The skid resistance behaviour of thin surface course systems
HA/MPA/RBA Collaborative Programme 2008-11: Topic 1 Final Report

by P G Roe and A Dunford

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by P G Roe and A Dunford (TRL)

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Client: Highways Agency, Mineral Products Association
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        (Donna James, Malcolm Simms and Chris Southwell)

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Executive summary

Proprietary thin surface course systems have been successfully used on UK trunk roads for over 10 years, providing quiet surfaces while maintaining good friction when the road is wet. However, a significant disadvantage of these materials from cost and sustainability viewpoints is that they use polish-resistant aggregate throughout the surface course rather than as a thin layer of chippings spread on the surface. The surface texture of “thin surfacings” as they are colloquially known, has specific characteristics – often described as “negative texture” – that interact with vehicle tyres in a different way to traditional materials such as hot rolled asphalt (HRA) and surface dressing, which have “positive texture”. This different interaction mechanism results in relatively low tyre noise and may also lead to a different polishing action and to different in-service skid resistance.

In bringing thin surfacings into wider use in the UK, the process of approving them focussed on compliance with existing specifications that had been derived from the properties of HRA and surface dressings, prevalent at the time. However, what was really needed was new research to find how the properties of thin surface course systems affect their performance so that requirements for new materials could be optimised to maintain safety standards, further improve durability and make more efficient use of resources.

For many years, the UK central government and road construction industry, through the Highways Agency (HA), the Mineral Products Association (MPA), the Refined Bitumen Association (RBA) or their predecessors, have commissioned a rolling programme of collaborative research. Carried out by TRL, this has focussed on the practical needs of the Agency and the Industry in providing and maintaining the UK road infrastructure. Known generically as the “Collaborative Programme” (CP), work is typically carried out in phases lasting about three years, with each phase including a number of specific topics for study.

During the 2004 -2007 phase of the CP, a study of the skid resistance performance of thin surface course systems was begun (Roe, Dunford, & Crabb, 2008). This was continued into the 2008 – 2011 CP, with the objective of understanding how thin surfacings should be specified in relation to the polished stone value (PSV) of the aggregates used and the texture depth needed to give adequate safety performance. As part of that work, eleven trial sites were constructed. On each site, sections of thin surfacing using the same coarse aggregate but in different sizes, generally 0/6 mm, 0/10 mm and 0/14 mm, were compared under the same traffic conditions. The sites covered a range of traffic levels and aggregate PSV but were confined to situations with low traffic stresses and a low overall skidding risk. On each site, skid resistance and texture depth were monitored from new until the site had been trafficked for sufficient time to have reached its equilibrium skid resistance level.

The monitoring programme included measurements of low-speed skid resistance with the sideway-force coefficient routine investigation machine (SCRM), together with measurements of high-speed locked-wheel friction using the Highways Agency’s pavement friction tester (PFT). As well as monitoring the skid resistance performance of the trial sites, laboratory studies were developed as the work progressed to help give a better understanding of the effects observed in the field.

The measurements showed that, at low speeds, skid resistance decreased with increasing maximum coarse aggregate size. Texture measurements showed some decrease after trafficking and the 0/6 mm materials tended to have lower texture depth than would currently be regarded as acceptable. However, in spite of their lower texture, at high speeds (100 km/h), the 0/6 mm thin surfacings gave higher skid resistance than would be expected from conventional surfacings.

The laboratory studies used cores taken from the trial sites to explore different texture measurement techniques and other ways of assessing surfacing characteristics, such as
contact area and pressure distributions in the tyre/road interface and compared these with the in-situ friction performance. These studies have demonstrated that current techniques for assessing texture depth do not satisfactorily explain the skid resistance effects observed on thin surfacings made with smaller aggregates.

As well as the high-speed performance of the 0/6 mm materials, the trial sites also demonstrated that in low-stress situations thin surfacings provide skid resistance well above the required Investigatory Level with lower PSVs than are currently permitted, giving scope to amend current specifications in this respect.

As a result, it has been possible to make recommendations for changes to the requirements in HD36 (Design Manual for Roads and Bridges, 2006) in relation to minimum PSV levels and texture depth specifically for negatively textured thin surfacings on sites with low traffic stress that will allow a wider range of aggregates to be used in some circumstances. In summary, these are:

1. For Site Categories A1, B1 and C, amend the background minimum PSV boundaries to 53, 58, 63 and 68 to more closely match the geology of sources available in the UK.
2. For Site Categories A1, B1 and C, reduce the minimum PSV for traffic levels below 5000 CVD by 7 units, with an underpinning minimum of 50.
3. Revise the texture depth requirements for thin surface course systems as follows:
   - For materials with an upper aggregate size of 14 mm, the mean texture depth (MTD) should be not less than 1.3 mm initially and not less than 1.0 mm after two years in service (this is the same as the current requirement)
   - For materials with an upper aggregate size of 10 mm, MTD should be not less than 1.1 mm initially and not less than 0.8 mm after two years in service
   - For materials with an upper aggregate size of 6 mm, MTD should be not less than 1.0 mm initially and not less than 0.7 mm after two years in service
   - Where 0/6 mm materials are to be used on high-speed roads a supplement to current HAPAS (highway authority product approval scheme) certificates will be required that provides evidence from a type approval installation trial (TAIT) to verify adequate high-speed friction performance.

The programme has not included sites in higher-stress locations. Proposals have therefore been included for:

- Extending the understanding to the more difficult higher-stress conditions
- Finding better ways to measure and interpret texture and its influence on skid resistance across the speed range for different surfacing types
- Developing an approach to future skid resistance policy and in-service monitoring that will take high-speed skid resistance more directly into account than is currently possible.

Overall, the study has yielded a new understanding of how thin surface course systems, including those utilising smaller aggregate sizes than would normally be used on high-speed roads, perform in terms of skid resistance in-service. The research has provided a sound foundation for revising specification requirements for those sites that represent a major proportion of the trunk road network, and many local authority roads, giving greater flexibility in sourcing appropriate aggregates and further improvements in durability without loss of performance in service, thereby enhancing sustainability.
1 Introduction

For many years, the UK central government and road construction industry, through the Highways Agency (HA), the Mineral Products Association (MPA), the Refined Bitumen Association (RBA) or their predecessors, have commissioned a rolling programme of collaborative research. Carried out by TRL, this has focussed on the practical needs of the Agency and the Industry in providing and maintaining the UK road infrastructure. Known generically as the "Collaborative Programme" (CP), work is typically carried out in phases lasting about three years, with each phase including specific topics for study.

The 2004 – 2007 CP “The performance and durability of asphalt roads” included, as Topic 1, “Surface requirements for asphalt roads”. This had as its main focus the skid resistance performance of thin surface course systems and hence how they should be specified, particularly in relation to the polished stone value (PSV) of the aggregates used and the texture depth needed to give adequate safety performance.

A significant component of this work was the construction of trial sites in which thin surface course systems using different coarse aggregate sizes were compared. Each site was monitored for skid resistance and texture depth from its completion so that the development of these properties and any changes over time could be observed. In particular, it would be important to allow the skid resistance to reach its equilibrium level before a full assessment could be considered.

In the event, there was insufficient time for the sites to be established and for them to reach their equilibrium performance level before the end of the 2004/2007 programme, so this aspect of the work was continued into the 2008-2011 CP.

Within the 2008-2011 CP, any general attempt to redefine PSV requirements based on historic data about the trunk road network was abandoned: the work in the previous phase had shown this to be impractical because of the lack of adequate or accessible records of what materials had been used in specific locations on the network that could then be compared with in-service skid resistance data. The component of the earlier work relating to spray was also regarded as completed for the purposes of the CP.

Consequently, Topic 1 in the 2008-2011 CP focussed on two components:

- Continuing the monitoring of the skid resistance performance of the trial sites until each of them had been trafficked for sufficient time to have reached their equilibrium skid resistance levels
- Laboratory studies, developed as the work progressed to help give a better understanding of the effects observed in the field.

An interim TRL report, PPR324 (Roe, Dunford and Crabb, 2008), described the work as far as it had progressed at the end of 2007. This report brings that work up to date. It includes a brief description of the trial sites and the monitoring programme, together with an analysis of the performance of the site surfacings after they had been in service for at least three years. This is followed by a summary and overview of the results from the additional laboratory studies. The implications for applying the results of the work to future standards are discussed at the end of the report.
2 Technical background to the study

Proprietary thin surface course systems have been successfully used on UK trunk roads for over 10 years. These systems can provide a quiet and durable surface course while maintaining good friction and spray properties when the road is wet. However, a significant disadvantage of these materials from a cost and sustainability viewpoint is that they use polish-resistant aggregate throughout the surface course rather than as a thin layer of chippings spread on the surface.

