MP 247/5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MP 248/5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MP 249/5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MP 251/5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MP 253/3</td>
<td>2</td>
</tr>
</tbody>
</table>

Despite the test being carried out at a less severe speed than was intended, none of the results complied with the 80 % target set after 72 hours rolling although the ‘control’ mixture with hydrated lime performed best. It was observed that the failures occurred because the aggregates had worn edges, which were no longer covered by the binder, rather than any binder stripping. Therefore, the test appears to be too severe for the type of aggregate used in the United Kingdom that has high polished-stone values and, hence, lower aggregate abrasion values than generally used in some other parts of Europe.

3 Design procedure for porous asphalt mixtures

3.1 Suitability of test methods

3.1.1 Permeability

Figures 4 and 5 indicate that there is a relationship between both the vertical and horizontal permeabilities measured in the laboratory and the relative hydraulic conductivity measured on site. Logically, the tests measure similar properties so there should be a relationship, but confidence in such a relationship would be stronger if the peaks in relative hydraulic conductivity and vertical permeability on the M1 Wakefield samples had coincided. The relationship is probably not particularly good because the material will have been ‘cleaned’ by the action of taking cores, as demonstrated by the limited change found when repeating the vertical permeability test on the M4 Cardiff samples. Therefore, the relative hydraulic conductivity was probably measured when the porous asphalt contained more detritus than when the permeabilities were measured. Furthermore, the range of measured relative hydraulic conductivity values from site was fairly limited.

Nevertheless, the results can be used to establish a correspondence between the vertical or horizontal permeability and the relative hydraulic conductivity so that the potential of a mixture to achieve the required limits on site can be estimated from laboratory-prepared samples prior to laying on site. The limited data available are plotted in Figure 8 from which the following relationships have been derived as Equations 1 and 2.

\[ RHC = +0.028 - 14.8k_v \quad \left( R^2 = 0.02 \right) \]  \hspace{1cm} (1)

\[ RHC = -0.006 + 172k_h \quad \left( R^2 = 0.59 \right) \]  \hspace{1cm} (2)

Forcing the regression line through the origin in the relationship for horizontal permeability gives Equation 3.

\[ RHC = 146k_h \quad \left( R^2 = 0.57 \right) \]  \hspace{1cm} (3)
These equations are likely to be lower bound estimates on the relative hydraulic conductivity because of bias in the base data caused by the detritus.

The correlation coefficient for Equation 1 is very poor and the associated regression line has a negative gradient, which is not expected. Both effects result from the larger values of vertical permeability and relative hydraulic conductivity from the Wakefield samples not coinciding. However, Equation 2 has the expected positive gradient on the regression line and a reasonable correlation coefficient, explaining about 60 per cent of the uncertainty; some of the remainder of the uncertainty could possibly be explained by differential cleaning of the cores during extraction. Forcing the regression line for horizontal permeability through the origin, and therefore simplifying the equation, only marginally reduces the correlation coefficient.

Using Equation 3, the expected relative hydraulic conductivity of the laboratory-prepared porous asphalt with 20 mm nominal size aggregate would be between 0.04 s\(^{-1}\) and 0.09 s\(^{-1}\) with an average of 0.06 s\(^{-1}\). This would imply that the mixture would not comply with the current requirements (MCHW 1) for individual determinations not being less than 0.06 s\(^{-1}\) and the running average of any six consecutive determinations being not less than 0.12 s\(^{-1}\). However, when used on the M1 at Wakefield at the same binder content (Colwill et al., 1993), the initial mean relative hydraulic conductivity across all three lanes was 0.15 s\(^{-1}\), two and a half times greater. This implies that there was a significant removal of detritus when cutting the cores on which the tests were carried out to derive Equation 3, and that the coefficient should be about 350 rather than 146.

Therefore, until more data are available from porous asphalt mixtures tested for both the laboratory and in-situ tests on new material, the best available laboratory predictor of the relative hydraulic conductivity of a porous asphalt mixture (in s\(^{-1}\)) is 350 times the horizontal permeability (in m³/s). Combining this estimate with the in-situ requirements, the mean horizontal permeability of laboratory-prepared samples not should be less than 0.000 34 m³/s nor should that of individual specimens be less than 0.000 17 m³/s in order to have an expectation that the material will just achieve the required in-situ hydraulic conductivity; higher values will have to be achieved to have a reasonable confidence of complying.

