THE PERFORMANCE OF SURFACING OVERLAYING BRIDGE DECK WATERPROOFING SYSTEMS

Version: 1.0

by R W Jordan, K Nesnas and M G Evans (TRL Limited)

Client: Highways Agency
Asset Management Performance – Structures
(Mr J Gallagher)

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Executive summary

TRL Report PPR 221: The performance of surfacing overlaying bridge deck waterproofing systems by R W Jordan, K Nesnas and M G Evans

Project Officer: Mr J Gallagher, Highways Agency
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Scope of the project

In 1999, TRL was commissioned to investigate the main factors that affect the performance of the surfacing on bridges, and to identify the possible causes of the premature failures that have occurred on some bridges with liquid-applied waterproofing systems. The project was to provide recommendations for Maintaining Agents and propose minor changes to the current specification that would improve the performance of the surfacing on bridges. Also, the role of red sand asphalt (or black sand asphalt overlaid with indicator mesh) as an indicator layer when replacing the asphalt layers below the surface course was to be reviewed and recommendations made concerning its use.

In order to meet the objectives, information on the specification and performance of surfacing on bridges was obtained from Maintaining Agents and from site visits. Laboratory tests were carried out to determine factors affecting the bond of surfacing to waterproofing systems, including wheel loading, and to determine the stiffness modulus of spray-applied waterproofing systems. Further work was commissioned in 2004 to investigate further the effect of the stiffness of the waterproofing system on the strains induced in the surfacing by wheel loading. This report describes all of the work carried out during the two projects.

Summary

In accordance with the current specification, most surfacing laid on bridges is 120mm thick and comprises a 20mm thick additional protective layer (APL) of red sand asphalt, and binder and surface courses of combined thickness 100mm. For historical reasons, most binder and surface courses have been hot rolled asphalt (HRA), and surfacing of this type has performed well on most bridges. Where there has been a lack of sub-surface drainage, sometimes water has accumulated in the surfacing on the high side of expansion joints and either flowed out of the surfacing or through the joints. These problems have tended to increase when HRA surface courses have been replaced by more permeable thin surface course systems (TSCSs).

Where the surfacing has been less than 120mm thick, and the APL or binder course has been omitted, there have been a number of premature failures involving cracking and potholing. These have been more prevalent where the thickness of the surfacing has been low, the surfacing has been poorly bonded to the waterproofing system, and water has accumulated in the surfacing.

A series of tensile and shear bond tests on two spray-applied waterproofing systems found little evidence that the bond of the surfacing is weakened simply by the presence of water in the surfacing. Further bond tests have shown that the tensile bond strength of the surfacing to the waterproofing system and/or the tensile strength of the surfacing itself can be weakened by wheel loading when the surfacing is saturated. The highest bond strengths were measured on a waterproofing system with a thick tack coat that limited the amount of water that could accumulate in the surfacing at the interface with the system.

The stiffness modulus and Poisson’s ratio of four waterproofing systems, three spray applied and one sheet system, have been measured at different strain rates and three temperatures in laboratory tests. Three systems behaved viscoelastically and one elastically. A finite element model has been developed to estimate how the strains induced in the surfacing are dependent on the properties of the...
waterproofing system and the bond of the waterproofing system to the concrete and the surfacing. The local strains induced in the surfacing by wheel loading were found to vary with the properties of the waterproofing system and the bond. However, the strains were calculated to be too low to have a significant effect on the performance of the surfacing overlaying membranes of thickness up to 5mm.

It appears that most premature surfacing failures on bridges are the result of more than one mechanism. It is postulated that most premature failures of surfacing less than 120mm thick have occurred because:

(i) the surfacing has become saturated
(ii) high hydrostatic pressures have been generated in the saturated surfacing by wheel loading
(iii) the high pressures have debonded the surfacing from the waterproofing system and/or caused the surfacing itself to fail.

However, the waterproofing systems on some bridges may be less dense than those tested. Also, large areas of membranes are sometimes significantly more than 5mm thick where surfacing has failed. Therefore, higher strains may be induced in the surfacing on bridges than have been calculated in the finite element analyses. It is recommended that samples of material are analysed when surfacing fails to determine the significance of different material properties and membranes thicker than 5mm.

A red sand asphalt APL has been used as an indicator layer to set the planer on only a few occasions to replace the asphalt layers below the surface course on bridges without rewaterproofing them. Few attempts have been successful because the APL and/or the waterproofing system have been damaged. It is considered impractical to use a red sand asphalt APL as an indicator layer to replace the binder course on bridges without rewaterproofing them. Therefore, it is recommended that the APL, if laid, is not tinted with red oxide and that red indicator mesh is not used.

Recommendations have been proposed to improve the performance of the surfacing on bridges. Sufficient surface and sub-surface drainage should be provided to prevent water accumulating in the surfacing. Edge drains should be provided to drain the full depth of permeable surface courses that are not free draining. The asphalt layer directly overlaying the waterproofing system should be effectively impermeable, and the asphalt and the waterproofing system should be selected so there are few voids at their interface and no interconnecting voids. The asphalt should be laid and compacted at temperatures that are sufficiently high to form a dense layer and to activate the tack coat of the waterproofing system so the asphalt is uniformly and well bonded to the system.

When the total thickness of surfacing is less than 120mm anywhere on a bridge, the APL of sand asphalt should be omitted and the waterproofing system should be overlaid with an asphalt layer of thickness 40mm (recommended). A 40mm asphalt layer should also replace the APL when it is necessary to optimise the compaction of the asphalt layer and its bond to the waterproofing system. The inclusion of polymer modified binder in the asphalt layer directly overlaying the waterproofing system should be considered to realise more of the service life of the waterproofing system.

The minimum adhesion and bond strength requirements in BD 47 should be increased when the waterproofing system is overlaid with asphalt with coarse aggregates and is less than 120mm thick. Site trials should be conducted on new waterproofing systems to ensure that the bond of asphalt to the waterproofing system is durable under trafficking.

**Implementation**

After they have been reviewed by the Highways Agency, the recommendations in this report should be issued separately to Maintaining Agents or be incorporated in the Specification for Highway Works and Departmental Standard BD 47: Waterproofing and Surfacing of Concrete Bridge Decks in the Design Manual for Roads and Bridges.
Abstract

Information on the specification and performance of the surfacing overlaying concrete bridge decks owned by the Highways Agency is described. The main factors that affect the performance of surfacing of total thickness less than 100 mm, and the possible causes of the premature failures that have occurred on some bridges with liquid-applied waterproofing systems are identified. The results from laboratory tests that were carried out (i) to identify factors that affect the bond of surfacing to two bridge deck waterproofing systems, including wheel loading, (ii) to investigate the flow of sub-surface water through surfacing, and (iii) to measure the stiffness modulus of four waterproofing systems are presented. The local strains inducing by wheel loading in surfacing overlaying waterproofing systems that were calculated using the finite element method are reported. Recommendations are proposed to improve the durability of the surfacing on bridges that concern the provision of sub-surface drainage, the characteristics of the waterproofing system, the void content of the surfacing directly overlaying the system, and the bond of the surfacing to the system. The role of the red sand asphalt layer that is currently specified as an additional protective layer to the waterproofing system and is intended to act an indicator layer during resurfacing works is discussed, and its replacement is recommended.
Introduction

Departmental Standard BD 47/99: Waterproofing and Surfacing of Concrete Bridge Decks (Design Manual for Roads and Bridges, Volume 2, Section 3, Part 4 (The Highways Agency et al, 1999a), subsequently referred to as BD 47), requires waterproofing systems on bridge decks to be overlaid whenever possible with a 20mm thick additional protective layer (APL) of red sand asphalt and other asphalt layers that are a minimum total thickness of 100mm. This thickness of asphalt with effectively impermeable binder and surface course has generally performed well on bridges, whatever the type of the waterproofing system. However, when it has been necessary to reduce the thickness of the asphalt layers overlaying the waterproofing system to significantly less than 100mm, some surfacing has failed prematurely.

In 1999, TRL was commissioned by the Highways Agency to investigate the main factors that affect the performance of surfacing on bridge decks, to identify possible causes of the premature failures, and make recommendations to improve the durability of surfacing on concrete bridge decks. Further work was commissioned in 2004 to investigate further the effect of the stiffness of the waterproofing system on the performance. This report describes all of the work carried out during the two projects, as follows:

- Section 2 lists the definitions that apply throughout the report;
- Section 3 summarises the information obtained from Maintaining Agents on the specification and performance of surfacing on bridge decks, including the role and use of either red sand asphalt or black sand asphalt with indicator mesh as an APL;
- Section 4 describes laboratory tests that were carried out to identify factors that affect the bond of the surfacing to two waterproofing systems, to investigate the flow of sub-surface water through surfacing and to measure the stiffness modulus of four waterproofing systems;
- Section 5 describes finite element analyses that determined the local strains induced in surfacing by wheel loading, and compares these strains with estimates of those induced by the global deformation of bridge decks;
- Section 6 describes the possible causes of the premature failures of surfacing on bridge decks, based on comparisons of the information obtained from Maintaining Agents, the test results and the finite element analyses, and discusses ways to improve the durability of surfacing on bridge decks;
- Section 7 considers the role of the APL, and the implications and practicalities of replacing the asphalt layers below the surface course without rewaterproofing bridges;
- Section 8 summarises the recommendations in Sections 6 and 7 for reducing the number of premature failures and improve the overall performance of the surfacing on bridges; and
- Section 9 summarises the main conclusions.

Further work to develop a specification for the surfacing of concrete bridge decks is given in Nicholls et al (2006) and some of the findings from that work are included in this report.
2 Definitions

The following definitions apply throughout this report

Additional protective layer (APL)
A 20mm thick layer of sand asphalt that is specified in BD 47 (The Highways Agency et al, 1999a) and is laid directly onto the waterproofing system to prevent the membrane being damaged before the binder course is laid, and by coarse aggregates in the binder course. The sand asphalt is normally tinted with red oxide, as specified in the Specification for Highway Works (The Highways Agency et al, 2004), so that the layer may indicate the proximity of the waterproofing system during planing operations. On some bridges, the sand asphalt is not tinted red, but it is overlaid with a red indicator mesh.

Binder course
The asphalt layer between the APL (or the waterproofing system when the APL is omitted) and the surface course. The binder course may comprise one or more layers, and may be omitted on certain bridges.

Resurfacing
A general term used to describe activities ranging from the replacement of just the surface course to the replacement of all the asphalt layers on bridges.

Surface course
The asphalt layer on which traffic runs. On certain bridges, the surface course can directly overlay the APL or the waterproofing system.

Surfacing
A general term that describes all of the asphalt layers that overlay the waterproofing system, including the surface course and, when applied, the binder course and the APL.

In order to avoid confusion, it should be noted that in Europe the APL is normally considered to be part of the waterproofing system, not the surfacing. In BD 47, the APL is not considered to be part of the surfacing.

Thin surface course system (TSCS)
A proprietary surface course material that can be laid at thicknesses less than 50mm and which has an Highways Authorities Product Approval Scheme (HAPAS) Roads and Bridges Certificate issued by the British Board of Agrément. Types of TSCS include thin stone mastic asphalt (TSMA) and thin asphalt concrete (TAC).

Waterproofing system
Dependent on the type of system, a waterproofing system may comprise:
- a primer for the concrete substrate (most systems);
- an adhesive to bond the membrane to the substrate (some sheet systems);
- a waterproofing membrane that is impermeable to water (either a liquid-applied membrane or a sheet membrane);
- a tack coat to increase the bond of the APL or surfacing to the membrane (some systems).

Systems 1, 2, 3, 4 and 5
Five waterproofing systems that were identified in the two projects. Systems 1 to 4 satisfy the requirements of BD 47, have a Roads and Bridges Certificate issued by the British Board of Agrément, and are currently registered by the Highways Agency. System 5 is an older system that does not satisfy the requirements and is not registered. Bond tests were carried out on Systems 1 and 2 during the first project, and stiffness modulus tests were carried out on Systems 1 to 4 during the second project.
3 Information obtained from Maintaining Agents

3.1 Information requested

In order to identify the factors that affect the performance of surfacing on bridges, a number of Agents that maintain the Highways Agency bridge stock were asked during 1999 to 2001 for information on the surfacing on bridges. Details of the types of surfacing and how the surfacings have performed were requested, focussing on surfacing less than 120mm thick and any specific problems.

The role of the red sand asphalt has a bearing on the type of surfacing laid on bridges and how they are resurfaced. Therefore, Agents were also asked whether they had replaced the asphalt layers below the surface course but not rewaterproofed bridges where the APL had been used as an indicator layer during planing operations.

3.2 The type of surfacing laid on bridges

3.2.1 Surfacing 100mm or more thick

3.2.1.1 General

As expected, Agents reported that most surfacing on bridges conforms to the BD 47. It is 120mm thick and includes a 20mm thick APL of red sand asphalt (see Figure 3.1). Table 3.1 shows the type of surfacing that was laid on most bridges until thin surface course systems (TSCSs) were introduced. Although TSCSs have been available for some time, when the information was requested, many bridges still had a hot rolled asphalt (HRA) surface course.

![Figure 3.1 Surfacing thicknesses specified in BD 47/99](image)
Table 3.1  Typical surfacing systems more than 100mm thick laid on bridges before the introduction of TSCSs

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>Mixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>APL</td>
<td>20</td>
<td>Red sand asphalt</td>
</tr>
<tr>
<td>Binder course</td>
<td>40-60</td>
<td>HRA or DBM binder course</td>
</tr>
<tr>
<td>Surface course</td>
<td>40-50</td>
<td>HRA surface course</td>
</tr>
</tbody>
</table>

3.2.1.2  APL

Most red sand asphalt that is laid on bridge decks complies with the requirements given in the Series 2000 Clauses of the Specification for Highway Works (The Highways Agency et al, 2004) and in BD 47. However, in the past, sand asphalt has been designed for a minimum Marshall stability (Jordan et al, 1997). Before 1993, the Specification for Highway Works specified a stability of (5.5 ± 2)kN. Some contracts have specified a stability in excess of 5kN.

On some bridges, black sand asphalt has been overlaid with a red indicator mesh as an alternative to red sand asphalt.

Several Agents reported that sand asphalt is often poorly compacted, so it is permeable and contains much sub-surface water, and is poorly bonded to the waterproofing system. However, a dense layer can be formed when sand asphalt is compacted properly (Nicholls et al, 2006; Pearson and Cuninghame, 1998).

3.2.1.3  Binder course

Before the introduction of TSCSs, most Agents preferred hot rolled asphalt (HRA) binder courses because they were considered to be less permeable and more resistant to cracking than dense bitumen macadam (DBM) binder courses. Over recent years, Agents have reported using other mixtures, including proprietary binder courses (PBCs) and heavy duty macadam (HDM). For the purposes of this report, it can be assumed that PBCs are designed using similar procedures as those used for TSCSs, but they are specifically for the lower layers where there are no texture depth or skidding resistance requirements. HDM is similar to DBM but the mixture has a higher stiffness modulus because the bitumen is normally penetration grade 50 pen rather than 100 pen. Some DBM mixtures also contain 50 pen bitumen. (It should be noted that the binder grades changed in January 2002, but old grades are used here because it is an historic review.)

Whereas PBCs have been used for the binder course in certain areas of some bridges where the surfacing thickness is more than 100mm, until at least the year 2000, they had been used on few bridges where the surfacing thickness is more than 100mm over the entire bridge.

3.2.1.4  Surface course

Before the introduction of TSCSs, almost all surface courses on Highways Agency bridges were HRA with embedded pre-coated chippings. When TSCSs were introduced, some Agents were keen to use them on bridges because they have better resistance to deformation than HRA and reduce traffic noise, and to be consistent with the adjacent pavement. The noise reduction is considered to be most beneficial on elevated sections in heavily populated areas. Other Agents were concerned about the permeability of TSCSs and were reluctant to use them on bridges.