The surface texture of thin surface course systems has specific characteristics – often described as “negative texture” – that interacts with vehicle tyres in a different way to traditional materials, such as hot rolled asphalt (HRA) and surface dressing, and results in relatively low tyre noise. This different interaction mechanism may also lead to different polishing action and, therefore, to different in-service skid resistance.

In bringing the new surface course systems into wider use in the UK, the process of approving them focussed on ensuring that the material characteristics met the existing specifications that had been derived from historic research into the behaviour of HRA and surface dressings, prevalent at the time. As experience with thin surface course systems has been gained, some changes to these specifications have been made, primarily to permit a modest relaxation of the initial and retained texture depth. However, what was really needed was new research that could provide a greater understanding of how the properties of thin surface course systems affect their performance so that requirements for new materials could be optimised to maintain safety standards, further improve durability and make more efficient use of resources.

If it could be shown that aggregates used in thin surface course systems generally provide higher skid resistance than they do in traditional materials, there might be scope for reducing PSV or texture depth requirements in some situations. This possibility was supported by historic research in the UK and elsewhere which found that in materials such as surface dressings, smaller chipping sizes can give slightly higher skid resistance when measured at low speeds, e.g. by SCRIM (sideway-force routine investigation machine).

However, the use of smaller aggregate sizes is associated with lower texture depth, thus potentially negating any advantage at low speeds by reduced high-speed skid resistance. Nevertheless, if the combination of smaller aggregate size and the form of the texture in a thin surface course system gave a sufficient improvement in skid resistance to overcome the adverse effects of lower texture depth, there could be increased scope for further changes to the texture depth specifications.

Optimising specifications to take account of these effects, if they can be shown, could also ease current issues with the supply of high PSV aggregates in two ways. Permitting the use of lower-PSV aggregates in a wider range of circumstances will reduce pressure on the limited range of high-PSV sources. The use of finer-sized thin surface course systems, albeit with lower texture, would also permit the use of a wider aggregate size range, thereby maximising the use of the currently available high PSV material.
3 Trial sites and monitoring programme

3.1 Locations of trial sites and materials used

The trial sites were originally conceived as validation trials to provide data from in-service roads that could be used to compare with predictive models developed from historic performance data. Each site was to provide a number of sections, on which thin surfacings\(^1\) using different coarse aggregate sizes but from the same source would be laid. Thus, on any one site, this would allow the effects of the different aggregate sizes to be directly compared under identical traffic and weathering conditions. Typically, the target would be for mixes with three coarse aggregate sizes to be used: 0/6 mm, 0/10 mm and 0/14 mm\(^2\). Different site locations would allow different aggregates and traffic levels to be included.

The sites were laid by inserting sections of trial materials into planned resurfacing contracts, for which the specified contract material could serve as one of the test surfacings. This approach considerably simplified the process of identifying and planning suitable sites, for which MPA members supplied and laid the materials as an in-kind contribution to the project. Where appropriate, HA would authorise a departure from standard if a PSV or texture depth on one of the trial sections was likely to be outside normal requirements for the location on the basis that the sites were to be monitored for performance more frequently and more fully than is normal practice for network level skid resistance management. As well as requiring existing resurfacing contracts, the choice of locations was also limited by the need for them to be suitable for monitoring with test vehicles operating at speeds up to 120 km/h.

A consequence of using this approach was that it was neither practicable nor economic to develop a full factorial experimental design matrix within the programme. This was not significant in the original context of providing validation data but, when the development of improved predictive models suitable for thin surfacings proved impractical to achieve, the trial surfacings were left as the main evidence for the performance of the materials. As a result, as will be discussed later, there are limitations to the conclusions which may be drawn.

In summary, eleven sites were laid at six locations on the trunk road network. Every site was on a two-lane dual carriageway and comprised sections having different aggregate sizes from the same source. In some places, by laying the materials on both lanes, two sites using the same aggregate with two different traffic levels could be established.

Table 3.1 provides a list of the sites arranged in the sequence in which they were first laid. The Table also indicates the suppliers and the generic proprietary product type of each material used. For reasons of commercial confidentiality, the coarse aggregate sources have been identified using code letters rather than quarry names. For consistency, the materials used at each site are listed in order of increasing coarse aggregate size; this does not typically relate to their order on the road. Estimated traffic levels were derived from information in the Highways Agency Pavement Management System (HAPMS). Fuller details of the various trial sites and their layouts can be found in PPR324.

The photograph in Figure 3.1 shows a general view of the trial location on the A5 at Gibbet Hill, with Site 1a and Site 1b in the lanes 1 and 2 respectively; Figure 3.2 shows part of Site 5a.

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\(^1\) Specification of Highways Works, Clause 942 thin surface course systems are often referred to as “thin surfacings”, for convenience.

\(^2\) For this report the European practice of describing the thin surfacings as 0/6, 0/10, 0/14 mm asphalt has generally been used, together with the proprietary product name where the context requires it. For reasons of space, in some charts the “0/” prefix is omitted.
Table 3.1 Summary of Trial site locations and materials used

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<tr>
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<th>Traffic level approx. CVD†</th>
<th>Aggregate source code</th>
<th>Materials used</th>
<th>Supplier and material brand</th>
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<td>A5 Gibbet Hill Leicestershire Northbound, Lane 1</td>
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</tr>
<tr>
<td></td>
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<td>0/14</td>
<td>Lafarge Axoflex</td>
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<tr>
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<td>0/6</td>
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<td>3</td>
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<td>D 60</td>
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<td></td>
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<td>0/10</td>
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<td>0/14</td>
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<td>0/10, 0/14</td>
<td>Lafarge Axoflex</td>
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†Commercial Vehicles per lane per Day
* Part of main contract included as a "control" for comparison.
‡At Site 4, part of the surfacing in Lane 2, had to be replaced soon after laying and Aggregate B was used
Figure 3.1 A general view of the trial sites on the A5 at Gibbet Hill (1a and 1b) in 2007
The surface change next to the dual carriageway sign is the start of the trial, which at this location begins with the 0/10 mm sections. Site 1a is in Lane 1, Site 1b in Lane 2.

Figure 3.2 A view of part of the trial sites on the A14 at Thrapston (5a and 5b) in 2008
The change of colour at the surface change in the centre of the picture (just beyond the lay-by) marks the change of aggregates between Site 5a and 5b.
3.2 Measurement techniques used

The techniques used for the monitoring programme were selected to allow repeated measurements to be made using standard test vehicles operating at traffic speeds, either with police escort or within a lane closure. All measurements were made, as is normal practice, in the nearside (left) wheel path of the traffic lane. Three properties of the road surfacing were monitored:

Low-speed wet skid resistance

This was measured using SCRIM, using a smooth-tyred test wheel set at an angle of 20 degrees to the direction of travel. At the standard test speed of 50 km/h used here, the test tyre contact patch slips over the road surface at about 17 km/h (hence it is a low-speed measurement). This is the standard method used to monitor the skid resistance condition of all trunk roads and many local authority roads in the UK. It was used to provide a convenient comparison with familiar measurements used within the trunk road skid resistance standards set out in HD28/04 (Design Manual for Roads and Bridges, 2004).

Texture depth

This was measured initially by the surfacing contractors as mean texture depth (MTD) using the volumetric patch method following the normal procedures for contractual verification required by Clause 92.1 of the Specification for Highway Works (Manual of Contract documents for Highway Works, 2008). Monitoring was by surface profile heights measured using a laser, mounted on SCRIM, from which sensor-measured texture depth (SMTD) is derived. This is the standard measurement used to monitor in-service trunk roads in the UK. The methods of measuring texture used in this work are explained in more detail in Appendix A.

Locked-wheel sliding wet friction

This was measured at various speeds using the pavement friction tester (PFT). The PFT uses an in-line wheel with a smooth tyre to measure wet friction at the same speed as that at which the test wheel is travelling. The test wheel brake is applied sharply until the wheel locks and it is held in this condition for a few seconds before the brake is released. The vertical and horizontal forces acting on the wheel are recorded every 0.01s throughout the brake cycle from which values representing the average sliding friction are determined.

Tests were made at a number of speeds ranging from 20 to 120 km/h, allowing the low- and high-speed friction behaviours of the different surfacings to be compared, a facility not available with the routine SCRIM method.

The PFT results are from individual skids which, because they are time-based, sample different lengths of the road surface depending on the test speed. For example, at 20 km/h the sampling length during the locked phase of the skid only lasts for about five metres whereas at 120 km/h the full skid cycle requires about 90 metres, of which the locked phase sample length is about 33 metres. Depending on the test speed, therefore replicate measurements were made along each test section to provide adequate sampling of the test surfaces.