3.1.2 Durability

Neither of the tests used for estimating the durability of porous asphalt mixtures identified any significant differences in the mixtures tested. However, the mixtures tested were all relatively durable with the site samples coming from successful road trials of the material. Therefore, it can be argued that neither method was fully tested.

The scuffing test is more simulative of the extreme forces that can be imposed on a surfacing layer, but there was minimal damage even after doubling the standard test period for high-friction surfacings. Part of the lack of damage is that, with high-friction surfacings, the damage can be either delamination or erosion of the veneer coating, exposing the substrate, whereas the damage to porous asphalt is removal, or at least moving, the aggregate particles of the asphalt. Nevertheless, given that the tested mixtures had adequate durability on site, an erosion index not greater than 3 after 24 min scuffing on other mixtures should provide some assurance of durability.

The particle loss test, also known as the Cantabrian test, has been developed specifically for porous asphalt, although the type of stresses imposed during the test are not simulative of those imposed on a porous asphalt surface layer in practice. The site samples, which would have age-hardened, had mean particle losses of about 5 per cent while the laboratory-made samples had values between 2 and 3 per cent using a less severe version of the test than was intended. Therefore, given that these mixtures have been found to be durable, a particle loss of not more than 5 per cent should provide some assurance of durability under the test as employed in this investigation, which is less severe than the standardised test.
Both tests were trialled to see if they could perform the same function, to assess the durability of mixtures, so that one of them should be identified as the preferred test. However, from this investigation, there is no reason to prefer one test to the other. The scuffing test is more simulative of the real situation, but the particle loss has wide acceptance elsewhere and is being harmonised as a European standard (CEN, 1997a). Therefore, given that there is no overriding reason to opt for the scuffing test, it would be expedient to use the particle loss test to assess durability because it will be necessary to do so when it is implemented as a CEN standard.

### 3.1.3 Affinity between binder and aggregate

From the results of the affinity between aggregate and binder test, it appears to be too severe for the type of coarse aggregate being used. Presumably, the excessive harshness of the test procedure results from it originating in Scandinavia, where coarse aggregates with high resistance to abrasion are generally used.

The test was proposed as a means of identifying material for which the inclusion of hydrated lime as the filler was unnecessary. The inclusion of hydrated lime is to minimise the risk of binder stripping from the aggregate. If the test is to be retained, the trial has demonstrated that:

- the minimum limit on the degree of bitumen coverage will need to be reduced to, say, 70 % after 72 h rolling at 40 rev/min; or
- the total rolling time will need to be reduced to, say, 36 h at 40 rev/min with the degree of bitumen coverage limited to a minimum of 80 %; or
- the speed of rotation will need to be reduced further to, say, 20 rev/min for a total rolling time of 72 h with the degree of bitumen coverage limited to a minimum of 80 %.

The test is intended to assess the affinity of bitumen to the aggregate rather than aggregate abrasion, so the last option is preferred because reducing the speed should minimise any abrasion. However, because no trials have been carried out at that speed of rotation, it will need to be confirmed by comparative testing that this reduction does reduce the damage to the aggregate itself.

Unless another test procedure that assesses the property more directly and/or less subjectively becomes available, this test method should be included in a future specification clause but with some amendments to the procedure included. It may be possible to amend the test method because it is currently in draft and has to pass through various comment stages within CEN prior to its acceptance.

### 3.1.4 Binder drainage

In addition to the tests discussed above, there is still a need to check that the binder in a porous asphalt mixture does not drain in transportation and laying. Therefore, the use of the binder drainage test (BSI, 1996b) needs to be retained. However, because it is a relatively labour-intensive test, it is suggested that it is not carried out until assurances of adequate hydraulic conductivity and durability have been established.