Therefore, on some bridges, deteriorated HRA surface courses have been replaced by TSCSs, sometimes only in lane 1 and often when the surface course on the adjacent pavement has been
replaced. The original surfacing thickness has normally been retained, even though many TSCSs can be laid significantly less than 50mm thick. On other bridges, an HRA surface course has been replaced with HRA, even if a TSCS has been laid on the adjacent pavement, but this is less far less likely at the present time.

3.2.2 Surfacing less than or equal to 100mm thick

3.2.2.1 General

The surfacing thickness has been reduced on some bridges because of a requirement to reduce the dead weight or increase the clearance height. On others, the surfacing has been less than 120mm historically, and there has been a reluctance to increase the thickness because of kerb and parapet heights. For example, much of the M5 was initially waterproofed with a 20mm layer of mastic asphalt that was overlaid with a 35mm to 40mm HRA surface course. Table 3.2 to Table 3.4 list the different types of surfacing system less than or equal to 100mm thick that have been laid on bridges.

Table 3.2 Typical surfacing systems from 80 to 100mm thick

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>Mixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>APL</td>
<td>20</td>
<td>Red sand asphalt, PBC</td>
</tr>
<tr>
<td>Binder course</td>
<td>15-55</td>
<td>HRA binder course, SMA, PBC</td>
</tr>
<tr>
<td>Surface course</td>
<td>25-50</td>
<td>HRA surface course, TSCS</td>
</tr>
</tbody>
</table>

Table 3.3 Typical surfacing systems up to 80mm thick with additional protective layer

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>Mixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>APL</td>
<td>20</td>
<td>Red sand asphalt, PBC</td>
</tr>
<tr>
<td>Binder course</td>
<td>0-35</td>
<td>HRA binder course, PBC</td>
</tr>
<tr>
<td>Surface course</td>
<td>25-50</td>
<td>HRA surface course, TSCS</td>
</tr>
</tbody>
</table>

Table 3.4 Typical surfacing systems up to 80mm thick without additional protective layer

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>Mixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder course</td>
<td>20-55</td>
<td>HRA binder course, SMA, PBC</td>
</tr>
<tr>
<td>Surface course</td>
<td>25-50</td>
<td>HRA surface course, TSCS</td>
</tr>
</tbody>
</table>

3.2.2.2 APL

When the surfacing thickness varies from around 80mm to 100mm, it has been common practice to lay an APL of red sand asphalt and reduce the thickness of the binder course or the surface course. When the surfacing thickness is less than 80mm, an APL of red sand asphalt has sometimes been overlaid directly with the surface course (see Figure 3.2). This has often been the case when bridges
were previously waterproofed with a 20mm thick layer of mastic asphalt that was directly overlaid with an HRA surface course. In effect, the mastic asphalt has been replaced by a waterproofing system of nominal thickness 2.5mm and a 20mm thick APL.

PBCs with a maximum aggregate size of 6mm have been used instead of an APL of red sand asphalt on some bridges because of their better resistance to deformation.

On some bridges, the APL has been omitted and the binder course has been laid directly onto the waterproofing system (see Figure 3.3).

![Figure 3.2 Typical surfacing thicknesses when there is no binder course](image)

![Figure 3.3 Typical surfacing thicknesses when there is no additional protective layer](image)

3.2.2.3 Binder course

When the surfacing thickness varies from around 80mm to 100mm, it has been common to lay an HRA binder course, but stone mastic asphalt (SMA) mixtures and PBCs have been laid on some bridges recently. PBCs with a maximum aggregate size of 6mm have been laid as thin as 15mm.

When the surfacing thickness is less than 80mm, and the APL has been omitted, the binder course has been a PBC, a SMA, an HRA binder or surface course mixture or a DBM binder course mixture. When the binder course has been laid directly onto the waterproofing system, the maximum aggregate size of the mixture has often been 6mm or 10mm, although some mixtures have had a maximum aggregate size of 14mm.
3.2.2.4 Surface course systems

In 1999, the surface course on most bridges with surfacing less than 100mm thick was HRA of thickness from 35mm to 50mm, mainly because they were surfaced before the introduction of TSCSs. However, TSCSs have been laid from 25mm to 40mm thick on bridges in recent years.

3.2.3 Surfacing of variable thickness

Many Agents have found it difficult to identify surfacing systems that are appropriate for the large range of surfacing thicknesses that are found on some bridges. Variations in thickness up to 50mm or more from midspan to pier positions are not uncommon on many large multispan bridges. The surfacing system can change from two to three layers as the surfacing thickness changes. However, even then, it is often difficult to identify mixtures that are suitable for the range of thickness of each layer. At the lowest thickness, the maximum aggregate size can be too large, the level of compaction can be compromised, and the layer may be more liable to suffer fatigue cracking. At the highest thickness, the maximum aggregate size can be too small, the mixture can be displaced during rolling, the layer may suffer excessive deformation, and, for surface course layers, loss of texture.

3.3 The performance of surfacing on bridges

3.3.1 Surfacing more than 100mm thick

Surfacing of the type shown in Table 3.1 and Figure 3.1 with an effectively impermeable surface course has generally performed well on bridges. The lower asphalt layers have lasted 20 years or more on many bridges. Problems such as deformation and loss of skidding resistance have been similar to those on pavements, although increased deformation on some bridges has been attributed to the deformation of the APL or the deformation of asphaltic plug joints (APJs). There has been little, if any, evidence of fatigue cracking.

Where there has been a lack of sub-surface drainage, water has ponded at the high side of some expansion joints and either leaked through the joints or flowed out of the surfacing over them. Water has also flowed out of the surfacing at locations away from joints and the low points of bridges where, apparently, there have been local variations in the permeability of the surfacing.

Agents reported that the void content of TSCSs varies widely with their type. Some types are considered to be reasonably impermeable, whereas others have a very open texture and are considered to be relatively permeable. Generally, more water had entered TSCSs than has entered HRA surface courses, and this has been cited as the reason for increased leakage through expansion joints and increased volumes of water flowing out of the surfacing on the high side of expansion joints. There have been no such problems on bridges with buried joints at their low end because they do not block the flow of sub-surface water.

3.3.2 Surfacing less than 100mm thick

3.3.2.1 General

There have been a number of premature failures of surfacing less than 100mm. The most notable failures reported by Agents are summarised in Table 3.5.
## Table 3.5 Notable surfacing failures on bridges

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Surfacing type and max. aggregate size (Thickness in parenthesis)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 1</td>
<td>Red sand asphalt (20mm) 0/6mm PBC (35mm) 14mm TSCS (30-65mm)</td>
<td>Section failed in lane 1 within 2 years where water had ponded, and was probably less than 120mm thick. Membrane was 3 to 4mm thick. Sand carpet was completely debonded.</td>
</tr>
<tr>
<td>System 1</td>
<td>0/6mm PBC (25mm) 14mm TSCS (35mm)</td>
<td>Surfacing failed initially after 6 months near a joint at the low end of the bridge following heavy rain. It was replaced after 2 years. The membrane was up to 7mm thick in places.</td>
</tr>
<tr>
<td>System 1</td>
<td>0/10mm SMA (20-70mm) 14mm TSCS (35mm)</td>
<td>The surfacing broke up frequency where it was less than 80mm thick and where water had accumulated. The deck was rewaterproofed after 2 years (see Section 3.2.2.1).</td>
</tr>
<tr>
<td>System 1</td>
<td>Red sand asphalt (20mm) HRA/TSCS (35-70mm)</td>
<td>On a route to an industrial estate, around 25% of the surfacing failed within 5 years. The failed area was rewaterproofed and surfaced with sand asphalt and a TSCS but this started breaking up within one year where braking forces were high.</td>
</tr>
<tr>
<td>System 1</td>
<td>Red sand asphalt (20mm) HRA (40mm)</td>
<td>The heavily trafficked surfacing failed where large centrifugal forces were generated by turning HGVs. Water had accumulated in surfacing on waterproofing system. There were no deck drains and the membrane was 3 to 4mm thick.</td>
</tr>
<tr>
<td>System 1</td>
<td>Red sand asphalt (20mm) HRA (50mm)</td>
<td>The HRA is rutted and has been breaking up. The failures appear to be randomly located.</td>
</tr>
<tr>
<td>System 1</td>
<td>Red sand asphalt (20mm) HRA (80mm)</td>
<td>Sections of surfacing failed after from 4 to 9 years. Most failures were due to bad workmanship. The deck was rewaterproofed in sections and there was debonding at overlaps, and longitudinal cracks in the surfacing.</td>
</tr>
<tr>
<td>System 2</td>
<td>HRA (35mm minimum, typically &gt;50mm total)</td>
<td>The surfacing broke up between lanes 1 and 2 where the thickness was 50 to 60mm. Repairs have been made and the condition is satisfactory.</td>
</tr>
<tr>
<td>System 2</td>
<td>Red sand asphalt (20mm) HRA (35mm)</td>
<td>The surfacing broke up at several locations. The APL was poorly compacted and saturated with water, and poorly bonded to the waterproofing system. Water had found a way under the membrane and high hydrostatic pressures may have been induced under the membrane by wheel loading.</td>
</tr>
<tr>
<td>System 5</td>
<td>Mastic asphalt (20mm) HRA (45mm)</td>
<td>Large area of surfacing had failed after 6 years. The mastic asphalt was poorly bonded to the waterproofing system. The stiffness of the waterproofing system was very low.</td>
</tr>
<tr>
<td>System 5</td>
<td>(70mm total)</td>
<td>The surfacing broke up frequently. The stiffness of the waterproofing system was low.</td>
</tr>
</tbody>
</table>
3.3.2.2 **Cracking**

The most significant type of failure is cracking of the surfacing. Cracked areas have broken up and debonded from the waterproofing system to form potholes. In almost every case, if not every case, water was present in the surfacing. This sub-section describes the types of failure that can occur. Although most of the examples shown are not on Highways Agency bridges, they have been included because they are typical and show how failures can develop. Generally, failures occur very quickly on Highways Agency bridges because of the high volumes of heavy goods vehicles and their development is, therefore, not so easy to record. Most failures are similar to those on standard pavements, but they tend to occur more quickly on bridges. For example, on one structure the waterproofing system was overlaid directly with a DBM binder course which failed under construction traffic. Subsequently, HRA was laid throughout the full depth of construction and this performed well.

Figure 3.4 shows a typical, reasonably extensive failure of a 60mm SMA binder course and a 30-40mm TSCS. The surface course had initially crazed and cracked, broken into pieces typically less than 150mm across, and some of the pieces had been removed. Some of the material around the pothole was similar in size to the coarse aggregates.

Figure 3.5 shows the cracking of a 40mm TSCS overlaying a 60mm DBM binder course before any potholes had formed, with water being forced out of the surfacing by the wheels of HGVs. Over time, crazing of the surfacing became widespread before there was total failure of large areas (Figure 3.6). Note the loose coarse aggregates on the surface course.

On other bridges, sand asphalt has been overlaid directly with a permeable surface course. The sand asphalt has become saturated and broken up, resulting also in failure of the surface course.

On some bridges, patch repairs have been successful where only small areas have failed. However, different areas have failed over a period of time on some bridges, requiring frequent repairs to remove hazards to road users. Bridges have been resurfaced and, normally, rewaterproofed when the area affected has become too great, or the frequency of the repairs has become too high.

Small patch repairs have not been successful where they have not extended well beyond the failed area or where measures have not been taken to prevent subsequent failure. Figure 3.7 shows the failure of a TSCS beyond a small patch repair, and Figure 3.8 shows a subsequent failure of a small patch repair. Figure 3.9 shows the failure of a large HRA patch repair which had replaced a TSCS and DBM binder course before the causes of the original failure were remedied.

Other large HRA patch repairs have been successful, but some have initiated failures elsewhere. The TSCS shown in Figure 3.7 was on a multi-span bridge where the thickness of the surfacing ranged from about 50mm at the pier positions, where the deck was hogged, to more than 120mm at midspan. The surfacing had failed in lane 1 on the high side of an expansion joint where the surfacing was thin and where sub-surface water had accumulated. When it became impractical to make small patch repairs, a length of surfacing in lane 1 on the high side of the joint, incorporating the badly cracked section, was removed down to the concrete deck/waterproofing system and the full depth of surfacing was replaced with HRA. The HRA was less permeable than the TSCS, so sub-surface water accumulated in the TSCS on the high side of the HRA. In time, this area of the TSCS failed in the same way as the section adjacent to the joint, so it was replaced by a second section of HRA as shown in Figure 3.10. At the top of the photograph, there is a light grey area at the far end of this patch where sub-surface water is coming out of the TSCS on the high side of this second section. The process described above was about to be repeated. Figure 3.11 shows a close-up of this area with the sub-surface water flowing out of the TSCS and over the HRA.

Lane 1 was on the high side of the carriageway but little, if any, sub-surface water appeared to be flowing from lane 1 into lane 2 through the surfacing. It is possible, but unlikely, that the TSCS was fairly impermeable in lane 2. The most likely reason is that sealant placed between the rips in Lane 1 and lane 2 acted as a dam in the same way as the expansion joint.
The TSCS also failed where it was thin at some pier positions away from the expansion joints and where sub-surface water had not accumulated.

Failures have been more evident in areas where the surfacing has been thinnest and at the low points of bridges where water has accumulated because of insufficient sub-surface drainage. Failures have often occurred after wet weather. Some have occurred after a few days when the asphalt layer directly overlaying the waterproofing system has had a high void content at the interface between the surfacing and the waterproofing system. When old surfacing has been removed from liquid-applied systems, it has sometimes been poorly bonded over large areas of the waterproofing system (Figure 3.12).

Premature failures have also occurred in HRA surface courses. Figure 3.13 shows a localised failure of a 35mm HRA surface course overlaying a 20mm sand asphalt layer. There were more extensive failures on the same bridge which, presumably, started in the same way with a small, isolated defect. Where failures were extensive, water was found under the membrane that may have passed through defective lap joints. However, because of the material types and the low surfacing thickness, it is unlikely that the presence of the water was solely responsible for the surfacing failures. Some high areas of the deck were waterproofed before the lower areas so sub surface water could flow into the lap joints. In some areas of the deck, it appeared that the bond of the membrane to the deck was poor. There was evidence that the membrane had been bonded to the deck initially, but the bond had failed in service. Much water and detritus were found under the membrane, as shown in Figure 3.14.

The failure of the surfacing on another bridge was attributed to bad workmanship during the application of the waterproofing system. Debris from grit blasting was found under the membrane.

3.3.2.3 Deformation

The deformation of the surfacing has been high on some bridges when an HRA surface course has been laid directly onto an APL of red sand asphalt.

The deformation on some bridges has been attributed to the break-up of the binder course and/or APL when saturated (because of stripping of the binder) which undermined the surface course.
Figure 3.4 Failure of a TSCS

Figure 3.5 Water forced out of a cracked TSCS by heavy goods vehicles
Figure 3.6 Break-up of a TSCS

Figure 3.7 Failure of a TSCS extending beyond a patch repair
Figure 3.8 Failure of a TSCS and patch repair

Figure 3.9 Failure of a large HRA patch repair in a TSCS
Figure 3.10 Two sections of HRA laid in Lane 1 to replace the TSCS on the high side of an expansion joint. Note sub-surface water coming out of the TSCS at the far end of the HRA.

Figure 3.11 Close-up of far end of HRA shown in Figure 3.10 where sub-surface water is coming out of the TSCS.
Figure 3.12  Large area where surfacing has debonded from the waterproofing system

Figure 3.13  Localised failure of an HRA surface course
Figure 3.14  Water and detritus beneath a membrane that has debonded from a deck
4 Laboratory tests

4.1 Bond tests

4.1.1 General
A number of bond tests were carried out to investigate how the bond of surfacing to Systems 1 and 2 varies with the type of surfacing, the water content of the surfacing and the effect of wheel loading. The tests were carried out during the first project when Systems 1 and 2 were the only registered systems. The bond strength of the systems tested was dependent on the adhesion of the tack coat to the membrane, the cohesion of the tack coat and the adhesion of the surfacing to the tack coat. The adhesion of the surfacing to the tack coat was dependent on the contact area between the surfacing and the tack coat, i.e. the void content at the interface between the surfacing and the waterproofing system.