In addition to the monitoring with test vehicles, visual inspection visits were made at least annually throughout the programme. Figure 3.3 shows SCRIM and the PFT making slow-speed measurements with a police escort vehicle in Lane 1 on the A14 (Site 6a).
3.3 Timing of test programme

The skid resistance of a road is dominated by two broad properties of the surfacing: the microtexture on the surface of the aggregate particles and the macrotexture formed by the shape and spaces between those particles. Theoretically, microtexture provides the underpinning frictional properties of the road while macrotexture influences the way in which skid resistance varies with speed. Both of these characteristics change with time.

However, when an asphalt surfacing is first laid, the coarse aggregate particles that will eventually provide the running surfaces are covered in a film of bitumen binder which masks the microtexture. Thus, for a time the skid resistance of the new surface is dominated by the properties of the bitumen and any fine-aggregate particles embedded in it rather than the aggregate itself. Gradually, the bitumen is worn off or weathers away from the upper surfaces to expose the coarse aggregate.

Once exposed, the aggregate is polished by traffic until an equilibrium skid resistance level is reached, at which stage (in the UK and similar climates) skid resistance remains broadly constant but with lower values in summer and an increase during the winter.

Macrotexture can also change as a result of traffic action, for example by compaction of the surface, in combination with natural weathering. The extent to which macrotexture changes varies with different types of surfacing, which can exhibit different wear mechanisms.

It was recognised at the outset that, where small differences in performance might prove important, it would be necessary to monitor both characteristics for some time, at least until it was certain that equilibrium skid resistance had been reached. How long that would take was unpredictable, being influenced by various factors including the time of year at which a surfacing is laid, traffic levels and weather conditions, as well as the quantity and nature of the bitumen binder on the surface. For some surfacings under heavy traffic it may be reached within a year whereas, for more lightly-trafficked surfacings it may take longer; it has been generally observed that at least three full summers of polishing are needed to provide confidence of the equilibrium level.

Accordingly, the monitoring programme was arranged so that the condition of the trial surfacings was measured at intervals from soon after they had been laid until they had

Figure 3.3 SCRRM and the PFT making measurements in convoy with police escort on site 6a in August 2008
been trafficked for at least three summers. Generally, skid resistance was measured at least twice during the summer period with occasional visits during the autumn or winter depending on developing circumstances at individual sites. The data from these visits provided a record of the evolution of the skid resistance and texture depth over time. However, there were some exceptions when weather conditions meant that the road surface was wet and valid texture data could not be obtained.

Measurements of locked-wheel friction with the PFT were less frequent since these tests were primarily to assess the friction/speed characteristics rather than the progress of traffic action. They were made at least once during each summer, generally, coinciding with SCRIM measurements.

Figure 3.4 shows the timeline for the laying of the sites and monitoring visits that were achieved at the various locations. At some of the locations where two sites were split between two lanes it was not always possible, for traffic management reasons, to make measurements in Lane 2. Monitoring on the first of the sites to be laid ceased in 2009 while monitoring on the last site to be laid was completed in the summer of 2010.
Figure 3.4 Timeline for trial sites showing service life and monitoring visits
4 Overview of the results of site monitoring

4.1 General principles used in the analysis

The following broad principles have been followed in analysing and summarising the data.

Low-speed skid resistance data from SCRIM

SCRIM records skid resistance at ten metre intervals and typically more than one pass was made over each test section on each visit. For analysis, the average SCRIM Coefficient at 50 km/h (SC) has been calculated for the whole length of each test section, applying a standard speed correction formula where necessary (this was seldom required) and averaging over repeated runs during the course of a visit. Boundary zones (the ten metres including, or either side of, the join between materials) have been ignored.

Sensor measured texture depth data

A similar approach to that used for the SC values has been followed for the measurements of average SMTD, although for these measurements speed adjustment is not needed.

For these tests, the measurement runs were made when the road was dry, i.e. before the road on the test line had been wetted by skid resistance measurements.

Data from the PFT

The locked-wheel friction as measured with the PFT is normally expressed as a Friction number (Fn). The Fn is determined from the average ratio of vertical load and horizontal drag recorded over a one-second interval after the test wheel has locked and been allowed to settle for half a second. Throughout this report, Fn is expressed as the average coefficient of friction multiplied by 100. A subscript is used where appropriate to indicate the test speed.

For each visit to each site the individual skids were plotted and a trend line was fitted to the data to give an average friction-speed curve with a quadratic function, as illustrated in Figure 4.1. The constants and coefficients of these curves were then used in the analysis to interpolate average friction values at selected speeds even though the actual test speeds may have differed. This is normal TRL practice for data of this type.\(^3\)

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\(^3\) For further background see TRL367 (Roe, Parry, & Viner, 1998)
In the remaining sections of this Chapter, the results of the various tests are summarised to provide an overview, covering the low-speed skid resistance behaviour of the surfacings as recorded with SCRFIM, the evolution of texture depth on the surfaces and the general high-speed skid resistance behaviour. A more detailed analysis of some specific aspects then follows in Chapter 5.

4.2 Low speed skid resistance

4.2.1 Polishing to equilibrium

All the sites showed the expected behaviour of gradually polishing to an equilibrium level of skid resistance. Initially, the surface was rich in bitumen and fines and this showed the high level of skid resistance typically found on such materials early in their lives. Discussion of the early-life behaviour is outside the scope of this report; data from these sites have been included in a detailed study of this topic, which will be reported elsewhere. Visual inspection showed that the aggregate took some time to become exposed in some locations, especially on the more lightly trafficked overtaking. This meant that, unlike traditional hot-rolled asphalt, on which weathering and traffic expose the chippings comparatively quickly, these thin surfacings were subject to a more gradual process of exposure and polishing, with some areas being polished while others were yet to be fully exposed to traffic action.

As might be expected, at those locations with sites in both lanes, different levels of equilibrium skid resistance were achieved with higher levels of skid resistance in Lane 2 compared with Lane 1.

The broadly typical process of polishing to equilibrium is illustrated by the results from Site 1a, Lane 1 on the A5 at Gibbet Hill, shown in Figure 4.2. The graph shows the average SC recorded at each visit with SCRFIM on the 0/6 mm, 0/10 mm and 0/14 mm sections that used Aggregate B.
This site was laid over the week between the end of November and the beginning of December 2005 and it can be seen that skid resistance starts high and gradually decreases until, by the summer of 2007, equilibrium had been reached. The seasonal increase recorded during a visit in October 2008 can also be observed. All three surfacings exhibit similar characteristics in terms of the polishing process, although it can also be seen that the materials appear to be ranked with skid resistance decreasing with increasing particle size.

Although not shown in Figure 4.2, the “control” section on this site, which was a 0/14 mm material using aggregate H with a nominal PSV of 68 gave SC levels that were similar to or slightly higher than the 0/6 mm with Aggregate B at a nominal PSV of 65.

Figure 4.3 shows an equivalent graph, on the same time scale, for Site 6a, Lane 1. This site was laid during the second half of the summer of 2007 and the first measurement on the graph was made the following spring, by which time the process of aggregate exposure would have been under way. In this case, skid resistance decreases, with some seasonal variation superimposed, with equilibrium being reached by the summer of 2009. At this location a lower PSV aggregate was used and traffic was heavier, so it is not surprising to observe that the average skid resistance is lower in 2009/10 at this site than was the case on Site 1a.
Similar effects were seen at the other sites, with variations in the time taken to reach equilibrium consistent with the effects of the different times of year at which they were laid and the different levels of traffic to which they were subjected.

4.2.2  Equilibrium skid resistance levels

Figure 4.4 summarises the equilibrium skid resistance on all eleven sites. The equilibrium level for each surfacing was calculated by taking the average of all summer measurements over the period after equilibrium had been reached. For the data in Figure 4.2 for example, this would include all measurements from the summers of 2007, 2008 and 2009 but exclude the example of the early autumn seasonal increase in 2008.

The bar chart is arranged with the sites in location order and within each site the colour-coded bars show the equilibrium SC for the different aggregate sizes. Throughout this report, the same colour coding – blue for 0/6 mm, dark red for 0/10 mm and green for 0/14 mm – has been used to distinguish between the sizes in the various graphs. Sites 2a and 2b did not include any 0/6 mm material, hence the missing blue bars in those cases. In the interests of clarity, some of the different aggregates or sizes on sites 1a/b and 4a/b have not been included here.

Figure 4.3 Development of low-speed skid resistance on Site 6a
A number of general observations may be made from these results:

(i) All sites, including that with the lowest PSV and heaviest traffic (6a) gave equilibrium SC values over 0.45, which is well above the investigatory level for these sites (all would typically be set at 0.35 as dual carriageway non-event sections). However, this does not necessarily mean that such good performance would be achieved in all cases were they in areas with greater braking or cornering stresses.

(ii) The equilibrium skid resistance level varies from site to site for all aggregate sizes, as might be expected given the different combinations of PSV and traffic.