### 3.2 Proposed procedure

The proposed procedure for checking the suitability of a porous asphalt mixture consists of the following steps:

1. Select a binder and, if required, an approved binder modifier.
2. Select the aggregate sources and target grading that complies with that specified.
3. If hydrated lime is to be incorporated into the mixture (mandatory for the current clause), go to step 7.
4. Carry out the affinity between aggregate and binder test in accordance with prEN 12697-11 except at a rolling speed of 20 rev/min*.
5. If the mean degree of bitumen coverage is less than 80 %*, go to step 7.
6. If the mean degree of bitumen coverage is less than 80 %*, either reconsider the incorporation of hydrated lime or change the source of binder and/or aggregate and start again from step 1.
7. Select a binder content that is not less than the specified minimum.
8. Manufacture not less than six 150 mm diameter samples and test for horizontal permeability in accordance with prEN 12697-19.
9. If each individual horizontal permeability result is greater than or equal to 0.000 2 m³/s and the mean is greater than or equal to 0.000 4 m³/s, go to step 10.
10. If any individual horizontal permeability result is less than 0.000 2 m³/s and/or the mean is less than 0.000 4 m³/s, revise the target aggregate grading to provide a larger gap in the grading and repeat from step 7. If the gap cannot be widened within the specified grading, select a different aggregate source and start again from step 2.
11. Manufacture not less than six 100 mm diameter samples and test for particle loss in accordance with prEN 12697-17.
12. If the mean particle loss result is less than or equal to 10 per cent, go to step 14.
13. If the mean particle loss result is greater than 10 per cent, revise the target aggregate grading to increase the fine aggregate content and/or the target binder content and repeat from step 7. If the fine aggregate content cannot be increased within the specified grading, select a different aggregate source and start again from step 2.
14. Carry out a binder drainage test on the target aggregate grading in accordance with DD 229.
15. If the maximum target binder content is less than the target binder content but greater than the specified minimum binder content, reduce the target binder content to the maximum target content and repeat from step 11.
16. If the maximum target binder content is less than the specified minimum binder content, select a different binder modifier and repeat from step 1.

* The appropriateness of the speed of rotation and the associated limit are unproven, and feedback would be particularly useful.
17 If the maximum target binder content is not less than the target binder content, the target grading and target binder content are suitable for use with the selected aggregate source, binder and, if required, binder modifier.

This procedure, which is shown graphically in Figure 9, is provisional and feedback on its use would allow the factors to be updated as experience is gained in its use.

4 Advice

4.1 General

The design procedure should help materials engineers involved with the design of porous asphalt for asphalt suppliers to be more assured that their design will be capable of complying with the performance-related aspects of a specification. This assurance should, in turn, allow the asphalt suppliers to have greater confidence that they will not have to allow for as large a contingency for non-compliance in their tenders. However, in order for the materials engineers to gain that assurance, they will need to understand and confirm the principles behind the procedure until they have built up experience with the procedure.

Therefore, some advice on what is intended to be achieved by the procedure is given. This advice is based both on the recent experience achieved whilst developing the procedure and the wider experience of TRL of porous asphalt over many years (Nicholls, 1997a).

4.2 Aggregate selection

The selection of the aggregate source, particularly of the coarse fractions, is dependent on the surfacing characteristics required, in particular for skid resistance. Tests have shown that porous asphalt provides skid-resistance at least as good as that of rolled asphalt when an aggregate having the same polished stone value (PSV) is used for the coarse aggregate in the porous asphalt and for the pre-coated chippings in rolled asphalt (Nicholls, 1997a). Therefore, the coarse aggregate has to have the PSV appropriate for the site as set out in Table 2.1 of HD 28/94 (DMRB 7.3.1). Ideally, in order to conserve the reserves of high-PSV aggregate, the PSV should not exceed the required value.

In addition, there are requirements for the ten per cent fines value to be at least 180 kN and the aggregate abrasion value to be not more than 12. These requirements are to ensure that the aggregate is sufficiently robust not to break up or abrade; this is particularly important because the stresses in the surfacing are transmitted through particle-to-particle contact. These requirements, together with the PSV, will determine which aggregate sources can be considered.

Another property, which is not specified directly but will assist in the selection of binder, is the affinity of the aggregate for the binder. An aggregate which cannot ‘carry’ much binder, such as, say, flint gravel (which is specifically not permitted), will create greater problems in the selection of an adequate binder than one to which binder will readily adhere, such as, say, gritstone. The selection of the aggregate from sources identified as possibilities will probably be based on such considerations together with their availability – it may be cheaper to use a more local source with less binder affinity, and use a more modified binder, than bring in an aggregate with greater affinity.

The final aggregate property is shape in which the crushing process does have some influence. There are two measurements of shape that could be used, flakiness and elongation. However, generally only flakiness is used in order to simplify the process. Generally, the less flaky the aggregate particles, the greater the permeability through the mat. However, it has been found in research yet to be published that, while the removal of flaky particles made the mixture more permeable, making it more flaky by adding flaky particles also increased the permeability, if to a lesser extent. Therefore, changing the flakiness index of an aggregate source, if that is practicable, may allow an improved permeability in the mixture.