The waterproofing systems were applied to concrete base slabs and overlaid with red sand asphalt, HRA binder course and HRA surface course mixtures. The specimens were stored at ambient temperature before they were tested, some in a dry condition, and others in water at a level 30mm above the waterproofing system after the concrete base slabs had been sealed with epoxy resin (defined as a ‘wet’ condition).

4.1.2 Tensile and shear bond tests

4.1.2.1 General
Tensile and shear bond tests were carried out at 23°C ± 2°C in accordance with the test methods described in clauses of B4.2(l) and B4.2(k), respectively, of Appendix B of BD 47.

For the tensile bond tests, two test sections were prepared on each 300mm square specimen by cutting through the surfacing and the waterproofing system and just into the base slab. The sections that were tested 7 days, 4 months and 12 months after surfacing measured approximately 100mm square and they were formed by sawcutting. The sections that were tested 6 months after surfacing were formed by coring with a 100mm diameter coring bit. When the tensile and shear bond test results were compared, it was evident that the tensile test sections had been weakened during the sawcutting and coring. The true tensile bond strengths of these sections would have been higher than the recorded failure stresses. The test sections most affected by the sawcutting and coring appeared to be those with red sand asphalt and those with inherently low bond strengths. In some tests, the sand asphalt failed rather than the bond at the interface with waterproofing system (see the ‘dry’ specimens tested at 4 months in rows 3 and 4 of Table 4.1). The sand asphalt was not defective because the same mixture was used for the shear test specimens, and they suffered no cracking. It was also well compacted, so it is concluded that the sawcutting weakened the sand asphalt.

Because of the weakening of the tensile test sections by sawcutting and coring, the variation in the bond strength with the factors considered is best assessed from the shear bond test results. However, the trends shown in the shear and tensile bond test results were reasonably consistent. It should be noted that the tests were designed to investigate trends that would benefit the interpretation of the tensile bond strengths measured after wheel loading. Some tests were repeated to investigate anomalies and this meant that, for some mixtures, both systems were subjected to the same test conditions.

The normalised failure stresses and details of the failure surfaces in the tests are given in Table 4.1 to Table 4.4. The normalised failure stresses were calculated by dividing the mean failure stresses by those for the 7 day specimens with red sand asphalt to facilitate investigation of the effects of age and water content.
### Table 4.1 System 1 tensile bond test results

<table>
<thead>
<tr>
<th>Surfacing mixture</th>
<th>Laying temp. (°C)</th>
<th>How stored</th>
<th>Approx. time stored</th>
<th>Test temp. (°C)</th>
<th>Normalised tensile failure stress</th>
<th>Main locations of failure surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Dry</td>
<td>7 days</td>
<td>22</td>
<td>1.00</td>
<td>Rsa&lt;sup&gt;2&lt;/sup&gt; to tack coat, Tack coat to membrane&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Dry</td>
<td>4 months</td>
<td>23</td>
<td>1.44</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Dry</td>
<td>4 months</td>
<td>23.5</td>
<td>0.72</td>
<td>Rsa</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Dry</td>
<td>6 months</td>
<td>23.5</td>
<td>0.70</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Wet</td>
<td>6 months</td>
<td>22.5</td>
<td>0.42</td>
<td>Rsa</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>150</td>
<td>Dry</td>
<td>7 days</td>
<td>22</td>
<td>0.51</td>
<td>HRA to tack coat, Tack coat to membrane</td>
</tr>
<tr>
<td>35% 0/14mm HRA surface course</td>
<td>150</td>
<td>Dry</td>
<td>4 months</td>
<td>23</td>
<td>1.53</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>35% 0/14mm HRA surface course</td>
<td>130</td>
<td>Dry</td>
<td>6 months</td>
<td>23.5</td>
<td>1.40</td>
<td>HRA to tack coat</td>
</tr>
<tr>
<td>35% 0/14mm HRA surface course</td>
<td>130</td>
<td>Wet</td>
<td>6 months</td>
<td>22</td>
<td>0.66</td>
<td>Tack coat to membrane</td>
</tr>
</tbody>
</table>

### Table 4.2 System 2 tensile bond test results

<table>
<thead>
<tr>
<th>Surfacing mixture</th>
<th>Tack coat</th>
<th>Laying temp. (°C)</th>
<th>How stored</th>
<th>Approx. time stored</th>
<th>Test temp. (°C)</th>
<th>Normalised tensile failure stress</th>
<th>Main locations of failure surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>Thin</td>
<td>150</td>
<td>Dry</td>
<td>7 days</td>
<td>22</td>
<td>1.00</td>
<td>Rsa&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>Thin</td>
<td>150</td>
<td>Dry</td>
<td>4 months</td>
<td>23</td>
<td>0.48</td>
<td>Rsa to tack coat</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>150</td>
<td>Dry</td>
<td>7 days</td>
<td>22</td>
<td>1.80</td>
<td>HRA to tack coat, Membrane to concrete, Tack coat to membrane</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>150</td>
<td>Dry</td>
<td>4 months</td>
<td>23.5</td>
<td>1.76</td>
<td>Concrete</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>130</td>
<td>Dry</td>
<td>12 months</td>
<td>22</td>
<td>1.92</td>
<td>Tack coat</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>150</td>
<td>Wet</td>
<td>4 months</td>
<td>23.5</td>
<td>1.78</td>
<td>Concrete</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>130</td>
<td>Wet</td>
<td>12 months</td>
<td>22</td>
<td>0.71</td>
<td>Tack coat</td>
</tr>
</tbody>
</table>

Key to Tables 4.1 to 4.4

1. Two tests were carried out on each tensile sample, two specimens were tested in shear
2. Rsa = red sand asphalt
3. When the failure surface was at the ‘tack coat to the membrane’, there were traces of the tack coat left on the membrane
### Table 4.3 System 1 shear bond test results

<table>
<thead>
<tr>
<th>Surfacing mixture</th>
<th>Laying temp. (°C)</th>
<th>How stored</th>
<th>Approx. time stored</th>
<th>Test temp. (°C)</th>
<th>Normalised shear failure stress</th>
<th>Main locations of failure surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Dry</td>
<td>7 days</td>
<td>22</td>
<td>1.00</td>
<td>Tack coat to membrane³</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Dry</td>
<td>4 months</td>
<td>23</td>
<td>0.74</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Dry</td>
<td>6 months</td>
<td>23</td>
<td>0.92</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>150</td>
<td>Wet</td>
<td>6 months</td>
<td>23</td>
<td>0.75</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>150</td>
<td>Dry</td>
<td>7 days</td>
<td>22</td>
<td>1.01</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>35% 0/14mm HRA surface course</td>
<td>150</td>
<td>Dry</td>
<td>4 months</td>
<td>23</td>
<td>1.04</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>35% 0/14mm HRA surface course</td>
<td>130</td>
<td>Dry</td>
<td>6 months</td>
<td>23</td>
<td>0.90</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>35% 0/14mm HRA surface course</td>
<td>130</td>
<td>Dry</td>
<td>12 months</td>
<td>23</td>
<td>1.23</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>35% 0/14mm HRA surface course</td>
<td>130</td>
<td>Wet</td>
<td>6 months</td>
<td>23</td>
<td>0.75</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>35% 0/14mm HRA surface course</td>
<td>130</td>
<td>Wet</td>
<td>12 months</td>
<td>23</td>
<td>0.75</td>
<td>Tack coat to membrane</td>
</tr>
</tbody>
</table>

### Table 4.4 System 2 shear bond test results

<table>
<thead>
<tr>
<th>Surfacing mixture</th>
<th>Tack coat</th>
<th>Laying temp. (°C)</th>
<th>How stored</th>
<th>Approx. time stored</th>
<th>Test temp. (°C)</th>
<th>Normalised tensile failure stress</th>
<th>Main locations of failure surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>Thin</td>
<td>150</td>
<td>Dry</td>
<td>7 days</td>
<td>22</td>
<td>1.00</td>
<td>Rsa to tack coat, Tack coat to membrane</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>Thin</td>
<td>150</td>
<td>Dry</td>
<td>12 months</td>
<td>23</td>
<td>0.48</td>
<td>Rsa, Rsa to tack coat</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>Thin</td>
<td>150</td>
<td>Wet</td>
<td>4 months</td>
<td>22</td>
<td>0.48</td>
<td>Rsa to tack coat</td>
</tr>
<tr>
<td>0% 0/2mm Red sand asphalt</td>
<td>Thin</td>
<td>150</td>
<td>Wet</td>
<td>12 months</td>
<td>23</td>
<td>0.24</td>
<td>Rsa</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>150</td>
<td>Dry</td>
<td>7 days</td>
<td>22</td>
<td>1.02</td>
<td>Tack coat</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>150</td>
<td>Dry</td>
<td>4 months</td>
<td>22</td>
<td>1.09</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>130</td>
<td>Dry</td>
<td>6 months</td>
<td>23</td>
<td>1.18</td>
<td>No failure - 10mm slippage of HRA</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>130</td>
<td>Dry</td>
<td>12 months</td>
<td>23</td>
<td>1.11</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>150</td>
<td>Wet</td>
<td>4 months</td>
<td>22</td>
<td>0.86</td>
<td>Tack coat to membrane</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>130</td>
<td>Wet</td>
<td>6 months</td>
<td>23</td>
<td>1.18</td>
<td>No failure - 10mm slippage of HRA</td>
</tr>
<tr>
<td>50% 0/14mm HRA binder course</td>
<td>Thick</td>
<td>130</td>
<td>Wet</td>
<td>12 months</td>
<td>23</td>
<td>1.11</td>
<td>Tack coat to membrane Tack coat</td>
</tr>
</tbody>
</table>

Key below Table 4.2
4.1.2.2 System 1

The shear bond strengths of the ‘dry’ specimens were similar for the 0% 0/2mm red sand asphalt and the 35% 0/14mm HRA surface course. The normalised shear bond strengths ranged from 75 to 123%, with the highest bond strength measured on a 35% 0/14mm HRA surface course specimen at 12 months. They were consistently lower for the ‘wet’ specimens than for the ‘dry’ specimens; the difference in the normalised strengths was greatest for the HRA surface course specimens tested at 12 months. The mean of the ‘wet’ and ‘dry’ shear bond strengths of the red sand asphalt and HRA surface course specimens at 6 months were almost identical.

The failure surfaces were mainly at the interface between the tack coat and the membrane. When the failure surface was predominantly at this interface, the tensile bond strengths showed similar trends to the shear bond strengths. The mean tensile bond strengths of the ‘dry’ red sand asphalt and HRA specimens after 4 months were similar, as were the ‘dry’ HRA specimens after 4 months and 6 months. It would appear that the tensile specimens tested at 6 months were weakened when they were cored. This may be due in part, if not fully, to the erosion of the tack coat at the periphery of the test sections. There was more erosion on the ‘wet’ specimens than the ‘dry’ specimens.

The mean tensile bond strength was lower for the 50% 0/14mm HRA binder course than for the red sand asphalt. Because the mean shear bond strengths were the same, it appears that the sawcutting weakened the HRA binder course specimen more than the red sand asphalt specimens, possibly because the void content at the base of the HRA binder course at the interface with the waterproofing system was high.

4.1.2.3 System 2 with thin tack coat

Only a few tests were carried out on System 2 with the thin tack coat overlaid with 0% 0/2mm red sand asphalt. The mean bond strengths were significantly lower after 4 and 12 months than after 7 days. However, there was a delay of 12 weeks after the application of the tack coat before the specimens were surfaced, not representative of site practice, which was probably responsible for the decrease.

Despite the delay, the mean shear bond strengths for System 2 measured after 12 months were comparable with those for System 1 after 6 months. The mean shear bond strength of the ‘wet’ System 2 specimens after 12 months were almost 50% lower than those of the ‘dry’ specimens, but part if not all of the decrease could be attributed to the delay in surfacing.

The failure surfaces were predominately within the red sand asphalt just above the tack coat at the centre of the specimen, and at the interface between the red sand asphalt and the tack coat at the periphery. This suggests that the 25mm thick sand asphalt layer may have cooled more rapidly or been less well compacted at the edge of the specimens. There was little evidence of edge effects when the bituminous layer laid directly onto the waterproofing system was 50mm thick.

4.1.2.4 System 2 with thick tack coat

The mean tensile bond strengths for System 2 with the thick tack coat overlaid with the 50% 0/14mm HRA binder course were generally higher than those for the red sand asphalt. The normalised shear bond strengths ranged from 86 to 118 per cent. The delay in applying the surfacing appeared not to be as significant for the thick tack coat as for the thin tack coat. The normalised shear bond strengths were identical for the ‘wet’ and ‘dry’ specimens at 6 and 12 months. They were lower for the ‘wet’ specimens than for the ‘dry’ specimens after 4 months, but these differences may not be significant and may be the result of small differences in the thickness of the thick tack coat (see below).

The failure surfaces were predominately at the interface between the tack coat and the membrane and within the tack coat.

Tests were carried out to determine the bond of the 35% 0/14mm HRA surface course with modified binder to System 2 with the thick tack coat that was specified for a viaduct. Tensile bond strengths measured on specimens taken from a slab produced by Nottingham University were almost identical.
to those shown in Table 4.2. Shear bond strengths measured on specimens taken from the same slab were approximately 25% lower than those shown in Table 4.4. Shear bond strengths measured on cores taken from a trial area prepared beneath the viaduct ranged from 42 to 138% of the mean shear bond strength for the 50% 0/14mm HRA at 7 days. The lowest values were where less than the specified amount of tack coat had been applied. Where there was sufficient tack coat and the asphalt was laid and rolled at similar temperatures as for the tests carried out by TRL, the shear bond strengths were very similar. Further cores were taken from the viaduct itself. The mean tensile bond strength of two cores tested at TRL was 36% of the mean tensile bond strength for the 50% 0/14mm HRA at 7 days. The mean shear bond strength of three cores tested at TRL was 64% of the mean shear bond strength for the 50% 0/14mm HRA at 7 days. Lower shear bond strengths were obtained in some tests on other cores carried out by the manufacturer of System 2 and observed by TRL.

4.1.3 Tensile bond tests after wheel loading

In order to investigate the effect of wheel loading on the bond of surfacing to the waterproofing systems, six pairs of specimens were subjected to up to 500,000 wheel loads of 35kN. One of each pair of specimens was stored and tested dry, while the other was stored and tested ‘wet’. The waterproofing and surfacing systems tested are listed in Table 4.5. The surfacing systems were representative of those that have overlaid waterproofing systems on bridges in the past. However, the waterproofing manufacturers now use others tack coats for some of the 85mm thick surfacing systems that were tested. Nevertheless, the tack coats used for the tests were chosen in order to investigate specific factors, and to correlate the performance in the tests with the performance on bridges.

After wheel loading, the surfacing was sectioned by sawcutting so tensile bond tests could be carried out in the wheel path and to either side of the wheel path. This was the only way that the bond strength could be assessed after the wheel loading, but the sawcutting appeared to weaken the test sections. It is likely that all test sections were weakened by sawcutting, but those that were most affected were those with inherently low bond strengths. The normalised results referenced to those measured on the tensile bond test specimens tested at 7 days are shown in Table 4.5.

The tensile bond strengths of the 120mm surfacing with red sand asphalt to both waterproofing systems were lower for the ‘wet’ specimens than for the ‘dry’ specimens. The bond strengths of the ‘wet’ specimens were also lower than those measured on the ‘wet’ specimens without wheel loading. It appears that, because water was present in the sand asphalt, the wheel loading weakened the sand asphalt itself and/or the bond of the sand asphalt to the waterproofing system.

The bond strengths of the 85mm surfacing with a 35% 0/14mm HRA surface course mixture directly overlaying System 1 that were measured on the ‘dry’ specimen away from the wheel path were similar to the those measured without wheel loading. The bond strengths were lower in the wheel path. Those measured on the ‘wet’ specimen after wheel loading were slightly lower than those measured on the ‘dry’ specimen, indicating any water that may have been present in the HRA surface course mixture directly overlaying the waterproofing system had a small effect on the bond strength. Although there were some voids in the HRA at the interface with the waterproofing system, they may not have been interconnecting.