(iii) At locations where the same aggregate has been used in two lanes (i.e. different traffic levels) – 1a/b, 2a/b, 5a/b and 6a/b, the Lane 2 results (b) tend to be higher than those in Lane 1.

(iv) In general, the 0/6mm material gives the highest skid resistance.

(v) The difference between the sizes with the same aggregate is less marked on the more lightly-trafficked sites: compare 1a with 1b, 2a with 2b, 4a with 4b (0/10 and 0/14) and 6a with 6b.

(vi) Sites 1a and 3, which use essentially identical materials but with respectively increasing traffic levels, show very similar relationships between the sizes but lower SC levels on the more-heavily trafficked Site 3.
4.3 Development of texture depth

When the surfacings were laid, the suppliers attempted to achieve the minimum initial texture depth required and were generally successful. However, in some cases, especially with the smaller aggregate sizes, it was not possible to achieve this. At Location 2, the supplier was not satisfied with the texture achieved and removed their 0/6 mm material.

The development of the texture depth on the trial surfacings is summarised in Table 4.1 which includes as-laid MTD values reported by the suppliers, SMTD measured by TRL in this programme very soon after laying and during the “settling period” of about four to eight months (where available), together with an average equilibrium SMTD determined in a manner analogous to the equilibrium SC discussed in Section 4.2.2. The equilibrium values are also presented graphically in Figure 4.5.

There were some decreases in texture depth on the test sections but they quickly settled to a generally uniform level. However, for the analysis of the high-speed skid resistance performance which is a major focus of this report, the important aspect of the macrotexture to consider is the texture depth at equilibrium.

It can be seen from Figure 4.5 that the equilibrium SMTD increases with increasing aggregate size and that at those locations where both lanes were used, the less-heavily trafficked Lane 2 sections retained higher texture levels than in Lane 1. Most noticeable are the very low SMTD values (approximately 0.4 mm) on both the 0/6 mm and 0/10 mm surfaces on Sites 5a and 5b. It was observed that the Urbanpave (0/6 mm) and Superflex (0/10 mm) branded materials on these sites appeared to be much more continuously graded and with a visually smoother texture than any of their Axophone/Axoflex or Masterflex/Masterpave counterparts on the other sites.

It was noticeable that on the 0/10 mm Superflex, although there was a reasonable proportion of aggregate exposed at the surface, the coarser particles did not dominate the running surface in the same way as could be seen on the other materials. This point is illustrated in Figure 4.6 which compares close-up photographs of examples of each of the three main 0/10 mm material types. The images were all taken in August 2008 when all three surfacings were in their third summer after laying, the running surfaces were essentially clear of bitumen and the aggregate had polished to close to its equilibrium level.
Table 4.1 Summary of texture depth measurements on the trial sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Size</th>
<th>Texture depth</th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>MTD as laid*</td>
<td>SMTD as laid</td>
<td>SMTD at 4-8 months</td>
<td>SMTD at equilibrium SC</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1a</td>
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<td>1.1</td>
<td>0.8</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
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<td>1.1</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>0/14 mm</td>
<td>1.7</td>
<td>1.3</td>
<td>1.2</td>
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<tr>
<td>1b</td>
<td>0/6 mm</td>
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<td>-</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>0/10 mm</td>
<td>1.5</td>
<td>-</td>
<td>1.3</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>0/14 mm</td>
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<td>-</td>
<td>1.5</td>
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<tr>
<td></td>
<td>0/10 mm</td>
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<td>1.2</td>
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<tr>
<td></td>
<td>0/14 mm</td>
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<td>1.5</td>
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<td>-</td>
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<td></td>
<td>0/10 mm</td>
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<td>-</td>
<td>0.7</td>
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</tr>
<tr>
<td></td>
<td>0/14 mm</td>
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<td>-</td>
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</tr>
<tr>
<td></td>
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<tr>
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<td>-</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
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<td>-</td>
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</tr>
<tr>
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<td>-</td>
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<td>0.7</td>
</tr>
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<tr>
<td></td>
<td>0/14 mm</td>
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<td>-</td>
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<td>0.8</td>
</tr>
<tr>
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<td>-</td>
<td>0.7</td>
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<tr>
<td></td>
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<td>-</td>
<td>1.4</td>
<td>0.4</td>
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<tr>
<td></td>
<td>0/14 mm</td>
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<td>-</td>
<td>1.2</td>
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<td>-</td>
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<tr>
<td></td>
<td>0/10 mm</td>
<td>1.9</td>
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<td>1.2</td>
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</tr>
<tr>
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<td>0/14 mm</td>
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<td>-</td>
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<td>1.2</td>
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<tr>
<td>6b</td>
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<td>1.2</td>
<td>-</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>0/10 mm</td>
<td>1.9</td>
<td>-</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>0/14 mm</td>
<td>1.9</td>
<td>-</td>
<td>1.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

*Initial MTD volumetric patch test data as provided by surfacing suppliers
†This measurement was made 2 months after laying
Figure 4.5 Texture depth (SMTD) on all the trial sites at equilibrium

Figure 4.6 Visual comparison of macrotexture on three 0/10 mm materials
The left-hand image is from Site 5b showing the dense Superflex (average SMTD = 0.4 mm), the central image is from Site 4a (Masterpave, average SMTD = 0.7 mm) and the right-hand image is from Site 3 (Axoflex, average SMTD = 1.0 mm). Image scaling is approximate.
4.4 High speed skid resistance behaviour

A major objective of this study is to assess the skid resistance performance of the materials across the speed range, especially for the sections with smaller aggregate sizes and lower texture depth. For any wet surfacing it is usual to observe a decrease in Fn with increasing speed, the curve typically following a quadratic form for most types of surfacing as explained in Section 4.1. All the surfacings in this study showed this characteristic behaviour.

To provide an overview of the comparative behaviour of the various trial surfacings, Fn values calculated from the friction/speed curves for each section over the equilibrium period were used to determine average values of Fn at 20 and 100 km/h at equilibrium. The results of this exercise are shown in Figure 4.7 and Figure 4.8 in a similar way to that used for the SCRIM and texture depth results.

The following general observations may be made here:

(i) Comparing Figure 4.7 with Figure 4.8, a marked overall reduction in friction at 100 km/h compared with 20 km/h can clearly be seen.

(ii) The 20 km/h data (Figure 4.7) show a trend for Fn values to decrease with increasing aggregate size similar to that observed with SCRIM (Figure 4.4). This was expected since the slip-speeds of the two measurement techniques are similar.

(iii) At 100 km/h (Figure 4.8), the 0/6 mm materials show greater friction levels than the larger sizes.

(iv) On Sites 2b, 4a, 5a and 5b, the trend for the 0/10 mm materials to have Fn levels similar to or greater than their 0/14 mm equivalents that is observed at 20 km/h is reversed at 100 km/h: the 0/10 mm materials on these sites have noticeably lower high-speed friction than the 0/14 mm. This behaviour may also be related to the differences in texture depth forms illustrated in Figure 4.6.
Figure 4.7 Equilibrium Fn at 20 km/h on all the trial sites

Figure 4.8 Equilibrium Fn at 100 km/h on all the trial sites
5 Further analysis of trial site data

5.1 Introductory comments

The overview in Chapter 4 has shown that, generally, low-speed skid resistance is greater for the smaller aggregate sizes and that at high speeds the 0/6 mm materials also have higher friction than the larger sizes but some of the 0/10 mm materials performed less well than their 0/14mm equivalents.

Some further questions also arise in consequence:

- What are the implications of the greater low-speed skid resistance in relation to the PSV of the aggregate used and the traffic on the sites?
- Is the high-speed behaviour consistent with what would be expected from the texture depth of the surfacings?
- What are the practical implications of the observations?

This chapter of the report describes some further analysis which, together with the laboratory work described in Chapter 6, is directed at arriving at answers to these questions in order to assist in deciding how the findings should be applied practically.

5.2 Low-speed skid resistance, PSV and traffic

It is clearly of interest to consider how the low-speed skid resistance performance of the thin surfacings on the trials sites fits in with the general behaviour expected given the levels of PSV and traffic. As Figure 4.4 shows, for each individual aggregate there was generally a difference in skid resistance between the aggregate sizes, with the 0/6 mm materials delivering higher skid resistance than the 0/10 mm and 0/14 mm materials under the same traffic in almost every case.

However, the differences in low-speed performance for the different aggregate sizes are generally small in comparison with overall equilibrium skid resistance level. For this reason, practically there is little advantage to choosing smaller sizes purely on the basis of low-speed skid resistance behaviour.

There are indications within the data that different traffic levels and PSV have some influence on skid resistance; to assess this further, the results from each aggregate source were represented graphically in the style of a box plot. This allows them to be compared with one another for the different broad levels of traffic and their nominal PSVs. The resulting graphic is shown in Figure 5.1, which indicates the combined range of equilibrium SC and mean level for all the test sections with each aggregate, broken down by general traffic level on each site.