4.3 Binder selection

The initial selection of the type of binder will be influenced by the aggregate source and the amount of binder that needs to be carried. The higher the required binder content and the less affinity to binder of aggregate, the higher the level of modification required to minimise the binder draining during transport and laying. In the extreme case, with a relatively low binder content required and an aggregate having good binder affinity, pure bitumen may be acceptable. However, in most cases the binder content required to ensure acceptable durability of the mixture precludes the use of paving grade bitumen without a modifier.

The choice of modified binder is between a pre-blended polymer-modified material and paving-grade bitumen with an additive, either a polymer or a fibre, added at the pug-mill. The advantage of the pre-blended binder is that there can be better control on the quality, particularly in terms of compatibility of the bitumen and polymer, but it requires separate storage and has a limited storage-life. The advantage of an additive is that it can be added as required for particular applications, but it requires a separate means of incorporating it into the mixture in the pug-mill, where it may be necessary to extend the mixing cycle to ensure homogeneity.

Polymer-modifiers alter the rheology of the bitumen to allow better adhesion whilst fibres increase the surface area over which the bitumen is spread. There are many different types of polymers that have been used for modification, including natural rubber, styrene-butadiene-styrene (SBS), styrene-butyadiene-rubber (SBR), ethylene vinyl acetate (EVA) and epoxy-resin. Different types of fibres, including mineral and organic, have also been used. If the modifier is only being added to reduce binder drainage, then compliance with the binder drainage test is all that is required and the choice can be based on a purely commercial basis of least cost to achieve minimal drainage.

There is some evidence, although inconclusive, that the inclusion of modifiers appears to be beneficial over and above the increased binder content they permit.
START

Select binder

Select aggregate source and grading

Hydrated lime included in mixture?

Yes

No

Test for affinity between binder and aggregate

Degree of coverage < 80%?

Yes

No

Select target binder

Test for horizontal permeability

Individual < 0.0002 m/s or Mean < 0.0004 m/s?

Yes

No

Test for particle loss

Mean > 10 per cent?

Yes

No

Test for binder drainage (if not already tested for aggregate grading)

Maximum target binder content < target binder content?

Yes

No

Maximum target binder content < specified minimum?

Yes

No

Reduce target binder content

Widen gap in aggregate grading

Increase fine aggregate and/or binder content

Does grading comply with specification?

Yes

No

Review component materials

START

END

Figure 9 Flow chart for design procedure
(Nicholls, 1997a). Therefore, there may be additional advantages for durability in selecting a polymer-modified binder to slow-down the hardening of the in-situ binder. With regard to the selection of the best type of modifier, the trials to date (Nicholls, 1997a) have not demonstrated any significantly superior performance of one generic type of modifier over another.

4.4 Fillers and adhesion agents
The selection of filler can also have an influence on the compatibility of the aggregate for the binder. The inclusion of hydrated lime, as required in the current specification (MCHW 1), gives the porous asphalt a longer service life and enables a small increase in the binder content to be obtained in the binder drainage test as well as appearing to retard the hardening of the binder and improving the resistance to stripping (Nicholls, 1997a). However, hydrated lime is a difficult material to handle, and some suppliers would rather use other means, which may be permitted under future proposed performance-related specification clauses provided that, say, the binder-aggregate affinity is checked (CEN, 1997b). The other means include the use of greater polymer-modification and/or a specific adhesion agent; alternative adhesion agents include amines and amides (Green, 1998).

4.5 Aggregate grading
The aggregate grading in the current specification is closely defined except at the 10 mm sieve size. The mixture is intended to be gap-graded in order to form the structure of the inter-connecting voids, and the gap is intended to be near the 10 mm sieve. Therefore, the only significant change in the grading is at that size, although smaller changes can be made at other sizes if the production control is good. Future specification clauses may allow for alternative maximum nominal aggregate sizes and, if performance-related, may widen the envelope, as well as permitting the combination of two different sizes of aggregate (twin-layer porous asphalt, Section 4.6).

The need to adjust the grading can result from several causes. A reduction in the coarse aggregate content, either by reducing the maximum nominal size or increasing the proportion passing the smaller sieves, will:

- increase the available surface area, so reducing the potential for binder drainage; and
- increase the quantity of mortar to maintain the structure of the aggregate skeleton, but this may reduce the permeability.