The bond strengths of the 85mm surfacing with a 35% 0/14mm HRA surface course mixture directly overlaying System 2 with a thin tack coat were low compared to the tensile bond strengths measured on specimens without wheel loading for both the ‘wet’ and ‘dry’ specimens. It is possible that that bond was low because the tack coat was not activated, although the mixture was laid and rolled above the specified activation temperature. If the initial bond strength had been low, the bond may have been weakened considerably by the sawcutting.
## Table 4.5 Wheel loading test specimens

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Additional protective layer</th>
<th>Binder course</th>
<th>Surface course</th>
<th>Total thickness of surfacing (mm)</th>
<th>Maximum normalised tensile strength</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mixture</td>
<td>Thickness (mm)</td>
<td>Mixture</td>
<td>Thickness (mm)</td>
<td>Mixture</td>
<td>Thickness (mm)</td>
<td>Wheel path</td>
<td>To side of wheel path</td>
<td>Wheel path</td>
<td>To side of wheel path</td>
<td></td>
</tr>
<tr>
<td>System 1</td>
<td>0% 0/2mm Red sand asphalt</td>
<td>20</td>
<td>50% 0/20mm HRA binder course</td>
<td>55</td>
<td>35% 0/14mm HRA surface course</td>
<td>45</td>
<td>120</td>
<td>0.83 (0.79)</td>
<td>0.98 (0.45)</td>
<td>0.34 (0.30)</td>
<td>0.04 (&lt;0.04)</td>
</tr>
<tr>
<td>System 2 (thin tack coat)</td>
<td>0% 0/2mm Red sand asphalt</td>
<td>20</td>
<td>50% 0/14mm HRA binder course</td>
<td>55</td>
<td>35% 0/14mm HRA surface course</td>
<td>45</td>
<td>120</td>
<td>0.95 (0.71)</td>
<td>0.18 (0.13)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.06 (0.01)</td>
</tr>
<tr>
<td>System 1</td>
<td>-</td>
<td>-</td>
<td>35% 0/14mm HRA surface course</td>
<td>45</td>
<td>35% 0/14mm HRA surface course</td>
<td>40</td>
<td>85</td>
<td>0.44 (0.42)</td>
<td>0.96 (0.64)</td>
<td>0.44 (0.15)</td>
<td>0.64 (0.42)</td>
</tr>
<tr>
<td>System 2 (thin tack coat)</td>
<td>-</td>
<td>-</td>
<td>35% 0/14mm HRA surface course</td>
<td>45</td>
<td>35% 0/14mm HRA surface course</td>
<td>40</td>
<td>85</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.02 (&lt;0.01)</td>
<td>&lt;0.01 (&lt;0.01)</td>
<td>0.02 (&lt;0.01)</td>
</tr>
<tr>
<td>System 1</td>
<td>-</td>
<td>-</td>
<td>50% 0/10mm HRA binder course</td>
<td>45</td>
<td>35% 0/14mm HRA surface course</td>
<td>40</td>
<td>85</td>
<td>&lt;0.07 (&lt;0.07)</td>
<td>0.30 (0.22)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>System 2 (thick tack coat)</td>
<td>-</td>
<td>-</td>
<td>50% 0/14mm HRA binder course</td>
<td>45</td>
<td>35% 0/14mm HRA surface course</td>
<td>40</td>
<td>85</td>
<td>0.83 (0.82)</td>
<td>0.88 (0.77)</td>
<td>0.94 (0.93)</td>
<td>0.91 (0.82)</td>
</tr>
</tbody>
</table>

1. Tensile bond test results for 50% 0/14mm HRA binder course used for normalisation
The 85mm surfacing with a 50% 0/14mm HRA binder course mixture directly overlaying System 1 debonded from the waterproofing system of the ‘wet’ specimen after about 102,000 wheel loads before bond tests could be carried out. The tack coat had debonded from the waterproofing system. The void content and permeability of the bulk of the 50% 0/14mm HRA binder course mixture appeared to be similar to that of the 35% 0/14mm HRA surface course mixture, but there were many voids at the base of the 50% 0/14mm HRA at the interface with the waterproofing system that would have filled with water.

The bond strengths measured on the ‘dry’ specimens were low. It is possible that the bond was more susceptible to weakening during sawcutting because the contact area at the interface between the surfacing and the waterproofing system was low. This was found in the tensile bond tests with the HRA binder course without wheel loading.

The bond strengths of the 85mm surfacing with a 50% 0/14mm HRA binder course mixture directly overlaying System 2 with a thick tack coat were similar for the ‘wet’ and ‘dry’ specimens, and similar to those measured on specimens without wheel loading. The bond strengths were significantly higher than those measured on the other wheel loading specimens. The void content of the surfacing at the interface with the waterproofing system was low. Any water that entered the ‘wet’ specimen had very little, if any, effect on the bond strengths.

4.2 Flow of water through surfacing

Pearson and Cuninghame (1998) describes two mechanisms by which sub-surface water flows through surfacing on bridges: permeation and absorption. Permeation occurs when water is forced through a medium by a hydraulic pressure gradient. On bridges, a slope or hydrostatic pressures generated in saturated surfacing by wheel loading may introduce a hydraulic gradient. Absorption occurs when there is capillary suction. Whether permeation or absorption is the dominant mechanism is dependent on the permeability and sorptivity of the surfacing.

The permeabilities and sorptivities reported by Pearson and Cuninghame were measured on cores of material and were the properties of the mixtures themselves. On bridges, water may also flow through the surfacing at the interface with the waterproofing system where, depending on the aggregate grading and binder content of the surfacing, and the thickness of the tack coat, the void content may be high. A series of ad-hoc tests on specimens comprising Systems 1 and 2 overlaid with different surfacing mixtures were conducted to investigate this phenomenon. It was hoped that the rate of the flow would give an indication of the void content at the interface.

The specimens were manufactured in the same way as the tensile bond test specimens described in Section 4.1. They comprised concrete base slabs measuring 300mm x 300mm x 55mm thick overlaid with a waterproofing system and surfacing of total thickness 50mm. The concrete base slabs were sealed in the same way as the tensile bond test specimens that were stored wet. A 100mm-diameter core of surfacing together with the waterproofing system was removed from the centre of each specimen. The concrete below the waterproofing system within the core was sealed with epoxy resin, forming a watertight seal at the exposed edges of the waterproofing membrane. The epoxy resin prevented any water that passed through the surfacing into the core from soaking into the concrete. The specimens were placed in a water bath with the water level maintained at about 30mm above the waterproofing system.

The details of the specimens tested and the test results are given in Table 4.6 and Figure 4.1. The red and black sand asphalt specimens comprised two 25mm thick layers of sand asphalt, the upper layer of both specimens being black.
Table 4.6 Summary of water flow test results

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Surfacing mixture</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 1</td>
<td>0% 0/3mm Red sand asphalt</td>
<td>No ingress of water after 52 weeks</td>
</tr>
<tr>
<td>System 1</td>
<td>35% 0/14mm HRA surface course</td>
<td>Water visible at interface after 7 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 28 weeks: Water depth 12mm after further 7 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 40 weeks: Water depth 6mm after further 4 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 46 weeks: Water depth 6mm after further 4 weeks</td>
</tr>
<tr>
<td>System 2 (thin tack coat)</td>
<td>0% 0/3mm Red sand asphalt</td>
<td>No ingress after 35 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 40 weeks: Water depth 27mm after 40 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 42 weeks: Water depth 23mm after 2 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 46 weeks: Water depth 34mm after 3 weeks</td>
</tr>
<tr>
<td>System 2 (thin tack coat)</td>
<td>0% 0/3mm Black sand asphalt</td>
<td>No ingress of water after 48 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 49 weeks: Water depth 15mm after 49 weeks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 49 weeks: Water depth 26mm after further 1 week</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restart after 50 weeks: Water depth 24mm after further 1 week</td>
</tr>
<tr>
<td>System 2 (thin tack coat)</td>
<td>35% 0/14mm HRA surface course</td>
<td>No ingress of water after 52 weeks</td>
</tr>
<tr>
<td>System 2 (thin tack coat)</td>
<td>50% 0/14mm HRA binder course</td>
<td>No ingress of water after 52 weeks</td>
</tr>
</tbody>
</table>

After 12 months, water had flowed into the centre of only three specimens. This water was emptied when its level approached the level of the water in the water bath so the variation in the flow rate with time could be assessed.

Water flowed predominantly along the interface between a 35% 0/14mm HRA surface course and System 1. Water was first observed at the interface after 7 weeks. The flow rate was then fairly low for 12 weeks before it increased, but it then varied little each time the centre of the specimen was dried and remained fairly low throughout the 12 months.

Water did not flow into the centre of two specimens with red sand asphalt and black sand asphalt directly overlaying System 2 with a thin tack coat until after 35 weeks and 48 weeks, respectively. The water flowed through the sand asphalt itself, and the flow rate was between 10 and 20 times faster through the red sand asphalt and black sand asphalt, respectively, than through the 35% 0/14mm HRA surface course. It should be noted that the addition of red oxide tends to increase the permeability of sand asphalt, so the results obtained on the red and black sand asphalt specimens should not be considered indicative of the relative permeabilities of the two mixtures.
No water flowed through 50% 0/14mm HRA binder course or 35% 0/14mm HRA surface course mixtures directly overlaying System 2 with a thick tack coat. No water flowed through the red sand asphalt directly overlaying System 1.

Nicholls et al (2006) describes tests that were carried out to determine the permeability of different types of asphalt, including mastic asphalt, sand asphalt, HRA, DBM and SMA. The air permeability ranged from $0.7 \times 10^{-17} \text{m}^2$ for mastic asphalt with a very low air void content, to $8.1 \times 10^{-17} \text{m}^2$ or less for six mixtures with an air void content less than 4%. The permeability of three mixtures with an air void content greater than 4% and one with an air void content less than 4% was $2.2 \times 10^{-15} \text{m}^2$ or greater. The increase in permeability was indicative of the presence of an interconnected system of voids when the total air void content is greater than about 3% or 4%. The results obtained by Nicholls et al and others show that, regardless of the mixture type, low permeability values are obtained when the air voids content is 4% or below and the permeability increases rapidly for air voids contents above 5% (Zoorob et al, 1999).

Nicholls et al (2006) describes further tests to determine the flow rate through test specimens of diameter 85mm and depth 25mm that comprised a section of surfacing, waterproofing system and concrete substrate. They were formed from specimens of the type used for the tensile bond tests by coring normal to the plane of the specimens so the waterproofing system was aligned with a diameter and the overlaying asphalt and concrete substrate were within the semicircles above and below the system, respectively. It was not possible to test deeper sections because the specimens were used primarily for bond tests. However, the flow rate was 160 times higher for sand asphalt than for mastic asphalt overlaying a waterproofing system with a thin tack coat. The flow rate was 2700 times higher for a 0/10mm (dense) SMA overlaying a waterproofing system with a thick tack coat than for mastic asphalt. It was thought that most of the flow would have been through the SMA rather than at the interface with the waterproofing system because of the presence of the thick tack coat.

![Figure 4.1 Water flow test results](image-url)
4.3 Material property tests on waterproofing membranes

Measurements were made to determine the compressive modulus and Poisson’s ratio of samples of waterproofing membrane material of four waterproofing systems, Systems 1 to 4. In addition, stress relaxation tests were conducted in order to develop mathematical models of the membrane materials in ABAQUS. The mathematical models were used to determine the strains induced in the surfacing overlaying the waterproofing membranes by wheel loading that are described in Section 5. TRL instructed the manufacturers to prepare the test specimens for Systems 1 to 3 by spraying the membrane material into steel moulds which were coated with silicon grease to prevent any bonding during demoulding.

The compressive moduli of the specimens were measured at varying strain rates at temperatures 5ºC, 23ºC and 40ºC. In one series of tests, half-sine single pulses of period 1 second were applied with maximum strains 0.01 and 0.05 and 0.1. In addition, tests were carried out where the specimens were compressed at a constant strain rate up to a maximum strain of 0.05. The strain rates used in these constant rate tests varied between 0.00083 per second and 0.139 per second.

The compressive moduli relative to the values measured in tests at 23ºC when the maximum strain was 0.01 are shown in Table 4.7. There was little change in the modulus of System 1 with temperature and maximum strain because the material behaved predominantly as an elastic material. The other three systems appeared to behave viscoelastically because the modulus varied greatly with temperature and, to a lesser extent, with the maximum strain. It should be noted that the reduction in the modulus with the maximum strain was lower for the sinusoidal loading than for the ramp loading because the strain rate increased with the maximum strain under sinusoidal loading.

Table 4.7 Compressive moduli measured on four waterproofing systems relative to values at 23ºC and a maximum strain of 0.01

<table>
<thead>
<tr>
<th>Temperature ºC</th>
<th>System number</th>
<th>Secant modulus at maximum strain under sinusoidal loading at 1Hz (MPa)</th>
<th>Secant modulus at maximum strain under ramp loading at strain rate of 0.0021/s (MPa)</th>
<th>Secant modulus at maximum strain under ramp loading at strain rate of 0.1/s (MPa)</th>
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<tbody>
<tr>
<td>40</td>
<td>1</td>
<td>0.88 0.86</td>
<td>0.89 0.79</td>
<td>0.90 0.82</td>
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<tr>
<td></td>
<td>2</td>
<td>0.21 0.18</td>
<td>0.25 0.17</td>
<td>0.24 0.12</td>
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<tr>
<td></td>
<td>3</td>
<td>0.45 0.32</td>
<td>0.43 0.22</td>
<td>0.50 0.28</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.43 0.56</td>
<td>0.36 0.25</td>
<td>0.48 0.37</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>1.00 0.95</td>
<td>1.00 0.91</td>
<td>1.00 0.91</td>
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<tr>
<td></td>
<td>2</td>
<td>1.00 0.92</td>
<td>1.00 0.63</td>
<td>1.00 0.58</td>
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<tr>
<td></td>
<td>3</td>
<td>1.00 0.81</td>
<td>1.00 0.54</td>
<td>1.00 0.59</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.00 1.02</td>
<td>1.00 0.85</td>
<td>1.00 0.78</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1.07 1.04</td>
<td>1.09 1.01</td>
<td>1.14 1.03</td>
</tr>
<tr>
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<td>2</td>
<td>2.10 1.75</td>
<td>3.82 2.05</td>
<td>2.39 1.51</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.45 1.16</td>
<td>1.91 1.03</td>
<td>1.79 1.04</td>
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<tr>
<td></td>
<td>4</td>
<td>1.61 1.75</td>
<td>1.33 1.45</td>
<td>1.23 1.07</td>
</tr>
</tbody>
</table>
5 Strains induced in surfacing on bridge decks

5.1 General

Strains can be induced in the surfacing on bridge decks as a result of the following:
- Local deformation of the surfacing in the vicinity of the wheel load; and/or
- Global deformation of the deck.

These are considered in turn in the next two sections.

5.2 Strains induced by local deformation of the surfacing

5.2.1 Finite element model

A three-dimensional finite element model of a bridge deck overlaid with a waterproofing system and surfacing was developed in order to investigate how the strains induced in the surfacing on bridge decks vary with:
- the stiffness properties of the waterproofing membrane;
- the thickness of the waterproofing membrane;
- the bond of the waterproofing system to the concrete deck and the bond of the surfacing to the waterproofing system.

The finite element model represented a 4m by 4m square section of bridge deck and surfacing loaded at the centre by a wheel load. The wheel load of 43kN was represented by a uniform pressure of 0.7MPa distributed over a circular footprint of radius 140mm at a frequency of 80Hz applied as a pulse load. This corresponds to the highest load applied by a 385/65 super single wheel with a tread width of 280mm travelling at 80km/h. Note that a 295/80 single wheel with a tread width of 220mm was used for the wheel loading tests described in section 4.1.3, so the wheel load was correspondingly lower at 35kN.