While there is some indication that heavier traffic leads to the expected lower equilibrium skid resistance (Aggregates B, C, A and H), the aggregate with the lowest nominal PSV (Aggregate F) does not demonstrate this. Similarly, there is some indication that, for light traffic, increased PSV gives increased equilibrium SC (Aggregates F, C, B and H) but again there are exceptions. Indeed, there is a considerable range of results and overlap between the various conditions.

Of particular note is the range of results from Aggregate F which shows no difference between the traffic levels on average. With a nominal PSV of 53, this is an aggregate that, under normal circumstances, would not be considered for use under such heavy traffic as in Lane 1 on the A14. Nevertheless, in this particular situation, it is delivering average skid resistance two bands higher than the required 0.35.

However, it must be pointed out that this is a limited set of data and that all the sites were “easy” locations, with free-rolling traffic and without repeated additional stresses from braking or cornering that could lead to greater variations in performance. The
results cannot necessarily be extrapolated to high-stress locations. Indeed, a greater range of skid resistance might be expected at high-stress locations, with the higher PSV aggregates (Aggregates A and G for example) performing relatively better than can be seen here.

<table>
<thead>
<tr>
<th>Agg'te Ref.</th>
<th>Nom. PSV</th>
<th>Traffic</th>
<th>Equilibrium SCRIM Coefficient (x100) Shaded areas indicate ranges over all sections and sizes; spot points represent mean values</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 53</td>
<td>Heavy</td>
<td>Medium</td>
<td>Light</td>
</tr>
<tr>
<td>E 55</td>
<td>Heavy</td>
<td>Medium</td>
<td>Light</td>
</tr>
<tr>
<td>C 60</td>
<td>Heavy</td>
<td>Medium</td>
<td>Light</td>
</tr>
<tr>
<td>D 60</td>
<td>Heavy</td>
<td>Medium</td>
<td>Light</td>
</tr>
<tr>
<td>B 65</td>
<td>Heavy</td>
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</tr>
<tr>
<td>A 66</td>
<td>Heavy</td>
<td>Medium</td>
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</tr>
<tr>
<td>G 66</td>
<td>Heavy</td>
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<td>Light</td>
</tr>
<tr>
<td>H 68</td>
<td>Heavy</td>
<td>Medium</td>
<td>Light</td>
</tr>
</tbody>
</table>

Figure 5.1 Ranges of equilibrium low-speed skid resistance achieved by the different aggregates under different traffic conditions on the trial sites

5.3 The influence of texture depth on high-speed friction

The current approach to setting requirements for minimum texture depth on higher-speed roads, i.e. those with a speed limit ≥40 mph (65 km/h), has its roots in historic research in the 1960s and 1970s that observed that the loss of skid resistance (measured with a locked-wheel technique and a small-diameter smooth tyre) which always occurs with increasing speed was less for surfaces with greater texture depths. The minimum MTD requirement of 1.5 mm for surfacings such as hot-rolled asphalt was introduced based on that research, as a pragmatic compromise between the idea of limiting the reduction in skid resistance at higher speeds and what could be practically achieved.

The findings of the early work were largely reinforced and developed by the study reported in TRL367 (Roe, Parry and Viner, 1998), in which data were collected using the PFT on over 100 sites deliberately chosen to provide examples of a wide range of surfacing types, textures and low-speed skid resistance conditions. That work showed that at texture depths (measured as SMTD) above about 0.8 mm, increased texture depth did not improve high-speed performance but below this level there was a marked tendency for high-speed skid resistance to decrease as texture decreased.

It is of interest, therefore, to compare the results from the CP trial sites with the TRL367 work. To do this, the equilibrium values for locked-wheel friction at 20 and 100 km/h (expressed as Fn, friction coefficient x 100) from the various trial sections have been plotted over comparable data used in TRL367. Separate graphs for the 0/6 mm, 0/10 mm and 0/14 mm sizes are shown in Figure 5.2. In this case, no distinction has been made between the various surfacing types in the historic data (which did, however, include some early thin surfacings). Porous materials, for which texture measurements have only limited meaning (and which are expected to behave differently), and calcined bauxite high-friction surfacings have been omitted for clarity.
Figure 5.2 High and low-speed friction against texture depth (SMTD): comparison of trial site data with historic data from TRL367
In the graphs in Figure 5.2 it is apparent that, while the 0/10 mm and 0/14 mm materials broadly follow the pattern of the historic data, the 0/6 mm materials do not. They are all showing Fn levels markedly above what might have been expected for surfacings with similar levels of SMDT and on a par with higher-textured materials.

There is no obvious explanation for this uncharacteristic behaviour (which, from private discussions with colleagues from the Laboratoire Central des Ponts et Chaussées, has also been observed in France). Various mechanisms have been suggested and possibilities include:

- The SMTD (or any) texture measurement technique may not adequately characterise the road surface
- A higher proportion of aggregate in the tyre/road interface allows for greater grip
- Smaller-sized particles lead to a different pressure distribution in the contact patch, also affecting the way in which the tyre and road interact
- Different contact areas or pressure distributions affect the polishing mechanism and the equilibrium skid resistance developed.

It was to explore some of these ideas further that most of the laboratory work reported in the next chapter was carried out.
6 Laboratory studies

6.1 Scope of the laboratory work
Two cores were taken from each of the trial sections to investigate, through more detailed laboratory work, the results emerging from the skid resistance monitoring. The cores were taken in August 2010, by which time all of the surfacings had reached their equilibrium skid resistance condition.

This phase of the work involved three interlinked experiments:
- Friction measurements on the cores using the rotating, friction head of the Highways Agency's Wehner-Schulze test machine
- Texture measurements using volumetric patch and laser measurement techniques
- Tyre/road contact interface measurements.

6.2 Friction measurements
Friction measurements were made on the cores, using the Wehner-Schulze (W-S) machine\(^4\), to establish that they were representative of the sites from which they were extracted. In the W-S machine, friction is calculated from measurements of torque imparted to the test sample surface when a test head, comprising three separate rubber sliders and rotating at a pre-determined speed, is dropped onto the wetted surface and allowed to slide to a halt under its own mass. The friction reported is the value calculated when the test head has slowed to a tangential speed of 60 km/h.

During the 2004-7 CP, the W-S machine had been used to apply a controlled amount of polishing to, and then investigate the skid resistance of, coarse aggregate specimens made with 6 mm, 10 mm, 14 mm and 20 mm particles (Roe, Dunford, & Crabb, 2008). It was found then that the friction measured on the 6 mm coarse aggregate specimens was higher than on samples made with 10 mm, 14 mm or 20 mm particles, in agreement with the skid resistance measurements being observed on the trial sites now.

Figure 6.1 shows the relationship between W-S measured friction and skid resistance, as measured by SCRIM, on the trial sites from which the cores were extracted. W-S values (\(\mu_{\text{wps60}}\)) are the average of both cores extracted from each site and site measurements are the SCRIM coefficient multiplied by 100. Results from friction measurements on the individual cores are shown in Appendix B. In order to compare W-S friction with locked wheel friction, a value for locked wheel friction at 60 km/h has been calculated, using the same method as before; this comparison is shown in Figure 6.2. For consistency with the August 2010 date of coring, the site skid resistance measurements used are the most recent available for each site.

\(^4\) The Wehner-Schulze machine is equipment developed in Germany as a possible alternative to the PSV test to provide a laboratory test procedure to assess polishing and skid resistance development. The machine operates on test specimens that are either asphalt cores or circular plates covered with aggregate particles, allowing either larger specimens of aggregate or samples of mixed asphalt to be studied. It comprises a rotating head with conical rubber rollers that are lowered on to the specimen to impart the polishing action. A separate rotating head with rubber sliders is used to measure wet friction on the test sample.
The correlation between the site and laboratory measurements confirms that the extracted cores are generally representative of the sites.

The graph in Figure 6.3 shows average measurements made on the cores with 0/6 mm, 0/10 mm and 0/14 mm coarse aggregate. Laboratory measurements of skid resistance on cores from the trial sites show the same trend for increasing skid resistance with reducing coarse aggregate size that was observed in the equilibrium SCRIM data for the more heavily trafficked sites (sites 1a, 2a, 3, 4a, 5a, 5b and 6a in Figure 4.4).
Although there is a generally good correlation between site and laboratory friction measurements, there are apparently anomalous results from the cores for one site which gave relatively high average W-S friction measurements compared with the locked wheel friction (Figure 6.2). The cores giving the anomalous results were taken from the 0/10 mm section on Site 5a on the A14 at Thrapston. Whether these particular cores were not representative of the section as a whole (the section was 500 m long so the cores could have been taken from a small area with different characteristics to those measured in the larger samples in the field tests) cannot be stated with any certainty but this is a possibility. Another possibility is that they were representative of the site but are showing an unexplained feature of the W-S test. It is difficult to comment further – the W-S machine and its operation are still the subject of ongoing research on behalf of Highways Agency.