Alternatively, an increase in the coarse aggregate content will:

- leave more voids open for increased permeability, but this may reduce durability.

The appropriate grading is, therefore, a compromise between durability and permeability.

The choice of maximum nominal aggregate size is related to the layer thickness. The thicker the layer, the more high-quality aggregate required, but the greater the capacity of the pavement to absorb surface water and the longer it takes to clog (Nicholls, 1997a). There is some dispute about the relative noise emitted from the different sizes of porous asphalts, primarily because the larger the nominal maximum size, the more the noise generated at the tyre/pavement interface and the more the noise is absorbed in the larger voids. Therefore, it depends on the balance between noise generation and noise absorption.

4.6 Twin-layer porous asphalt
Twin-layer porous asphalt is a recent variation that was developed in the Netherlands. The use of two different porous asphalts allows the lower one to use lower-quality aggregate because there is no direct interface with vehicle tyres while the thinner upper layer, with a smaller maximum nominal aggregate size, to act as a sieve to stop larger particles of detritus from reaching the larger voids in the lower layer. It is unlikely to be economic unless a relatively thick layer of porous asphalt has been specified in order to allow for relatively high rainfalls to be carried within the porous asphalt.

4.7 Durability
4.7.1 Binder durability
In this context, binder durability is the service life of the surfacing that is controlled by the influence of the climate, in particular the oxidation of the binder. The useful life of porous asphalt is generally governed by progressive binder hardening until the binder is no longer able to accommodate the strains induced by traffic (Nicholls, 1997a). Brittle fracture generally begins during winter and, if the surfacing survives the winter, it usually remained serviceable during the following warmer months. An indication of imminent failure is often provided by the onset of fretting in the wheel-paths accompanied by an increase in texture depth.

The penetration of the binder recovered from porous asphalt has been shown to harden with time. Between mixing and laying, the typical reduction in penetration is 30 per cent and then proceeds at about 20 per cent reduction in penetration per year. Irrespective of the presence or type of modifier, the critical binder penetration is about 15 dmm with the softening point generally close to 70 °C, after which failure generally occurred when sub-zero temperatures are next encountered. Porous asphalts with higher binder contents, or that have hydrated lime incorporated, have lower hardening rates, and hence increased durability. The increase in service life with increased binder content is attributed to a thicker binder film that takes longer to oxidise. Ideally, the film thickness would be calculated, but this would require calculating the available surface area in the various fractions of aggregate, with the need to quantify their shape. Therefore, the binder content for a particular maximum nominal aggregate size is taken as the surrogate for binder film thickness, and hence durability.
4.7.2 Mixture durability

Mixture durability, in this context, is the ability of the surfacing to remain serviceable under the influence of traffic stresses. Generally in the United Kingdom, the mixture durability has not been a problem until the binder has hardened to its critical penetration (Section 4.7), but there have not been extensive areas of the material laid. The material, with its interconnecting voids, appears inherently weak, and so some reassurance about the durability of the mixture has been required in other countries where it is used.

The particle loss test (CEN, 1997a), also known as the Cantabrian test, has been developed specifically for porous asphalt. The test involves rotating specimens in a Los Angeles machine, without steel balls, and measuring the weight loss after a set number of rotations. The stresses imposed during the test are not simulative of those imposed on a porous asphalt surfacing layer, but they do indicate how well a material will remain intact under stress. From limited trials (Sections 2.3 and 3.1.2), a particle loss of not more than 10 per cent provides an assurance of mixture durability.

However, mixture durability depends on suitable laying and compaction procedure being used as well as the selection of the appropriate mixture. Therefore, the test is used to check on compaction by taking cores from the completed mat and measuring the particle loss, which should not be significantly greater than that achieved at the laboratory design stage. Obviously, there will be some differences due to the different form of compaction, but a large increase in particle loss will indicate that inadequate compaction has taken place and that the material may not achieve the expected design life.

4.8 Permeability

The ability of air and water (air to allow the absorption of noise and water to remove the rainwater from the surface and so reduce spray and aquaplaning) to pass through porous asphalt is the main reason for using the material. The current method to check the permeability is the in-situ relative hydraulic conductivity test (BSI, 1996a), using a falling head permeameter on site. The dimensions of the permeameter have been chosen so that the time taken depends on the resistance to flow vertically downwards rather than horizontal away from the spot, because the latter would be influenced by the thickness of the layer at that point.