To take advantage of symmetry, the model comprised only one quarter of the section with a quarter of the tyre footprint at a corner (Figure 5.1). The following parameters were assumed for the model:
- The thickness of the concrete deck was 30mm
- The thickness of the waterproofing membrane was assumed to be either 3mm or 5mm. Although the thickness of System 4 is dependent on the thickness of the sheet membrane (around 3.5mm), the same thicknesses used for the spray applied systems, Systems 1 to 3, were assumed in the analyses for comparative purposes.
- The thickness of the surfacing was 70mm, comprising a 45mm thick HRA binder course and a 25mm thick TSCS.

The finite element model was built using a combination of 20 nodded brick elements and 15 nodded hexahedral elements. The model was restrained horizontally in the transverse and longitudinal directions, and in all three directions at the lower face of the bridge deck so that the strains induced by wheel loading were not due to global deformation of the deck.

The surfacing was assumed to be either fully bonded to the waterproofing system or debonded from the waterproofing system. For the debonded case, a zero friction interface was used.
5.2.2 Material properties

The elastic modulus and Poisson’s ratio of the concrete deck were assumed to be 30GPa and 0.2, respectively.

Mathematical models of the waterproofing membranes of each system were developed from the stress relaxation and Poisson’s ratio data described in Section 4.3. The accuracy of the models was demonstrated by comparing the stress-strain curves measured in the compressive modulus tests at a constant strain rate with those predicted by the models.

The bituminous mixtures forming the surfacing layers were assumed to be elastic. The stiffness moduli and fatigue properties of the different layers were calculated from the rheological properties of the mixtures. Table 5.1 give the values of the stiffness moduli used in the numerical calculations. Poisson’s ratio was assumed to be 0.35.
Table 5.1 Values of stiffness modulus used for the finite element analysis

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Mixture</th>
<th>Temperature (°C)</th>
<th>Stiffness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>TSCS</td>
<td>5</td>
<td>17300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23</td>
<td>4670</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>983.1</td>
</tr>
<tr>
<td>45</td>
<td>HRA binder course</td>
<td>5</td>
<td>11500</td>
</tr>
<tr>
<td></td>
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<td>2390</td>
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<td></td>
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<td>40</td>
<td>357.4</td>
</tr>
</tbody>
</table>

5.2.3 Strains induced – fully bonded case

Table 5.2 and Table 5.3 give the maximum principal strains induced in the binder and surface courses at 5°C, 23°C and 40°C when overlaying the four waterproofing systems. It was assumed that the waterproofing system was fully bonded to the concrete and the binder course was fully bonded to the waterproofing system. The results show that:

1. The maximum principal strains in the binder course are higher than those in the surface course for all four systems. The contour plots of the maximum principal strain shown in Figure 5.2 to Figure 5.4 illustrate this for System 1.
2. The maximum principal strains are higher for Systems 1 and 4 than for Systems 2 and 3.
3. The maximum principal strain increases with the membrane thickness, and the increase, although small, is greater for the binder course than for the surface course. Figure 5.5 shows how the development of the maximum principal strain close to the pavement surface when the wheel load is applied varies with the membrane thickness for Systems 1 to 3.
4. The maximum principal strains are low and comparable with those that are induced on pavements.

Table 5.2 Maximum principal strains induced in binder course

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Membrane thickness (mm)</th>
<th>Maximum principal strain (10^-6)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>1</td>
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</tr>
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</tr>
<tr>
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<td>48.0</td>
</tr>
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</tr>
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<tr>
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<td>5</td>
<td>20.8</td>
<td>75.6</td>
</tr>
</tbody>
</table>
Table 5.3 Maximum principal strains induced in surface course

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Membrane thickness (mm)</th>
<th>Maximum principal strain (10^6)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>12.2</td>
<td>41.9</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>10.0</td>
<td>38.4</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>10.2</td>
<td>37.8</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>11.0</td>
<td>40.3</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>13.9</td>
<td>45.3</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>10.8</td>
<td>40.6</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>11.0</td>
<td>39.6</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>12.0</td>
<td>42.7</td>
</tr>
</tbody>
</table>

Figure 5.2 System 1: Membrane 3mm thick, surfacing fully bonded, 5°C: Contour plot for maximum tensile strain
Figure 5.3 System 1: Membrane 3mm thick, surfacing fully bonded, 23°C: Contour plot for maximum tensile strain

Figure 5.4 System 1: Membrane 3mm thick, surfacing fully bonded, 40°C: Contour plot for maximum tensile strain
5.2.4 Strains induced – weakly bonded cases

To determine the significance of the bond between the binder course and the waterproofing system, and between the waterproofing system and the concrete, zero friction interfaces were introduced at these locations in the model. Figure 5.6 shows the model with the debonded area in red, the loaded area in blue, and a green area where the waterproofing system is fully bonded to the surfacing and the concrete.

Three debonded cases were investigated as follows:

Case 1: The waterproofing system debonded from both the concrete and the binder course (i.e. fully debonded).
Case 2: The waterproofing system bonded to the concrete and debonded from the binder course.
Case 3: The waterproofing system debonded from the concrete and bonded to the binder course.

The variation in the maximum principal strain near the pavement surface for System 1 is shown in Figure 5.7 for the fully bonded and three weakly bonded cases. The figure shows that the largest increase in the maximum principal strain with respect to the bonded case is when the waterproofing system is debonded from both the binder course and the concrete (Case 1). The other cases give a much smaller increase in the maximum principal strain.

Table 5.4 gives the percentage relative increase in the maximum principal strain between the fully bonded and fully debonded cases.

The results show that:

1. The relative increase in the maximum principal strain is higher for Systems 1 and 4 than for Systems 2 and 3.
2. Comparing the relative increase in the maximum principal strain for the surface and binder courses, the highest relative increase occurred for Systems 1 and 4 in the surface course; and for Systems 2 and 3 in the binder course.
Figure 5.6 The debonded area of the waterproofing system is shown in red and the loaded area is shown in blue.

Figure 5.7 Development of maximum principal strain near the pavement surface at 23°C for different bonding conditions of the waterproofing system (System 1)
Table 5.4  Relative increase (%) in maximum principal strain between the fully bonded and fully debonded cases for a membrane thickness of 3mm and a pavement temperature of 23°C

<table>
<thead>
<tr>
<th>System</th>
<th>Surface course</th>
<th>Binder course</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>47</td>
<td>41</td>
</tr>
</tbody>
</table>

5.2.5  Fatigue lives

The fatigue lives of the binder and surface courses have been estimated for the maximum principal strains shown in Table 5.2 and Table 5.3, respectively, at 5ºC, 23ºC and 40ºC. Table 5.5 and Table 5.6 show, at each temperature, the fatigue lives for the binder and surface courses for each system relative to the fatigue lives for System 1. The fatigue lives are reduced by, on average, a factor of about 2 when the membrane thickness is increased from 3 to 5mm. The fatigue lives are generally lowest for Systems 1 and 4, being around 5 times longer for the binder course overlaying Systems 2 and 3 rather than System 1 at mid to low temperatures when most fatigue damage occurs.

Table 5.7 shows the fatigue life of the surface course relative to that of the binder course. The fatigue life is lower for the surface course than the binder course for each system and membrane thickness, but more so for Systems 2 and 3. However, the fatigue life of the surface course is less dependent on the properties and thickness of the waterproofing system than that of the binder course. The fatigue life of the surfacing will be mostly affected by environmental conditions such as ageing of the surface course and variation of the temperature profile in the pavement structure.

Table 5.8 shows how the fatigue life increases when the waterproofing system is fully debonded from the concrete and the surfacing. The increase is much higher for Systems 1 and 4 than for Systems 2 and 3, but such debonding is unlikely to occur and the increase in fatigue life is insignificant when there is debonding at only one interface. However, more investigations are required in order to ascertain this.

Table 5.5  Relative fatigue life of binder course

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Membrane thickness (mm)</th>
<th>Relative fatigue life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>1</td>
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<td>4</td>
<td>3</td>
<td>1.55</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>2.98</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>2.56</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.91</td>
</tr>
</tbody>
</table>
### Table 5.6 Relative fatigue life of surface course

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Membrane thickness (mm)</th>
<th>Relative fatigue life</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>23</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1.00</td>
<td>1.00</td>
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<td>2.45</td>
<td>1.67</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>1.68</td>
<td>1.21</td>
</tr>
</tbody>
</table>

|                      |                         | 1                     | 5                 | 0.52              | 0.68 | 0.80 |
| 2                    | 5                       | 1.84                  | 1.17              | 0.87              |
| 3                    | 5                       | 1.68                  | 1.33              | 1.15              |
| 4                    | 5                       | 1.09                  | 0.91              | 0.74              |

### Table 5.7 Fatigue life of surface course relative to fatigue life of binder course

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Membrane thickness (mm)</th>
<th>Fatigue life of surface course</th>
<th>Fatigue life of binder course</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>23</td>
<td>40</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.35</td>
<td>0.56</td>
<td>0.26</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.13</td>
<td>0.22</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.14</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.38</td>
<td>0.58</td>
<td>0.41</td>
</tr>
</tbody>
</table>

|                      |                         | 1                              | 5                              | 0.36              | 0.80 | 0.47 |
| 2                    | 5                       | 0.22                           | 0.38                           | 0.42              |
| 3                    | 5                       | 0.23                           | 0.29                           | 0.16              |
| 4                    | 5                       | 0.42                           | 0.87                           | 0.72              |

### Table 5.8 Effect of bond on fatigue life of surface course at 23°C

<table>
<thead>
<tr>
<th>Waterproofing system</th>
<th>Fatigue life when fully debonded</th>
<th>Fatigue life when fully bonded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.13</td>
</tr>
</tbody>
</table>
5.3 Strains induced by global deformations

It was beyond the scope of the project to determine accurately the strains induced by the global deformation of decks. However, in order to compare the ‘global’ and the ‘local’ strains for the purposes of this report, an attempt has been made to estimate the ‘global’ strains from the serviceability limit state criteria.

The maximum stress due to bending in the concrete of a reinforced concrete bridge deck at the serviceability limit state is 0.5 times the characteristic cube strength. The modulus of elasticity of concrete with a characteristic strength of 40MPa is 31GPa, so the maximum strain in the concrete at the serviceability limit state should be $645 \times 10^{-6}$.

The maximum stress in the reinforcement at the serviceability limit state is 0.75 times the characteristic strength. Since the modulus of elasticity of steel is 200GPa, the maximum strain at the serviceability limit state should be $938 \times 10^{-6}$ for steel with a characteristic strength of 250MPa and $1725 \times 10^{-6}$ for steel with a characteristic strength of 460MPa.

The surfacing in areas of bridge decks that are subjected to sagging bending moments will be in compression. This includes single span bridge decks and areas of multi-span continuous decks away from the supports. The surfacing in areas of decks that are subjected to hogging bending moments will be in tension, such as at the supports of multi-span continuous decks. Tensile strains have a far greater effect than compressive strains on the fatigue life of surfacing, so hogged areas of decks are of greatest concern.

The magnitude of the strains induced by ‘normal’ traffic conditions in relation to the strain induced at the serviceability limit state is dependent on the following factors:

- The strains induced by the dead weight of the deck and surfacing
- The live loading of the deck in ‘normal’ traffic conditions compared to the design HA and HB loading (The Highways Agency et al, 2001).
- The distance of the surfacing and the reinforcing steel from the neutral axis of the cross section (deck construction overlaid with surfacing).

The global strains are induced by the dead weight of the structure as well as HA and HB loading. The strains induced in the reinforcing steel and concrete by HA and HB loading in the surfacing will be somewhat lower than those at the serviceability limit state. Those induced by normal traffic will be much lower, so the strain range induced in the steel in ‘normal’ traffic conditions may be about 10% of the maximum strain induced at the serviceability limit state.

Because the surfacing is further from the neutral axis than the reinforcing steel, the strain range induced in the surfacing will be higher than the strain range induced in the steel. The surfacing could be as much as twice the distance from the neutral axis for a slab, to less than 20% further for beam and slab construction. Therefore, taking all factors into account, the maximum strain range induced in the surfacing in the hogged areas of multi-span continuous decks in ‘normal’ traffic conditions may range from $100 \times 10^{-6}$ to $300 \times 10^{-6}$.
6 Review of causes of failure of surfacing on bridges

6.1 Modes of failure

It is likely that most premature surfacing failures on bridges are the result of more than one mechanism. It is difficult to identify the effect of each mechanism separately, but the presence of water in the surfacing appears to be one of the most significant. This study has focussed on three areas that, it was thought, could contribute to the failures, namely:

- The strains induced in the surfacing
- The bond of the surfacing to the waterproofing system
- The presence of water in the surfacing, especially at the interface with the waterproofing system.

The finite element analyses, based on the properties of the waterproofing membrane materials tested, have estimated that the local strains induced in surfacing by wheel loading that are dependent on the properties of the waterproofing system are low. Higher strains were estimated for some waterproofing systems than others, and these will influence the fatigue lives. Strains may be significantly higher if the densities (and hence stiffness modulus and Poisson’s ratio) of membrane materials on bridges are lower than those of the materials tested. However, the finite element analyses indicate that the strains induced by the global deformation of bridge decks in areas subjected to hogging bending moments appear to be as significant as, if not more significant than, the strains induced by wheel loading. Dependent on the position of different vehicles on a deck that contribute to the local and global strains, the total strain will be the sum of the separate components.

During the study, failures were noted at the pier positions on one multi-span viaduct where the surfacing was thin and water had not accumulated (Section 3.3). Strains induced by the global deformation of the deck may have contributed to these failures, because the deck was lively. However, the surfacing was poorly compacted in these areas so there may have been some fatigue damage because the stiffness and fatigue strength of the asphalt would have been less than was assumed in Section 5.2. Nevertheless, failures have been attributed to the liveliness of decks in Germany.

The finite element analyses have also shown that the effect of increasing the membrane thickness from 3 to 5mm on the strains induced by wheel loading is low. Furthermore, the debonding of the waterproofing system from the concrete or the surfacing from the waterproofing system is estimated to have little effect on the magnitude of the local strains induced by wheel loading. Only when the waterproofing system is fully debonding from the concrete and the surfacing, which is highly unlikely, do the strains increase by more than a few per cent. Even then, because the increase cannot explain fully the decrease in service life of surfacing that has failed prematurely on bridges, it is concluded, that the variations in local strains induced by wheel loading considered in Section 5.2 are too low to be significant.

The above may imply that the bond of the waterproofing system to the concrete and the bond of the surfacing to the waterproofing system need not be high, but the bonds are highly significant in the context of the resistance to turning, traction and braking forces and the movement of water. The strains induced in the surfacing by the lateral forces imparted by vehicles are assumed to increase when the waterproofing is not bonded to the concrete and/or surfacing, the strains being higher the thinner the surfacing. If a waterproofing system is debonded from the concrete, the amount of leakage through defects in the membrane can be considerable and reach a large area of the deck. If the surfacing is debonded from the waterproofing system, sub-surface water that reaches the waterproofing system can travel unimpeded across the deck and accumulate at the low-points.

The tensile bond tests on specimens stored dry and wet (Section 4.1) have shown that, at least in the short term, the bond is weakened only slightly solely by the presence of water in the surfacing. However, the wheel loading tests decreased the tensile bond of the surfacing to the waterproofing system and/or the tensile strength of the surfacing when the void content of the sand asphalt or binder course enabled the surfacing to become saturated.
Agents have indicated that failures can occur rapidly following rainfall when the surfacing becomes saturated (Section 3.3 and Table 3.5). Therefore, it appears that premature failures have occurred mainly when the asphalt directly overlaying the waterproofing system has become saturated. It is postulated that high hydrostatic pressures have then been generated in the surfacing by wheel loading that have weakened the bond of the surfacing to the waterproofing system and the surfacing itself. The binder course (or APL) has failed because the pressures have stripped the binder from the aggregates, the asphalt has broken up and undermined the surface course, causing it to crack, break up and form pot holes and, sometimes, to rut. It is concluded that, generally, the cracking of the surface course on bridges has been because the binder course (or APL) has failed in the presence of water, rather than because high strains have been induced in the surfacing as described in Section 5.2.