### 6.3 Texture measurements

It has been seen that, although skid resistance did decrease with increasing speed, the 0/6 mm surfacings did not fit the established trend for a greater reduction on surfaces with less texture (Figure 5.2). This observation might be a result of poor characterisation of the available texture by the SMTD method so texture depth was measured on the cores removed from the trial sites using alternative measurement techniques.

There are several well-defined methods for characterisation of road surface macrotexture that are used, in different contexts, in the UK. Two of these have already been mentioned:

- SMTD, used for in-service monitoring
- MTD, widely used for contractual performance requirements.

A third measure is Mean Profile Depth (MPD), used mainly for noise characterisation; it is the CEN/ISO standard texture parameter. All are described in more detail in Appendix A.

If the volumetric patch measurement technique is used then texture depth is measured almost directly. The other, laser techniques rely on algorithms to calculate a value for texture depth from surface profile measurements. SMTD, for example, uses a root mean square (RMS) calculation to summarise the surface profile and it incorporates a...
methodology for removing the longer wavelengths associated with the shape of the pavement surface and a defined cut-off or inspection length (300 mm). A very important point to note is that, given identical road surfaces and even identical sets of height measurements, the reported value for macrotexture may be different depending on which characterisation principle is used.

For example, two surfaces can have the same SMTD or RMS value, but very different volumetric patch (MTD) measurements, as illustrated in Figure 6.4. This diagram, following an example given by McGhee and Flintsch (2003), shows an idealised surface in mirror image – both surfaces would have the same SMTD but the volume of granular material required to fill the spaces in the texture obviously differs. This explains the observation that empirical correlations can vary widely depending upon both the measurement technique and the form of the texture for a particular type of surfacing.

![Figure 6.4 Texture measurement by sand patch on idealised profiles with the same SMTD](image)

To investigate whether different techniques influenced the assessment of skid resistance performance, the texture was measured on each individual core using all three techniques (MTD, MPD and RMS). A circular texture meter (CTM), described in section A.4 of Appendix A, was used to measure profiles from which MPD and RMS values could be calculated. Detailed results of the different measurements on the individual cores are included in Appendix C.

The average RMS values from the CTM for each pair of cores were compared with the most recent SMTD measurements made on-site (Figure 6.5). As with the skid resistance measurements, a good relationship between the texture measurements made on the extracted cores and those on-site demonstrates that cores are representative of the site in this context.
Figure 6.5 Comparison of RMS texture measured on the extracted cores with SMTD measured on site

The graph in Figure 6.6 shows locked wheel friction measurements plotted against texture depth in a similar manner to the graphs in Figure 5.2 (without the background data from TRL367). In this case, the volumetric MTD measured on the extracted cores has been used instead of the in-situ SMTD measurements. It will be noted that, not only are all the texture values greater (one of the known characteristic differences between the two methods), the cloud of points representing the 0/6 mm coarse aggregate sections has been shifted further towards the greater-texture part of the scale relative to the other sizes.

Figure 6.6 High-speed friction against MTD
For comparison, the graphs in Figure 6.7 and Figure 6.8 show the equivalent information for the RMS and MPD texture measurements made on the extracted cores.

![Figure 6.7 High-speed friction against RMS texture from the CTM](image1)

![Figure 6.8 High-speed friction against MPD from the CTM](image2)

It is clear that none of the laser measurements (RMS, MPD of SMTD) explain the relatively good high speed skid resistance performance of 0/6 mm surfacings compared with the other sizes. This is true for the MPD algorithm even though this was designed to simulate the volumetric patch, and measurement by volumetric patch does indicate that there is more texture available on these small-aggregate surfacings. There may therefore be limitations in the laser measurement technique itself, rather than the algorithms used. For example, laser measurements are two-dimensional whereas volumetric patch measurements are clearly three-dimensional, and there may be an
incompatibility with the pavement geometry whereby laser light is not properly returned to the measurement sensor because of steep angles and narrow gaps in the shape of the pavement or because light is scattered on the surface.

However, notwithstanding the different indication from the alternative texture measurements, skid resistance (at all speeds) on the 0/6 mm surfacings is still higher than that on surfacings with larger coarse aggregates and the volumetric measurement does not fully explain this phenomenon. Furthermore, since volumetric patch testing cannot be performed as part of routine surveys on high speed roads, it will be necessary to further develop traffic-speed measurements that can adequately characterise these surfacings.

6.4 Tyre/road contact interface measurements

Consideration of the interface between the tyre and road surface is a first step in exploring the properties of the surface that might lead to the increased skid resistance observed. The third laboratory experiment, therefore explores alternative methods to characterise the tyre/road contact interface.

6.4.1 Tyre contact measurements

The differences in skid resistance measured between aggregate sizes may be related to the contact area and pressure between the tyre and the road surface. To investigate this, measurements of the contact area and the pressure within it were made using a pressure sensitive film system, “Prescale”, made by Fujifilm. The pressure film system was placed on top of each of the extracted cores and loaded with a smooth test tyre from the PFT using an Instron compaction device, as shown in Figure 6.9.

![Image of loading rig for contact pressure measurements](image)

**Figure 6.9 Loading rig for contact pressure measurements**

The film measures the pressure distribution and magnitude between two contacting surfaces. The version used in this work had two components: a transfer sheet and a developer sheet, each 0.1 mm thick, as illustrated in Figure 6.10. The transfer sheet contains a layer of tiny microcapsules and force applied to the film ruptures them and
produces an instantaneous, permanent, high-resolution map of pressure variations across the contact area on the developer sheet. The colour intensity of the image directly relates to the amount of pressure applied.

![Cross sectional view showing the operating principle of Prescale](image)

**Figure 6.10 Cross sectional view showing the operating principle of Prescale**

The colour intensity of each point of contact can be compared to a colour correlation chart (Figure 6.11) to provide absolute measurements of pressure.

![Colour correlation chart used to quantify contact pressure](image)

**Figure 6.11 Colour correlation chart used to quantify contact pressure**

A limitation of the system is that the pressure film measures in a discreet range (0.2 MPa to 0.65 MPa for the film used in this case) but the highest pressures in the contact patch are outside this range. Film that measures a higher pressure range (0.5 MPa to 2.5 MPa, for example) is available but to capture the full range of pressures in the tyre/road contact patch it would be necessary either to layer the film (which would reduce the ability of the film to conform to the surface texture) or to make repeat measurements with the different films to build up an image (with consequent problems of alignment). It was decided, therefore, that measurements would be confined to the lower range for this exploratory exercise, capturing the area of contact at the expense of underestimating the maximum pressures experienced.

The pressure images were digitally scanned and the pressure distribution was then analysed using the software supplied as part of the pressure film measurement system. Examples of the imprints obtained are shown in Figure 6.12 for pressure applied to cores extracted from Site 1a. The images in Figure 6.13 show resulting pressure film patterns from the same extracted cores after colour intensity has been converted to pressure measurements. It can be seen that the maximum pressure measured is 0.65 MPa.
Figure 6.12 Pressure film imprints on cores from Site 1a: 0/6 mm, 0/10 mm and 0/14 mm (top to bottom), not to scale
Figure 6.13 Pressure distributions derived from film imprints in Figure 6.12
A simple function of the pressure film software is to calculate the total amount of contact area. Figure 6.14 shows the average contact area for cores extracted from the site using each coarse aggregate size. It can be seen that the increase in contact area on 0/6 mm cores, relative to contact area on 0/10 mm and 0/14 mm cores, is in line with the trend seen for skid resistance measurements. Furthermore, if locked-wheel friction (from site measurements) is plotted against pressed area rather than against a texture measurement, then the points representing 0/6 mm surfaces are shifted further to the right and become part of the overall distribution, as in Figure 6.15. There are two apparently outlying points for cores taken from two 0/10 mm sites; one is from Site 5b on the A14 at Thrapston and the other is from Site 2a on the A5 at Tamworth. Although the material at Site 5b is known to be particularly dense, which may lead to increased contact, there is no similar explanation for Site 2a. Contact area measurements for all cores can be found in Appendix C.

![Figure 6.14 Contact area against coarse aggregate size](image-url)
6.4.2 Alternative characterisation of surface texture from laser measurements

For the texture and contact measurements discussed above it is the volumetric patch measurements and contact area measurements that begin to explain the increase in low speed skid resistance available, and the lack of reduction in skid resistance with speed, on 0/6 mm thin surfacings. However, since neither of these measurements can be made at traffic speed it may be worth investigating the potential for use of surface profile measurements (which can be made at traffic speed) to estimate these metrics. In fact, the mean profile depth (MPD) algorithm is already intended to estimate MTD, but this has shown limited improvement over STMD in this context (Figure 6.8). To explore the possibility of making a crude estimate for contact area, profiles from the CTM were analysed to identify and count peaks. The profiles were corrected for the slope of the core surface by subtraction of a polynomial best-fit curve from the raw data, and a peak was defined as any measurement higher than the preceding and succeeding two measurements.