The permeameter is not designed for use with small laboratory-made specimens. Therefore, more compact equipment has been developed for the testing of either cores or laboratory-prepared cylinders using a constant head permeameter (CEN, 1998). The test can be used to measure either the vertical permeability down through the sample by sealing the sides or the horizontal permeability out from sample by sealing the base.

The in-situ hydraulic conductivity should be able to be estimated from the permeability of laboratory-prepared samples. From initial studies (Section 2.2), the horizontal permeability correlated reasonably well with relative hydraulic conductivity whereas the vertical permeability did not. This finding is surprising because the in-situ test is supposed to predominately measure the vertical permeability. Nevertheless, the relative hydraulic conductivity, in inverse seconds, can be estimated from the horizontal permeability, in cubic metres per second. The ratio of relative hydraulic conductivity to horizontal permeability, in standard units, is estimated to be 350 : 1.

The permeability of porous asphalt will change with time in service because of the effect of detritus clogging the interconnecting voids. The outflow time from the hydraulic conductivity test and the age of the surfacing have been found to be linearly related with a high correlation coefficient. Therefore, any measurement of permeability must take into account whether, and if so for how long, the material has been in service. If the permeability is being measured using cores in the constant head permeameter, the effects of the coring in ‘cleaning’ the sample should also be allowed for. Generally, cleaning of a porous asphalt pavement is not very effective (Nicholls, 1997a) but, in coring, the water is around every exposed face of a relatively small specimen and it is under some pressure and, therefore, penetrates the core.

5 Conclusions

Currently, there is uncertainty that a material designed to comply with the composition requirements for porous asphalt will also comply with the performance-related requirements of the specification. Therefore, a design procedure has been developed which should help to reduce that uncertainty. In addition, advice is given on the reasoning behind the development of, and the implications of using, that procedure.

Specific conclusions that arose from this investigation are as follows:

1. The horizontal permeability correlated reasonably well with relative hydraulic conductivity whereas the vertical permeability did not.
2. The results from site samples were biased by the loss of detritus in coring after in-situ measurements of relative hydraulic conductivity and before laboratory measurements of permeability.
3. The scuffing test and the particle loss test showed only minor damage because all the mixtures tested were durable and so their relative effectiveness could not be established. However, the particle loss test is preferred because it is being standardised by the Comité Européen de Normalisation.
4. The affinity between binder and aggregate test as currently drafted in CEN is too severe for aggregates with a high polished stone value.

6 Acknowledgements

The work described in this report was carried out in the Infrastructure Division of TRL Limited under the highways research programme for the Highways Agency. The assistance of Mr D M Colwill, OBE, in reviewing the paper is acknowledged.
7 References

*Volume 1: Specification for Highway Works (MCHW 1)*
*Volume 2: Notes for Guidance on the Specification for Highway Works (MCHW 2).*

*HD 27/94: Pavement Construction Methods (DMRB 7.2.4)*
*HD 28/94: Skidding Resistance (DMRB 7.3.1)*


Abstract

Four laboratory tests, permeability (both vertical and horizontal), particle loss, scuffing and affinity between binder and aggregate, were used to assess porous asphalt samples taken from site with those manufactured in the laboratory. The results indicate that the potential of a mixture to achieve requirements for hydraulic conductivity on site can be assessed from laboratory mixtures, but there was insufficient variation between the samples in the laboratory tests to be able to predict the durability of the material in service. A laboratory design procedure for porous asphalt is proposed which should assist in reducing the current high cost of the material when procured under the current specification clause or, in future, under a performance-related clause. Also, supporting advice on binder selection, aggregate selection, fillers and adhesion agents, aggregate grading, durability and permeability is included.

Related publications

TRL499  Material performance of porous asphalt, including when laid over concrete by J C Nicholls (In production)
TRL461  The harmonised European standard test methods for asphalt mixtures by J C Nicholls (price £35, code J)
TRL376  Effectiveness of edge drainage details for use with porous asphalt by J C Nicholls and I G Carswell. 2001 (price £25, code E)
TRL264  Review of UK porous asphalt trials by J C Nicholls. 1997 (price £35, code H)
TRL176  Laboratory tests on high-friction surfaces for highways by J C Nicholls. 1997 (price £35, code H)

Prices current at June 2001

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