The review of surfacing failures on bridges has shown that more failures have occurred of surfacing overlaying System 1 than System 2. This would appear to be due to the low bond of some surfacing to System 1 with a thin tack coat when overlaid with asphalt with coarse aggregates. Although the review found relatively little information on the thickness of membranes below failed surfacing, it was reported that large areas of membranes of System 1 are sometimes significantly more than 5mm thick in failed areas. This may be because the membrane thickness was increased at defects in the deck as an alternative to deck repairs.

Because the density, hence stiffness modulus and Poisson’s ratio, of membranes on bridges may sometimes be less than that of the membrane materials tested in this study, the strains induced in the surfacing may be higher than those reported here. Therefore, it is recommended that samples of membrane material are analysed when surfacing fails prematurely to determine the significance of different material properties and membranes thicker than 5mm.

Another factor that may have contributed to the failures is the variation in the stiffness modulus of the waterproofing system with temperature. The stiffness moduli of Systems 2 to 4 change (viscoelastically) with temperature in a similar way to the change in the stiffness of surfacing materials. This is not the case for System 1 because it behaves elastically. The finite element analysis has not shown this effect to be significant, but it may be more so if membranes are thicker.

Ways to prevent premature failures are discussed below. They concern the ‘design’ of the surfacing system, sub-surface drainage, optimising the bond of the surfacing to the waterproofing system and surface preparation.

6.2 Surfacing design

Detailed information on the asphalt surfacing to bridge decks can be found in Nicholls et al (2006), and only the main points are summarised here.

Well compacted surfacing overlaying the waterproofing system on bridge decks should be such that the local strains induced in the surfacing by wheel loading do not cause premature fatigue cracking. Because the finite element analyses have indicated that waterproofing systems up to 5mm thick are unlikely to have a significant effect on the fatigue life of the surfacing, it is not appropriate to specify fatigue requirements. However, research is being undertaken into a test for flexibility and such requirements could be specified when it has been incorporated into a European Standard.

The deformation of each surfacing layer due to wheel loading is dependent on the compressive stresses induced in the layer and the deformation resistance of the mixture. Mixtures with a high coarse aggregate content are the most resistant to deformation. Stiffer mixtures and thicker layers have better load spreading characteristics for reducing the compressive stresses in the lower layers. Thick layers may not deform more than thin layers if they can be compacted better to improve their resistance to deformation.

The total deformation of the surfacing is the sum of the deformations of the component layers. Whereas it is often found that the deformation on bridges is similar to that on the adjacent pavements which have the same binder course and surface course (Nunn et al, 1997), greater deformation on some bridges has been attributed to excessive deformation of the sand asphalt, especially when the
surfacing is less than 100mm thick. It appears that surfacing of this thickness does not have the load spreading characteristics to limit the compressive stresses in an APL of sand asphalt, hence its deformation. Therefore, the APL should be omitted on heavily trafficked bridges if the surfacing is less than 120mm thick.

It should be noted that if the waterproofing system is not directly overlaid with sand asphalt, the binder course must be of a type that will not allow sub-surface water to accumulate at the waterproofing system (see Section 6.3).

As TSCSs are more resistant to deformation than HRA surface courses, there may be significant differences in the deformation on bridges and the adjacent pavements if an HRA surface course is laid on a bridge and a TSCS on the adjacent pavement. This may be unacceptable to road users in terms of the ride quality as well as noise. The differences in deformation susceptibility can be reduced by designing the HRA accordingly, but this process may marginally increase its permeability.

6.3 Drainage

6.3.1 Objectives

To prevent hydrostatic pressures from being induced in the surfacing by wheel loading, either:

- water should be prevented from entering the surfacing; or
- water that has entered the surfacing should be drained quickly before it can accumulate.

Drainage of the surface and binder courses (and APL) must be considered separately.

6.3.2 Drainage of the surface course

Clause 4.1 of BD 47/99 (DMRB 2.3.4) requires surface water to be removed from bridge decks by the provision of gradients, crossfalls and suitable surface drainage systems.

The amount of water that enters an asphalt layer is dependent on its void content. Surface courses with a void content of less than 4 or 5% are effectively impermeable so most of the surface water can be drained from the road surface with relatively little entering it. Some water may enter the surfacing through joints between rips or small surface cracks, but little should enter the body of the material. However, significant quantities of water can enter the body of the material of surface courses with a void content greater than 5%.

Once in the surfacing, the movement of the sub-surface water is dependent on the permeability of the surface course, the binder course and the APL. Whereas sub-surface water can permeate downwards through several bound and unbound layers as it flows towards sub-surface drainage systems on pavements, sub-surface water on bridges can only flow downwards as far as the waterproofing system. It must then flow horizontally across or along the deck towards any sub-surface drainage systems that are located at low points. These may be well over 10 metres away from where the water entered the surfacing. The flow of water vertically and horizontally will be impeded in areas where the surfacing is effectively impermeable, and at barriers such as the waterproofing system and expansion joints. Sealant at joints in the asphalt can also impede the flow (Section 3.2.2). The sub-surface water will follow the path of least resistance, which may be out of the surfacing or through defects in the waterproofing system or expansion joints. High hydrostatic pressures generated by wheel loading in saturated surfacing may contribute to the failure of the waterproofing system or expansion joints as well as the surfacing.

Because premature surfacing failures are more likely to occur when water accumulates at the waterproofing system, as much water as possible should be prevented from reaching it. Therefore, when large quantities of water can enter a relatively permeable surface course, edge drains should be provided at the low points of bridges to drain the surface course at the top of the binder course. In addition, the binder course should have a low void content so little water enters it, and the bond coat
of TSCSs should be applied uniformly to the binder course in order to help seal it, and preference
should be given to TSCSs with thick bond coats.

Clause 5 of HA 79/97 shows a proposed combined drainage and kerb system for porous asphalt which
would be suitable for a relatively permeable surface course, but non-proprietary systems may suffice.

6.3.3 **Drainage of the binder course and the APL**

Clause 4.2 of BD 47 (DMRB 2.3.4) requires sub-surface drainage at all low points on bridges where
natural drainage is not possible. Some expansion joints provide sub-surface drainage by incorporating
20 mm square slotted drainage channels that run across the carriageway. However, these drains can
become clogged over a period of time so they no longer drain away the water quickly enough.

Through-deck drains at the low points are considered to be a more effective means of sub-surface
drainage. Whilst these may be installed on new bridges, they are not always installed on old bridges
during maintenance works unless specific problems have been encountered. It can be difficult or
impossible to locate drains through box beams, concrete beams and tendons, but measures must be
taken to overcome these problems. Through-deck drains or alternative sub-surface drainage systems
should be installed everywhere they are needed to prevent water accumulating.

It is considered essential that not only should the binder course and the APL be effectively
impermeable, the void content at the interface between the waterproofing systems and the APL or
binder course directly overlying should be low to prevent water accumulating at the waterproofing
system. The binder course and APL must be sufficiently permeable to enable any sub-surface water
that enters them to reach the sub-surface drainage systems. However, any mixture than enables water
to enter it should have sufficient permeability. Any mixture that does not have the required
permeability, e.g. mastic asphalt, will enable very little water to enter it so it should not become
saturated. Clearly large variations in the permeability throughout a layer must be avoided that prevent
water that enters a layer from reaching sub-surface drainage systems.

6.3.4 **Reducing the void content at the interface with the waterproofing system**

When asphalt with coarse aggregates is compacted onto a ‘hard’ surface, the body of the material may
have a low void content but there may be large voids at the base of the layer. The voids tend to be
larger with larger aggregate sizes and with higher proportions of coarse aggregate. Above a certain
proportion of coarse aggregate, the voids may be interconnecting.

The permeability of the interface between the waterproofing system and the asphalt is dependent on
the properties of both the asphalt and the tack coat of the waterproofing system. Whereas a tack coat
may comprise more than one layer, the upper layer that is in contact with the asphalt and which
aggregates can penetrate can be described as ‘thin’ (generally <0.2 mm) or ‘thick’ (generally
>1.0 mm). When the tack coat is ‘thin’, an asphalt layer with a small aggregate size and low
proportion of coarse aggregate will yield no large interconnecting voids. However, as shown in
Figure 6.1, any mixture that contains large aggregates yields some voids at the interface (coloured
yellow) where water may accumulate and a reduction in contact area between the mixture and the
waterproofing system.

Figure 6.2 shows that a ‘thick’ tack/bond coat can (partially) fill the voids at the base of an asphalt
layer with coarse aggregates and, thereby, limit the accumulation of water and interconnecting voids
and, potentially, improve the bond. Therefore, a waterproofing system incorporating a thick tack coat
should be specified for mixtures with coarse aggregates. The tack coat must not be too thick
otherwise ‘bleeding’ of the excess binder through the overlying asphalt layer may occur during its
laying and compaction. Also, the asphalt layer may be more susceptible to fatigue if it ‘floats’ on a
thick layer of ‘soft’ tack coat. Ideally, the coarse aggregates should almost fully penetrate the
tack/bond coat as the tack coat material fills the voids at the base of the layer.

Although System 2 incorporating the thick tack coat performed well in the wheel loading test when it
was overlaid with a 50% 0/14mm HRA binder course, it is preferable to use a binder course with a
lower course aggregate content. Samples taken from a viaduct where a 35% 0/14mm HRA surface course mixture directly overlaid the waterproofing system had some voids at the interface because the thickness of the tack coat was less than that of the wheel loading test specimens and towards the low end of the range specified. Variations in the thickness of the tack coat are inevitable on bridges and, where it is thin, the void content may be too high if it is overlaid with a coarser mixture.

Currently, there is no standard test to determine the void content or permeability of the surfacing at, and just above the interface with the waterproofing system. However, the bond of the surfacing to the waterproofing system is more likely to decrease as the void content at the interface increases. Therefore, a low void content can be encouraged by specifying bond strengths that should not be achievable without a high interface contact area (see Section 6.4).

![Figure 6.1 Interface between surfacing and waterproofing system with thin tack coat](image1)

![Figure 6.2 Interface between surfacing and waterproofing system with thick tack coat](image2)
6.4 Bond of the surfacing to the waterproofing system

6.4.1 General

When surfacing less than 100mm thick has failed on bridges, it has been found to be poorly bonded to the waterproofing system. Surfacing of thickness 120mm or more has also been found to be poorly bonded to the waterproofing system. The wheel loading tests have indicated that high hydrostatic pressures can be generated in saturated sand asphalt that can weaken its bond to the waterproofing system. Therefore, it is possible that the bond between the APL and the waterproofing system is low on a significant number of bridges so sub-surface water can move freely across the deck and accumulate at the low points. Surfacing above a certain thickness may have sufficient dead weight and integrity to prevent a significant reduction in the service life if the surfacing has a low void content, as appears to be the case when sand asphalt is overlaid with effectively impermeable binder and surface courses. However, when the waterproofing system is overlaid with a course mixture or the surfacing is less than 120mm thick, measures should be taken to ensure that the surfacing remains uniformly bonded to the waterproofing system throughout its service life, whatever its thickness. This is required to limit the flow of water to the lower points on bridges, and the effect of turning, traction and braking forces (see Section 6.1).

The bond in service is dependent on the initial bond and the change in bond with time. These factors depend on the properties of the waterproofing system and the surfacing. To optimise the bond, the contact area between the surfacing and the waterproofing system must be high, the void content at the interface must be low, and the surfacing must be laid and rolled at sufficiently high temperatures.

6.4.2 Minimum bond strength requirements for surfacing less than 120mm thick

It can be argued that the minimum bond strength requirements specified in BD 47 are for surfacing of thickness 120mm or more, and that higher bond strengths should be specified for surfacing of lower thickness. Much higher bond strengths are specified in other countries where the surfacing is less than 120 mm thick. For example, the current Japan Highway Public Corporation specification requires waterproofing systems to be overlaid with asphalt of total thickness 75mm. The 35mm thick layer directly overlaying the waterproofing system is SMA with a 0/5mm aggregate size. The 40mm thick surface course is a drainage (porous asphalt) layer with a 0/13mm aggregate size. Performance tests on waterproofing systems include tests to measure the shear and tensile bond strength of the weakest interface of specimens comprising a concrete block, the waterproofing system and an asphalt layer. The shear bond strength must not be less than 0.8MPa at -10°C and 0.15MPa at 20°C. The tensile bond strength must not be less than 1.2MPa at -10°C and 0.6MPa at 20°C.

The current German specification requires sheet waterproofing membranes on major roads to be overlaid with surfacing of total thickness from 70mm to 80mm. A 35mm thick protective layer of Gussasphalt with a 0/8mm aggregate size directly overlays the sheet membrane - the protective layer and the sheet membrane are both considered to be part of the waterproofing system. The surface course is 35mm to 45mm thick. The tensile bond strength of the weakest interface of specimens comprising a concrete block and the waterproofing system must not be less than 0.7MPa at 8°C and 0.4MPa at 23°C. The shear bond strength of the weakest interface of specimens comprising a concrete block, the waterproofing system and an asphalt layer must not be less than 0.15MPa at 23°C when the shear force is applied at an angle of 15° to the plane of the specimen.

On some UK contracts, the minimum tensile adhesion of the waterproofing membrane to the deck is specified as 0.7MPa. On one contract, when the minimum surfacing thickness was 65mm, the minimum tensile bond of the surfacing to the waterproofing system was required to be four times the minimum value specified in BD 47. The minimum shear bond of the surfacing to the waterproofing system was required to be 50% higher than the values specified in BD 47. Because of the effectiveness of these specifications, the minimum tensile adhesion and shear and tensile bond strength requirements given in Table 6.1 are recommended. The minimum values increase in steps of
30mm down to 60mm. Any total depth of surfacing less than 60mm is regarded as a special case, requiring further requirements, and is not recommended.

6.4.3 Minimum bond strength requirements for surfacing of thickness 120mm or greater

The minimum bond strength requirements in BD 47 (for surfacing of thickness 120mm or greater) are the same when the waterproofing system is overlaid with a mixture with course aggregates or sand asphalt.

BD 47 specifies a 50% 0/10mm HRA binder course for bond tests on coarse mixtures. It could be inferred by users of BD 47 that such a mixture would perform satisfactorily when overlaid with surfacing of thickness 120mm or greater. Such a mixture is likely to have a high void content at the interface with a waterproofing system with a thin tack coat, so water is likely to accumulate at the interface and premature failure is possible. Therefore, in order to encourage the use of a suitable waterproofing system and asphalt when the thickness of the surfacing is 120mm or greater, it is proposed that the minimum bond strength requirements in BD 47 are increased to those shown in Table 6.1 for this thickness of surfacing when sand asphalt is omitted.

It is preferable for the tensile adhesion of the waterproofing system to the concrete deck to be higher than the tensile bond of the surfacing to the waterproofing system if the lower asphalt layers are replaced without rewaterproofing. Therefore, a minimum tensile adhesion greater than 0.4MPa at 23°C could be specified. However, since replacement of the lower asphalt layers without rewaterproofing is not recommended (see Section 7), this is not considered necessary when the surfacing greater than 120mm thick.