Figure 6.16 illustrates this analysis for the site 1a cores. Connecting lines are included to highlight the shape of the texture and the peaks identified are highlighted by open red circles in the graphs.

This treatment was applied to all the extracted cores (the number of peaks identified is included in Appendix C), and the locked-wheel friction at 100 km/h measured on the trial sites was plotted against the average number of peaks for each core pair in Figure 6.17.
Figure 6.16 CTM profile measurements on cores from Site 1a
Counting the number of peaks in the two dimensional profiles is a fairly crude way to estimate the amount of contact that is likely to occur between the surface and a tyre. However, as can be seen in Figure 6.17, use of this measurement in place of texture depth for comparison against lock-wheel friction results in the cloud of points representing the 0/6 mm coarse aggregate sections to shift to the right. The correlation is not strong but there is a weak relationship between locked-wheel friction and the number of peaks in surface profile measurements. The dataset is limited of course by the small area of surface sampled by surface profile measurements compared with the area of surface represented by the friction measurements, which have been calculated using a large number of individual tests.

A more realistic estimate of contact area may be achieved if three-dimensional surface profiles could be obtained with sufficient accuracy; these could be used to derive parameters that might better relate to skid resistance. Towards the end of the programme, an experimental laser scanning system was used that makes a measurement every 1 mm transversely over a width of 100 mm and approximately every 5 mm along the road. This device was used in an exploratory manner to obtain three-dimensional profile measurements on four new, untrafficked, surfacings: 0/6 mm, 0/10 mm and 0/14 mm thin surfacings (Axophone and Axoflex) and HRA.

The images in Figure 6.18 show profile height measurements made on 100 mm x 100 mm areas of these surfaces. The images appear to have a directional characteristic but this is because the measurement technique provided less resolution along the road than across it. Although it is beyond the scope of the current research, it may be possible to use information like this to better model the contact between a tyre and the surface.
Figure 6.18 3D profiles of the texture on four new surfaces

0/6 mm Axophone

0/10 mm Axoflex

0/14 mm Axoflex

HRA with 20 mm pre-coated chippings
7 Application of results

As explained in the Introduction to this report, one of the main drivers of this research was to find out how thin surfacings actually behave in terms of their skid resistance so that specifications could be improved. There was some indication that thin surfacings might deliver greater skid resistance for the same PSV of aggregate than more traditional materials had been capable of doing. Also, it had been found that requiring the high levels of initial texture depth derived from research on older types of surfacing may sometimes lead to problems with durability.

In this chapter, therefore, the practical implications of the results of this research are discussed, together with suggestions as to how they might be applied to enable the findings to be utilised. For convenience the discussion is divided into three parts: low-speed skid resistance, high-speed skid resistance and longer-term developments.

7.1 Low speed skid resistance

On the UK trunk road network and on many Local Authority roads, the delivery of adequate low-speed skid resistance is managed in two ways:

- Each section of road is assigned an Investigatory Level (IL) of in-service skid resistance, based on accident risk, which is routinely monitored
- Specifications for new surfacing materials are set that are intended to ensure that, in the majority of cases, skid resistance above the IL is achieved and maintained for the life of the surfacing.

This is achieved in HD36/06 (Design Manual for Roads and Bridges, 2006) using a table that indicates the minimum PSV required for different types of site, different ILs and the level of heavy traffic expected to be using the road surfacing at the end of its design life (for ease of reference this table is reproduced in Appendix D).

The current requirements are based on research in the 1990s (Roe and Hartshorne, 1998) and the concept behind the Table is that surfacings should deliver in-service skid resistance at least one band higher than that required by the IL. In other words, if the IL for CSC is 0.35, the surfacing should generally deliver at least 0.40. This provides a safety margin that allows equilibrium skid resistance in specific site circumstances to fall below the expected level without the need for resurfacing. This has been found to be effective in practice, with very few sections of the trunk road network now requiring maintenance to improve skid resistance alone.

This research has provided evidence that, for low-risk sites with free-rolling traffic, negatively textured thin surface course systems are able to deliver equilibrium skid resistance of at least 0.45 (two bands above the IL) even with a nominal PSV as low as 53 and traffic levels over 4000 CVD. Clearly, there is scope for relaxation of the requirements in these situations for these types of surfacings. Such locations comprise the bulk of the trunk road network, so this should deliver both economic savings from allowing wider use of lower-PSV aggregates and sustainability advantages by concentrating the use of the increasingly scarce resource of the highest-PSV aggregates on areas of road where they are most needed.

The current boundaries between PSV levels were set in 5-unit bands chosen primarily for numeric convenience (see Appendix D). Although it is not a direct outcome of the present research, it has been noted that, in practice, the geology of the UK means that aggregates typically fall into slightly different categories and these could also be adjusted for the low-risk sites, again giving greater flexibility in sourcing appropriate aggregates, without loss of practical performance in service.

It is therefore recommended that a new PSV Table should be introduced into HD36 for hot mixed, negatively textured, thin surfacings, with revised PSV requirements for low-risk site categories, A1, B1 and C, using the following principles:
A minimum level of 50 should be retained but above this, to better reflect geology, the background PSV boundaries should be altered to 53, 58, 63 and 68.

Subject to an underpinning minimum of 50, for traffic below 5000 CVD the minimum PSV requirement should be reduced by 7 units; thus 50 remains unchanged, 55 becomes 50, 60 becomes 53, 65 becomes 58.

Above 5000 CVD the minimum PSV requirement should be reduced to the next lowest PSV boundary (e.g. 65 becomes 63), except that 68 remains unchanged.

There is no evidence from this research regarding the relative performance of aggregates used in HRA or surface dressing; current standards for these materials should be retained.

7.2 High speed skid resistance

Although there is currently no policy defining levels of in-service high-speed skid resistance for UK roads, the importance of limiting the reduction of friction with increasing speed is recognised and texture depth is currently used as a surrogate for measurement of high speed skid resistance. As explained in Section 4.3, minimum levels of texture depth are specified for new surfacings on high-speed roads and the property is monitored so that it can be taken into account together with low-speed skid resistance during site investigations.

Evidence from the trial sites does not affect validity of this solution for 0/10 mm and 0/14 mm thin surfacings which generally behave similarly to traditional materials. For 0/6 mm thin surfacings, however, measurement of texture depth does not characterise high speed skid resistance performance. High speed skid resistance has been maintained sufficiently well on the trial surfacings throughout trials even though the texture depth in service is often lower than would be regarded as acceptable for materials using larger aggregates.

Given the excellent performance of the 0/6 mm materials in the trials, a specification is needed that will allow their use on high-speed roads but that includes controls to provide confidence that the performance of future materials will be consistent with those in this trial. A reduced texture depth requirement could be introduced for 0/6 mm thin surfacings. However, an alternative control mechanism is needed since it would not be sufficient to assume that asphalt with 6 mm coarse aggregate will always have a form similar to the surfacings in the trials and should perform as expected. In fact, as Figure 7.1 illustrates, 0/6 mm materials can have varying appearance and low textures.

The current standard for thin surface course systems does not distinguish between particle sizes but sets a common minimum texture depth requirement for all materials with an upper aggregate size of 14mm or less at an average MTD not less than 1.3 when laid with a minimum for individual 50 m lengths of 1.0 mm.
Figure 7.1 Visual comparison of macrotexture on three 0/6 mm materials
The left-hand image is from Site 5a showing the Urbanpave (average SMTD = 0.4). The central image is from Site 4a (Masterflex, average SMTD=0.6) and the right-hand image is from Site 3 (Axophone, average SMTD= 0.6). Image scaling is approximate

It is proposed that the following principles should apply to specifying thin surfacings for high-speed roads in future:

- For materials with an upper aggregate size of 14 mm, the texture depth (MTD) should be not less than 1.3 mm initially and not less than 1.0 mm after two years in service (this is the same as the current requirement)
- For materials with an upper aggregate size of 10 mm, the texture depth (MTD) should be not less than 1.1 mm initially and not less than 0.8 mm after two years in service
- For materials with an upper aggregate size of 6 mm, the texture depth (MTD) should be not less than 1.0 mm initially and not less than 0.7 mm after two years in service.
- Where 0/6 mm materials are to be used on high-speed roads a supplement to current HAPAS (highway authority product approval scheme) certificates will be required that provides evidence from a type approval installation trial (TAIT) to verify adequate high-speed friction performance.