Table 6.1 Minimum adhesion and bond strengths for waterproofing systems when overlaid with coarse mixtures

<table>
<thead>
<tr>
<th>Surfacing thickness</th>
<th>≥ 120 mm</th>
<th>&lt; 120 mm; ≥ 90 mm</th>
<th>&lt; 90 mm; ≥ 60 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile adhesion test (waterproofing system to concrete)</td>
<td>@ -10°C 0.30MPa</td>
<td>0.50MPa</td>
<td>0.70MPa</td>
</tr>
<tr>
<td></td>
<td>@ 23°C 0.30MPa</td>
<td>0.50MPa</td>
<td>0.70MPa</td>
</tr>
<tr>
<td></td>
<td>@ 40°C 0.20MPa</td>
<td>0.30MPa</td>
<td>0.30MPa</td>
</tr>
<tr>
<td>Shear bond test (surfacing to waterproofing system)</td>
<td>@ -10°C 0.30MPa</td>
<td>0.30MPa</td>
<td>0.40MPa</td>
</tr>
<tr>
<td></td>
<td>@ 23°C 0.30MPa</td>
<td>0.30MPa</td>
<td>0.40MPa</td>
</tr>
<tr>
<td></td>
<td>@ 40°C 0.10MPa</td>
<td>0.15MPa</td>
<td>0.15MPa</td>
</tr>
<tr>
<td>Tensile bond test (surfacing to waterproofing system)</td>
<td>@ 23°C 0.40MPa</td>
<td>0.45MPa</td>
<td>0.50MPa</td>
</tr>
</tbody>
</table>

6.4.4 Laying and compaction temperatures

The Design Manual for Roads and Bridges (DMRB) and the Specification for Highway Works (SHW) (The Highways Agency et al) specify requirements that are intended to:

- prevent the waterproofing systems from being damaged when it is overlaid with hot asphalt, and
- ensure that asphalt remains bonded to the waterproofing system over its service life.

Clauses B4.2 (i) and (j) of BD 47 (DMRB 2.3.4) require the waterproofing system to pass tests that simulate the conditions when it is overlaid with hot asphalt materials. The test specified in Clause B4.2 (j) assesses the effects of high temperatures encountered during surfacing on the crack bridging ability of the waterproofing membrane by overlaying it with hot material to achieve a
temperature of 145°C on its surface. Clause B4.2 (i) assesses the resistance to aggregate indentation during the compaction of the asphalt. Currently, all membranes must be permanently indented by no more than half their thickness after a force of 500N has been applied by an aggregate indentor heated to a temperature of 80°C. If the system is to be overlaid with mixtures containing coarse aggregates, the membrane must pass the test with the aggregate indentor heated to 125°C. Not all of the waterproofing systems currently registered for use on Highways Agency bridges have passed this test at 125°C and can be overlaid with coarse mixtures.

Allied to the aggregate indentation requirements are those in Clause 901.9 of the SHW (MCHW 1), which states that:

‘With the exception of sand asphalt carpet, bituminous materials with a temperature greater than 125°C shall not be deposited on a bridge deck waterproofing system unless adequate precautions are taken to avoid heat damage in accordance with a good industry practice. A maximum temperature of 145°C is permitted for sand asphalt carpet.’

The British Board of Agrément (BBA) Roads and Bridges Certificates for the different waterproofing systems currently registered include the following statements:

‘Temperature of the …. surfacing when applied should exceed the minimum reactivation temperature of 80°C (for one system, 100°C for another) required for the tack coat ……’

‘The rolling temperature of the surfacing must not fall below the minimum reactivation temperature of 85°C (for one system, 90°C for another) required for the tack coat.’

‘Temperature of the APL when applied should be as specified in BS 594-1: 1992 and BS 594-2: 1992’.

Clause 2005.5 of the SHW (MCHW 1) states that:

‘The additional protective layer of surfacing laid on the waterproofing system shall be fully bonded to the system for the life of the system. The bond shall be achieved by either:
(i) the binder within the directly applied additional protective layer of surfacing; or
(ii) a separate tack coat … details of which are given on the BBA Roads and Bridges Agrément Certificate. Where the tack coat is of the type activated by the heat of the succeeding bituminous layer the temperature of this layer shall be sufficient to ensure adhesion.’

When a layer of asphalt is laid onto a substrate such as a waterproofing system, the base of the layer cools rapidly as heat is transferred from the layer into the waterproofing system and concrete substrate. After a short period of time, the temperature of the waterproofing system will have risen so that it is similar to that of the base of the layer. However, the waterproofing system will then cool as heat is lost by conduction to the concrete substrate and also by convection and radiation through the top of the layer.

The asphalt layer must be laid at a sufficiently high temperature so that the rolling/compaction temperature is high enough to activate the tack coat and form a dense layer. Table 6.2 and Table 6.3 show, respectively, the times after laying for 20mm and 40mm thick layers to reach a given temperature at mid-layer that were estimated using the method proposed by Daines (1985). The temperature at the base of a layer (i.e. at the tack coat) could be about 10°C below the mid-layer temperature (dependent on the type of asphalt). Therefore, the SHW gives little time to complete compaction at a sufficiently high temperature when the activation temperature of the tack/bond coat is 100°C, especially when the asphalt layer is only 20mm thick.

There is more time to complete the compaction of a 40 mm layer, even if it is laid at only 125°C. Much more time would be available if mixtures containing coarse aggregates were laid at temperatures higher than 125°C, which probably already happens on a number of bridges. Some asphalts with a high coarse aggregate content are normally laid and compacted at temperatures higher than 125°C on pavements, and it would be inappropriate to use them at lower temperatures on bridges in order to prevent damage to the waterproofing system because the required level of compaction could not be achieved. Clause 901.9 of the SHW allows surfacing to be laid at higher temperatures if ‘adequate precautions are taken to avoid heat damage’, but just what these are is unclear. It could be
implied that the aggregate indentation test indicates that rolling should not occur when the temperature at the waterproofing system is greater than 125°C, but the preconditioning temperature of the waterproofing system for the test is only 50°C. Therefore, although the SHW could be changed to prevent rolling when the mid-layer temperature is 125°C (rather than specify a laying temperature of 125°C), this may be unwise. Clearly, waterproofing suppliers should provide details of the temperature at the tack coat to achieve a good bond in the BBA Roads and Bridges Certificates. To ensure that the tack coat is activated, the target temperature should be at least 10°C higher than the activation temperature. The laying temperature must be high enough to allow for cooling of the asphalt at the interface with the waterproofing system when heat is transferred to the substrate and increases the temperature of the substrate and the waterproofing system. Control of the laying and compaction temperatures is important because the bond of asphalt to waterproofing systems tends to increase with the rolling temperature.

Table 6.2 Effect of environmental conditions on time available to compact a 20mm thick layer

<table>
<thead>
<tr>
<th>Air temperature (°C)</th>
<th>Wind speed at 2 m height (km/h)</th>
<th>Laying temperature (°C)</th>
<th>Time after laying to reach given temperature at mid-layer (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>120 °C</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>145</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>145</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>145</td>
<td>1.7</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>145</td>
<td>2.9</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>145</td>
<td>2.3</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>145</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 6.3 Effect of environmental conditions on time available to compact a 40mm thick layer

<table>
<thead>
<tr>
<th>Air temperature (°C)</th>
<th>Wind speed at 2 m height (km/h)</th>
<th>Laying temperature (°C)</th>
<th>Time after laying to reach given temperature at mid-layer (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>120 °C</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>125</td>
<td>3.9</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>125</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>125</td>
<td>2.6</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>125</td>
<td>4.6</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>125</td>
<td>3.7</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>125</td>
<td>3.0</td>
</tr>
<tr>
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<td>0</td>
<td>145</td>
<td>8.6</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>145</td>
<td>7.0</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>145</td>
<td>5.8</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>145</td>
<td>10.1</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>145</td>
<td>8.0</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>145</td>
<td>6.6</td>
</tr>
</tbody>
</table>
If surfacing is likely to produce temperatures higher than 145°C at the waterproofing system, crack bridging tests should be carried out in which such temperatures are induced during the thermal shock preconditioning phase.

Aggregate indentation tests should be carried with the indentor and membrane at temperatures higher than those currently specified if compaction is to take place at temperatures higher than currently permitted. The current test simulates the effect of compaction, so the temperature of the membrane and the load applied in the test do not necessarily represent those experienced during compaction on bridges. Therefore, determining the appropriate test conditions for compaction at high temperatures is not straightforward, but it would seem more appropriate to preheat the membrane to a temperature at least greater than the activation temperature of the tack coat, rather than 50°C.

6.4.5 Site practice

One of the purposes of the APL is to prevent damage to the waterproofing system by site plant and staff when kerbs are laid and when the binder and surface courses are not laid until some time after the installation of the waterproofing system. When the APL and the binder and surface courses are laid several days apart, an APL of sand asphalt may be laid by hand on small bridges. However, this should be discouraged because of the difficulties of laying and rolling such a thin layer at sufficiently high temperatures to achieve a good bond and form a dense layer.

When a waterproofing system includes a tack coat to produce a durable bond between the waterproofing system and the surfacing, it is essential that the tack coat remains in place during surfacing. Tack coats can be stripped off the waterproofing membrane by the wheel of the paver and other site vehicles. They can be sticky at high ambient temperatures and when they are not cured, and they can be brittle and break up at low temperatures. Contactors should provide a method statement detailing how they propose to minimise the stripping of the tack coat and nullify its effects. The loss of tack coat over, say, 20% of each square metre should be the maximum considered acceptable. When there is a possibility that the tack coat may be removed during surfacing, the wheels of the paver should be positioned so they are not coincident with the wheel paths on the carriageway.

Stripping can be reduced by limiting the number of vehicles that drive over the waterproofing system, reducing the time that vehicles are on the system, limiting the amount of asphalt in the paver so traction forces during start-up are reduced, and minimising the number of times the paver stops and starts. The application of soap solution to the pre-cleaned wheels of the paver and other site vehicles has been effective. On at least one bridge, repair patches of a thick tack coat were prepared that were inserted behind the wheels of the paver and in front of the screed bar where the tack coat had been removed. It was assumed that tack coat was bonded to the waterproofing system when it was melted by the hot surfacing and the surfacing was compacted.

6.4.6 Site trial to determine durability of bond of surfacing to waterproofing system

It has been concluded that the performance of surfacing less than 120mm thick is very dependent on the bond of the surfacing to the waterproofing system. Therefore, when the performance of a waterproofing system on a heavily trafficked road has not been demonstrated, it is proposed that site trials are carried out to determine the initial bond and durability of the bond in service. The site trial should also determine the effectiveness of the method statement designed to prevent the tack coat being stripped from the waterproofing membrane during surfacing.

The first trial should be carried out on a concrete slab which is waterproofed in accordance with the manufacturer’s method statement in order to determine whether the required bond can be achieved at the specified activation temperature of the tack coat. Surfacing should be laid in 5m lengths, each length at a different temperature, and rolled after the normal time delay experienced on bridges. The laying temperature and the temperature at the interface or at mid-layer immediately before compaction should be recorded. Test sections should be prepared in each test length by coring or sawcutting, and tensile bond tests should be carried out at a temperature between 10°C and 23°C.
Laying temperatures and compaction temperatures that achieve the bond strengths specified in Table 6.1 should be used on bridges.

A further four trials should be conducted on bridges of increasing importance to build up knowledge on the performance on the system. The second trial should be on an accommodation (lightly trafficked) bridge and the fifth on a small heavily trafficked bridge. Performance should be assessed by carrying out six tensile bond tests before and after one year of trafficking in different trafficked locations. The tensile bond strengths should comply with those specified in Table 6.1, and the mean tensile bond strength after trafficking should be no less than 70% of the mean bond strength before trafficking. When these requirements have been satisfied, the system can be used on other bridges of the same importance or level of trafficking (provided the tensile bond strengths measured after trafficking satisfy the requirements for the surfacing thickness), and the next trial can be undertaken. However, even then, it is recommended that use of the system is limited to small bridges until its performance has been demonstrated over a period of five years. The testing will damage the waterproofing system so measures should be taken to minimise the ingress of chlorides to the deck.

6.5 Surface preparation of the deck

There should be no large hollows or low points on bridge decks that cannot be drained by the gradients and cross falls, or by sub-surface drainage.

Small hollows or surface irregularities can be filled by increasing the thickness of spray applied membranes above the nominal thickness of 2.5mm, but it may be more cost effective to use a repair material, especially if the repair material is durable and will not have to be replaced when the deck is rewaterproofed.

The finite element analyses have shown that increasing the thickness of spray applied waterproofing systems in trafficked areas from 3 to 5mm decreases the fatigue life by a factor of about 2 and this is unlikely to be significant because the strains induced by wheel loading are low. (However, this may not be the case if the properties of membranes on bridges are different to those of the materials tested.) Increases in thickness to greater than 5mm should have little or no effect on performance in trafficked areas with a maximum dimension exceeding 150mm in plan, a dimension that is approximately half the maximum dimension of a tyre footprint.

Repair materials should be compatible with the waterproofing system. They must have similar properties to the deck concrete (coefficient of thermal expansion and elastic modulus) if they are to remain firmly bonded to the deck. Layers should not be less than the minimum thickness recommended by the manufacturer of the material. Generally, layers less than 5mm thick should be avoided as they are more likely to debond, and feathered edges should be removed as required.

The bond of the waterproofing system to the deck is reduced if the deck is contaminated with dirt or detritus, or the deck is wet. Although the BBA Roads and Bridges Certificates do not permit waterproofing to proceed under these circumstances, some surfacing failures have been attributed to such problems, so care is always necessary.

It is important that lap joints are free of contamination and that, wherever possible, they are formed with the lower layer of the joint on the lower side, i.e. waterproofing should commence from the lowest areas of bridges whenever possible. The bond between the different components (e.g. primer, membrane and tack coat) of a waterproofing system may be low if there are delays during the installation of the system. To ensure that a good bond is formed, overcoating time requirements for each material and interface should be followed, i.e.

- primer on primer
- membrane on primer
- membrane on membrane
- tack coat on membrane.
7 The role of the APL and replacing the lower asphalt layers without rewaterproofing

7.1 Using red sand asphalt as an indicator layer

Since Advice Note BA 47 (The Highways Agency, 1999b) was first introduced in 1994, it has stated that “The red tint (of the APL) is specified as a visible warning that the waterproofing system is being approached when planing off surfacing materials.”

Only three of the twenty-two Agents that provided information for this study said that they have attempted to use an APL of either red sand asphalt or black sand asphalt overlaid with red indicator mesh as an indicator layer when attempting to replace the asphalt layers below the surface course on a bridge without rewaterproofing it. The following reasons were cited:

- most bridges with surfacing more than 100mm thick that are being resurfaced are being resurfaced because a mastic asphalt or sheet waterproofing system has failed or is near the end of its expected service life;
- red sand asphalt has been used for a relatively short period, red indicator mesh for even less time, and, during that period, waterproofing systems and surfacing more than 100mm thick have performed well so that replacing the lower asphalt layers without rewaterproofing has not been required; and
- when it has been necessary to replace the lower asphalt layers on bridges because the surfacing has failed or when there have been major works on the pavement, the opportunity has usually been taken to rewaterproof the bridge.

Those Agents and local authorities (Jordan et al, 1997) that have tried to use an APL as an indicator layer have had varying degrees of success, as follows:

- the waterproofing system was damaged during planing, and the system had to be replaced (three occasions);
- planing damaged the sand asphalt and it had to be removed, but the waterproofing system was damaged when the sand asphalt was removed and it had to be replaced (one occasion);
- planing displaced the sand asphalt from the waterproofing system, the sand asphalt was removed successfully and minor repairs were made to the waterproofing system before a new sand carpet and binder course were laid (one occasion); and
- the sand asphalt suffered little or minor damage when the binder course was removed and, after minor repairs, it was overlaid with a new binder course (four occasions).

It appears that, if planing damages the APL, it is not always possible to remove it without damaging the waterproofing system. Damage to the waterproofing system can be repaired, but great care must be taken to ensure that lap joints at patch repairs are completely watertight. The integrity of the patch repairs and the old waterproofing system should be checked, but some test methods may be ineffective on the old waterproofing system, dependent on the tack coat. Furthermore, it is not known if a new APL can be bonded to an old waterproofing system to provide a durable bond and, generally, this is not recommended over large areas.

If the sand asphalt is not to be damaged, the planer must be set well above the APL. For example, the binder course has been planed off some bridges in two passes. The first pass left at most 10mm of the layer so the remaining binder course could be removed by hand tools or by a second pass of the planer. However, surfacing records were used to set the height of the planer, rather than the red sand asphalt, although the red sand asphalt was clear to see when the entire binder course had been removed. Several Agents reported that the colour of red sand asphalt is not distinctive. Synthetic red oxides have improved the colour, but the APL is still difficult to detect at night when much planing is done.

Another reason for setting the planer above the APL is the local variations in the level of the deck and the depth of the surfacing on many bridges. The planer must be set at least 20mm above the mean
level of the waterproofing system if the waterproofing system is not to be damaged. However, a level nearer 30mm above the system is preferable to allow for adjustment of the planer when there are uniform changes in the thickness of the surfacing, e.g. from pier to midspan positions. The planer must then be set a little higher if the APL is not to be damaged.

Therefore, in order to remove (most of) the binder course, the planer must be set well above the APL, but the APL is then not used as an indicator layer. Even then the APL and waterproofing system may be damaged, and there are no suitable, if any, test methods to check the integrity of both the waterproofing system and the old APL with the old APL in place. Clearly, the service life of the old waterproofing system, the old (or new APL), and the new binder and surface courses must be long enough to ensure economic viability. However, very little is known about the long-term performance of the waterproofing system and surfacing after replacing the lower asphalt layers without rewaterproofing.

Taking all the above-mentioned factors into account, it is concluded that it is impractical to use the APL as an indicator layer to replace the binder course without rewaterproofing bridges. The APL could still be used as an indicator layer when rewaterproofing bridges. However, most Agents prefer to set the planer from the depth of the surfacing measured from trial holes, rather than use the APL as an indicator layer.

Some Agents said that red sand asphalt may be of some benefit in verges and footways so utility companies are aware of the presence of the waterproofing system. However, it is not known if all companies are aware of the significance of red sand asphalt, and whether it is referred to in their maintenance procedures. Because most excavations by utility companies involve the use of excavators and hand tools, other Agents consider that it is unlikely that an APL of red sand asphalt will always be identified before the waterproofing system is damaged. Therefore, a stronger and thicker layer than sand asphalt should be used in verges and footways, e.g. 50mm thick no-fines concrete.

7.2 Replacing the asphalt layers below the surface course without rewaterproofing

As indicated several times throughout this report, effectively impermeable surfacing not less than 120mm thick has generally performed well on bridges. The service lives of certain types of waterproofing system that were applied before the requirements of BD 47 were fully implemented have been shorter than the service life of the binder course of such surfacing so when the waterproofing systems have failed after around 20 to 30 years, the bridges have been rewaterproofed and resurfaced at the same time.

Waterproofing systems that comply with the requirements of BD 47 should have longer service lives than pre-BD 47 systems. Only time will tell what the service life should be, but leakages should be less common and less significant for BD 47 systems than for pre-BD 47 systems, and BD 47 systems should be firmly and uniformly bonded to the deck. Therefore, the tendency may be for the service life of the waterproofing system to be longer than the service life of surfacing of thickness 120mm or more.

Because it is impractical to replace the entire binder course without replacing the APL and rewaterproofing the deck, it may be more cost effective to design the APL and the binder course so that their service lives are similar to the service life of the waterproofing system. Surfacing works would then be limited to the replacement of the surface course. However, the benefits of laying sand asphalt, even when it is overlaid with 100 mm of surfacing, have been questioned by many in the industry. The performance of an APL of the current specification could be improved with the addition of polymer modified binder or coarse aggregates, but then the compaction of a 20mm thick layer with polymer modified binder would need to be more timely than for such a layer with normal binder. Aggregates of maximum size 6.3mm could be incorporated into a 20mm thick layer, but again the timing of the compaction would be more critical than for a layer with no coarse aggregates.
In order to improve the performance of the surfacing on bridges, it is necessary to optimise the compaction of the asphalt layer directly overlaying the waterproofing system and its bond to the system. This requires an increase in the thickness of the layer to around 40mm so the APL currently specified would be omitted. A mixture with course aggregates is required for a 40mm thick layer, but this could only be laid on a waterproofing system that is capable of passing the aggregate indentation test at 125°C (or higher if required). Also, the tack coat of the waterproofing system would need to be sufficiently thick to reduce the void content at the base of the layer at the interface with the waterproofing system, and measures would need to be taken to prevent damage to the waterproofing system during site activities that is afforded by an APL. However, an improvement in the performance of the asphalt layer directly overlaying the waterproofing system so its service life is significantly greater than that of the surface course should help to realise the benefits of the longer service life of waterproofing system that comply with BD 47. The use of polymer modified binder in the lower asphalt layer(s) is likely to be cost effective on heavily trafficked bridges.

Systems that have not passed the aggregate indentation test at 125°C could be overlaid with black sand asphalt, although the performance of the surfacing overall may be compromised for the reasons given above. The cost of black sand asphalt is less than that of red sand asphalt. Black sand asphalt is readily available, whereas there is often a reluctance to supply red sand asphalt because it contaminates mixing plant.

The advantages of omitting the APL can be summarised as follows:
- One less surfacing operation may be required
- The bond of the lower asphalt layer to the waterproofing system can be optimised
- The compaction of the asphalt layer directly overlaying the waterproofing system can be improved, although an appropriate tack coat must be used to prevent interconnecting voids at the interface with the system
- Rutting of the surfacing should be reduced

The disadvantages of omitting the APL can be summarised as follows:
- The waterproofing system will cost more and take longer to apply
- The waterproofing system may be damaged during site activities before the binder course is laid
- The waterproofing system may be damaged by coarse aggregates and high temperatures during surfacing works (if these temperatures are higher than those appropriate for the system)
- Water may accumulate at the waterproofing system if the thick tack coat of the waterproofing system is not applied uniformly.

The total thickness of surfacing may range from less than 60 mm to over 120 mm over a bridge. Such surfacing may require one, two or three asphalt layers, each of which can be a different material. On most bridges, there are small variations in the level of the deck that can be accommodated without varying the number of asphalt layers. However, it has been necessary on a few bridges to vary the number of layers, requiring some degree of compromise in the regions where the number changes. Under these circumstances, when the surfacing is less than 120mm thick anywhere on a bridge, the APL should be omitted and the waterproofing system should be overlaid with a layer of reasonably uniform thickness (40mm is recommended) of the same impermeable material. Changes in thickness should be accommodated in the upper layers, with tapered layers trimmed so that any material which is too thin to have been compacted sufficiently is removed.
8 Requirements for the surfacing on bridge decks

8.1 General
This section summarises the recommendations made throughout this report that are intended to improve the performance of surfacing on bridge decks. These recommendations, together with those given in Nicholls et al (2006), should be considered for inclusion in BD 47 and the SHW.

8.2 Surface and sub-surface drainage
- Surface drainage systems, longitudinal gradients and cross falls should be provided to minimise the amount of water that can enter and accumulate in the surfacing on bridges.
- Edge drains should be provided to drain the full depth of relatively permeable surface courses (e.g. air void content > 6%) (i) at the low points of the deck and (ii) where the flow of sub-surface water though the surface course is impeded, e.g. at expansion joints that are not the buried type.
- Sub-surface drainage should be provided at the level of the waterproofing system as specified in BD 47 at all locations were water may accumulate.
- The sealant at joints between adjacent rips of asphalt should prevent an easy flow of water into an asphalt layer. Fully sealed joints will prevent the flow of water horizontally across a bridge deck so provision must be made to prevent water accumulating in the surfacing in such circumstances.

8.3 Surface preparation and application of the waterproofing system
- After the waterproofing membrane has been applied, there should be no hollows or depressions of maximum dimension 150mm in plan and depth greater than 5mm in trafficked areas of the deck that are not drained naturally by the longitudinal gradient or cross fall, or by the provision of sub-surface drainage.
- The waterproofing system must be uniformly bonded to the deck and it must not be applied if contamination of the deck or the environmental conditions threaten to compromise the bond.
- The nominal thickness of spray applied waterproofing membranes should not be greater than 3mm.
- The membrane thickness can be increased to 5mm to fill hollows that are not free draining, providing the use of a repair material is not more cost effective. Also, the membrane thickness can be increased to 5mm to form a continuous membrane when the surface finish does not comply with the requirements of a U4 finish or contains voids or surface irregularities. However, any surface finish worse than U4 is a departure and should certainly not be found on new decks.
- Repair materials should be compatible with the waterproofing system and have similar properties to the deck concrete (coefficient of thermal expansion and elastic modulus). Repair materials should not be used at less than their recommended minimum thickness. Layers less than 5mm thick should be avoided as they are more likely to debond. Repairs of lower thickness should be used only if a durable bond can be demonstrated.

8.4 Surfacing and waterproofing system
- When total thickness of surfacing is less than 120mm anywhere on a bridge, the APL of sand asphalt should be omitted and the waterproofing system should be overlaid with an asphalt layer of thickness 40mm (recommended). A 40mm asphalt layer should also replace the APL when it is necessary to optimise the compaction of the asphalt layer and its bond to the waterproofing system.
When there are variations in the total surfacing thickness over a bridge, the asphalt layer directly overlaying the waterproofing system should be of uniform thickness (40mm is recommended). Variations in thickness should be accommodated in the upper asphalt layers, and tapered areas should be trimmed to remove asphalt too thin to be sufficiently well compacted.

Care should be taken to minimise damage to the waterproofing system after it has been applied and before it has been overlaid with asphalt, especially when the APL is not laid. Any damage to the system should be repaired.

The asphalt layer directly overlaying the waterproofing system should have a design air void content of no more than 4% so that the amount of sub-surface water that enters the layer is low.

When the asphalt layer directly overlaying the waterproofing system contains coarse aggregates, the waterproofing system should have a thick tack coat that fills the voids at the base of the layer and prevents them from being interconnecting.

The flow of sub-surface water into the binder course and APL (if present) should be minimised by specifying (i) a TSCS with a thick bond or tack coat that will help to seal the binder course and (ii) a binder course which has a low void content.

Waterproofing suppliers should provide details of (i) the temperature at the tack coat to achieve a good bond in the BBA Roads and Bridges Certificates, and (ii) how stripping of the tack coat is to be minimised and repaired before and during surfacing.

The asphalt layer directly overlaying the waterproofing system should be laid and compacted at temperatures that are sufficiently high (i) to form a dense layer and (ii) to activate the tack coat so the asphalt is uniformly and well bonded to the system. The temperature at the waterproofing system should be measured immediately after the asphalt has been laid, and when compaction is essentially completed.

The inclusion of polymer modified binder in the lower asphalt layer(s) should be considered on heavily trafficked bridges so that the service life of the layer(s) is significantly greater than that of the surface course. This should help to realise more of the service life of the waterproofing system.

If the surfacing is to be laid and compacted at temperatures that exceed those permitted by the SHW, it must be demonstrated before works commence on site that this will not damage the waterproofing system.

An APL, when required, should be black sand asphalt, and should not be laid by hand if the bridge is on a motorway or trunk road;

8.5 Bond of surfacing to the waterproofing system

The minimum adhesion and bond strength requirements in BD 47 should apply only to surfacing of thickness 120mm or more including an APL of sand asphalt.

When the waterproofing system is overlaid with asphalt with coarse aggregates, the minimum adhesion and bond strengths in Table 6.1 should apply.

A site trial should be conducted to determine whether the required bond can be achieved at the specified activation temperature of the tack coat of any waterproofing system without a history of good performance. A further four trials should be conducted on bridges of increasing importance from an accommodation (lightly trafficked) bridge to a small heavily trafficked bridge to build up knowledge on the performance on the system. Only when the bond has been found to be durable in a trial should the system be used on other bridges of the same importance or level of trafficking, and the next trial be undertaken. Even then, it is recommended that use of the system is limited to small bridges until its performance has been demonstrated over a period of five years.
9 Conclusions

9.1 Specification and performance of surfacing
1. Surfacing more than 100mm thick has performed well on most bridges.
2. There have been a number of premature failures of surfacing less than 100mm thick involving cracking and potholing of the surfacing. These have been more prevalent where the thickness of the surfacing has been lowest, the surfacing has been poorly bonded to the waterproofing system and water has accumulated in the surfacing.

9.2 Laboratory tests
3. Bond tests have found little evidence that the bond of the surfacing to the waterproofing system is weakened simply by the presence of water in the surfacing. Further bond tests have shown that the tensile bond strength of the surfacing to the waterproofing system and/or the tensile strength of the surfacing itself can be weakened by wheel loading when the surfacing is saturated.
4. The highest bond strengths were measured on System 2 with a thick tack coat that limited the amount of water that could accumulate in the surfacing at the interface with the system. Low bond strengths were measured with sand asphalt after wheel loading when the sand asphalt was saturated.
5. The stiffness modulus and Poisson’s ratio of four waterproofing systems have been tested at different strain rates and three temperatures. Three of the systems behaved viscoelastically and one elastically.

9.3 Finite element analyses
6. A finite element model has been developed to estimate how the strains induced in the surfacing are dependent on the properties of the waterproofing system, and the bond of the system to the concrete deck and the bond of the surfacing to the system.
7. The local strains induced by wheel loading in the surfacing overlaying the waterproofing systems tested were calculated to be too low to have a significant effect on the performance of surfacing overlaying membranes of thicknesses up to 5mm.

9.4 Causes of failure of surfacing on bridges
8. It appears that most premature surfacing failures on bridges are the result of more than one mechanism. It is postulated that most premature failures of surfacing less than 120mm thick have occurred because (i) the surfacing has become saturated, (ii) high hydrostatic pressures have been generated in the saturated surfacing by wheel loading, and (iii) the high pressures have debonded the surfacing from the waterproofing system and caused the surfacing itself to fail.
9. Surfacing less than 120mm thick that has been poorly bonded to the waterproofing system has been particularly susceptible to premature failure.
10. The properties of waterproofing systems on some bridges may be different to those measured in the laboratory tests. Also, it was reported that large areas of membranes are sometimes significantly more than 5mm thick when surfacing has failed. Therefore, higher strains may be induced on bridges than have been calculated in the finite element analyses.
11. It is recommended that samples of membrane material are analysed when surfacing fails prematurely to determine the significance of different material properties and membranes thicker than 5mm.
9.5 Replacing asphalt layers below surface course without rewaterproofing

12. A red sand asphalt APL has been used as an indicator layer to set the planer on only a few occasions to replace the asphalt layers below the surface course on bridges without rewaterproofing them. Few attempts have been successful because the APL and/or the waterproofing system have been damaged.

13. It is considered impractical to use a red sand asphalt APL as an indicator layer to replace the binder course on bridges without rewaterproofing them. Therefore, it is recommended that the APL, if laid, is not tinted with red oxide and that red indicator mesh is not used.

9.6 Improving the performance of surfacing on bridges

14. Recommendations have been proposed to improve the performance of the surfacing on bridges.

15. Sufficient surface and sub-surface drainage should be provided to prevent water accumulating in the surfacing. Edge drains should be provided to drain the full depth of permeable surface courses that are not free draining.

16. The asphalt layer directly overlaying the waterproofing system should be effectively impermeable, and the asphalt and the waterproofing system should be selected so there are few voids at their interface and no interconnecting voids. When the layer has coarse aggregates, this will normally require a waterproofing system with a thick tack coat.

17. The asphalt should be laid and compacted at temperatures that are sufficiently high to form a dense layer and to activate the tack coat of the waterproofing system so the asphalt is uniformly and well bonded to the system. Temperatures should be measured at the tack coat during surfacing to ensure this is achieved.

18. When the total thickness of surfacing is less than 120mm anywhere on a bridge, the APL of sand asphalt should be omitted and the waterproofing system should be overlaid with an asphalt layer of thickness 40mm (recommended). A 40mm asphalt layer should also replace the APL when it is necessary to optimise the compaction of the asphalt layer and its bond to the waterproofing system.

19. The inclusion of polymer modified binder in the asphalt layer directly overlaying the waterproofing system should help to realise more of the service life of the waterproofing system.

20. The minimum adhesion and bond strength requirements in BD 47 should be increased when the waterproofing system is overlaid with asphalt with coarse aggregates and is less than 120mm thick.

21. Site trials should be conducted on new waterproofing systems to ensure that the bond of asphalt to the waterproofing system is durable under trafficking.

22. A stronger and thicker layer than sand asphalt should be used in verges and footways to prevent utility companies from damaging waterproofing systems, e.g. 50mm thick no-fines concrete.
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