The inclusion of a minimum texture requirement for 0/6 mm materials is proposed in order to constrain manufacturers to use clean and angular particles in their asphalt designs so that the surfacings should have characteristics similar to those in the CP trials.

The suggestion for a TAIT to verify high-speed friction behaviour would, as with current HAPAS certificates, initially be a generic approach showing that a general design is acceptable rather than a requirement for a two-year duration TAIT for every variant of aggregate that might be used.

For this purpose, measurements with the PFT at 100 km/h would need to show that the surfacing provides Fn > 30 This level is suggested on the basis that it maintains the current status quo regarding high-speed friction generally provided by current surfacings that are regarded as acceptable. Use of 0/6 mm materials should be subject to accurate recording of their location so that routine in-service measurements of low texture depth (SMTD) on these materials can be recognised without causing further investigation.
Section 4.4(iv), commented on the relatively lower equilibrium $F_{n_{100}}$ measured on some of the 0/10 mm materials in the trial. It is of interest to note that, assuming that the results are representative of those surfacings as a whole, the MTD values measured on the cores extracted from those surfacings (Appendix C) were all below the two-year texture depth requirement proposed above.

A further point to consider is that providing too-high a texture depth on these materials has the potential to lead to problems with durability. The indications, both from historic research and the current programme, are that increasing texture depth beyond a certain level brings no benefit in terms of high-speed skid resistance performance. There is therefore an argument for considering the introduction of a maximum texture requirement for thin surfacings to help maintain or improve durability without compromising on safety.
8 Future developments

8.1 Moving beyond the limitations of the current research

The research reported here has provided a significant improvement in knowledge of the skid resistance performance of thin surfacings. This has, in turn, provided a sound basis for proposing pragmatic improvements to UK standards that can be expected to deliver both economic and sustainability benefits without compromising safety standards.

However, while these proposed changes are important and will have an impact on much of the trunk road network, the current research has been confined to low-stress locations and a small number of aggregate sources. The performance on more difficult sites such as bends and approaches to roundabouts and other hazards has not been studied.

The issue of high-speed skid resistance has formed an important part of this study. Currently, specifications still rely on using texture depth as a surrogate for setting and monitoring standards for high-speed friction. As has been seen, while different behaviours of different materials have been observed in empirical tests, it is not currently possible to explain satisfactorily why this should be so or to take advantage of any particular property in developing new surfacing designs.

Current proposals maintain a status quo that has been in existence for several decades even though traffic and vehicle characteristics have changed. For progress to be made in this area, developments are needed both to measurement techniques and to the way in which standards for skid resistance, especially at high speeds, are established and monitored.

In the following sub-chapters some ideas for future development are outlined.

8.2 PSV requirements for high stress locations

The bulk of the current research was carried out using trial sites inserted into non-event sections of dual carriageways. As noted above, this means that implications from the results of skid resistance testing can only be applied to similar non-event sections on the trunk road network (i.e. site categories A1, B1 and C as defined in HD36/06). It may be possible to gain additional benefit from the apparently enhanced performance of thin surface course systems by extending the research to consider higher-stress locations. Furthermore, the trial sites used only a relatively small range of the aggregates available in the UK. While it is a low-risk assumption that these few aggregates are representative of all aggregate sources for use in non-event locations, the same may not be true for higher stress locations. Indeed, anecdotal evidence suggests that aggregates with the same PSV may perform identically except under conditions where sufficient additional stress is applied by traffic.

There are significant limitations for performing full scale trials at locations where the road geometry or layout cause vehicle manoeuvring. Major factors are the difficulty in achieving a consistent stress level for different trial materials and the impracticality of making skid resistance measurements with moving vehicles, especially at higher speeds or where there is a risk of conflicting movements. The feasibility of testing a large number of different aggregate types, each in its own trial section, is also questionable.

It may be possible to develop a methodology to carry out the required skid resistance testing in the laboratory, on cores extracted from road sites. This would remove the difficulties of testing on site, and it has already been shown that in terms of skid resistance (particularly that measured by SCGRIM) and texture depth, cores extracted from a site can be representative of the whole site. However, it would be necessary to demonstrate the fidelity of a laboratory-based test for high speed skid resistance as a surrogate for direct measurements at various speeds such as those made by the PFT.
In order to examine a wide range of aggregates or examples of different thin surface course systems under identical traffic conditions, it may be possible to employ a core insertion technique utilised in the past to compare polishing by traffic with polishing by laboratory device and further developed recently in research based on the Wehner-Schulze machine. The method involves simply removing cores (225 mm in diameter to fit the Wehner-Schulze machine) from the surface course in the nearside wheelpath of a trial site and replacing them with asphalt specimens of the same size made in the laboratory, using an epoxy resin material to secure the replacement in place. The inserted cores could then be removed after a period of trafficking. Some care would be needed for use of this technique on corners where introduction of a discontinuity in the surface may be problematic for vehicles, and especially for motorcycles. However, the use of lower risk, but still high-stress, locations such as at ramp metering on slip roads\(^5\) could be considered.

High stress sites are only a small proportion of the trunk road network as a whole but they are particularly important in relation to managing skidding accident risk and greater flexibility in specifying surfacings in these locations could be of considerable value. Research of this type may be particularly useful for Local Authority road operators whose networks have a larger proportion of roads with such sites.

### 8.3 Texture characteristics

The present work has shown that, while texture characteristics are clearly important, current measurement techniques limit what can be inferred about skid resistance performance. The classical theory that texture depth is important for mitigation of the loss of skid resistance at higher speeds because of the surfacing’s ability to remove water from the interface between the tyre and road may only provide a partial explanation of the interaction. This research has suggested that other properties such as the pressure and area of contact between the tyre and the road surface may be related to friction generation at different speeds.

Research looking towards better characterisation of road surface texture, sponsored by Highways Agency, is already under way and the work in the Collaborative Programme has demonstrated that consideration of tyre/road interaction should be a priority. Further development of three-dimensional measurements of surface texture could also be pursued with a view to providing a basis for parameters that can take additional factors such as contact area into account and also be measured at traffic speed. The contribution made by the “texture” provided by the tread on vehicle tyres might also need to be considered in this context.

### 8.4 Development of a high speed skid resistance policy

Current skid policy, including the changes proposed here, relies on equalisation of accident risk by direct measurement of low speed skid resistance and measurement of texture depth as some protection against reduction of skid resistance at speed. However, as has been discussed earlier, texture depth cannot necessarily be relied upon to characterise the friction/speed performance of some surfacings.

The proposed addition (Section 7.2) of direct measurement of high speed skid resistance, as part of the HAPAS approval for 6 mm materials, with a required locked wheel \(F_{n100}\) value of at least 30, is based on the assumption that current surfacings provide the required level of high speed skid resistance.

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\(^5\) These are sites where at certain times of day the volume of traffic attempting to join a motorway or dual carriageway can cause disruption to flow on the main line. This is managed by creating gaps in the traffic on the slip road using short-phase traffic signals. The approaches to these signals are therefore subjected to frequent braking stresses when the lights are in operation. The success of such a site, however, would depend on there being sufficient heavy traffic to make a marked difference in the stresses applied.
A move towards direct measurement of high speed skid resistance could both allow greater flexibility in the types of material used in the surface course and provide greater confidence in the management of this risk without reliance on a surrogate measurement.

However, to add such a component to skid resistance policy it would be necessary to develop a rationale for the specification of acceptable levels of high speed skid resistance at all locations on the trunk road network, as is in place in HD28/04 for management of low speed skid resistance. This might be achieved by pragmatic consideration of the demand for skid resistance at high speed by road users, rather than by analysis of high speed skid resistance found at locations where accidents are known to have occurred.

Locked wheel friction is known to be less than the peak friction available, occurring in the moments before a wheel stops rotating and starts to slide and it is the peak friction that anti-lock braking systems (ABS) are designed to exploit. In addition to measurement and specification of locked wheel friction, it will be necessary to explore the relationship between locked wheel and peak friction and their dependence on surface characteristics.

Importantly, in order for a high-speed skid resistance policy to be of any use, it must be possible to implement with minimum disruption to road users. In practice this would mean development of equipment that is capable of measuring skid resistance at high speed on a vehicle that can operate at speeds which do not require lane closures or other special traffic management arrangements.
9 Conclusions

Overall, the present study has yielded a new understanding of how thin surface course systems, including those utilising smaller aggregate sizes than would normally be used on high-speed roads, perform in terms of skid resistance in-service. The research has provided a sound foundation for revising specification requirements for those sites that represent a major proportion of the trunk road network giving greater flexibility in sourcing appropriate aggregates and further improvements in durability without loss of practical performance in service.

The study has been confined to hot mix, negatively textured, thin surfacings laid on sites with a low level of polishing stress (and also with a low skidding risk in relation to skid resistance Investigatory Level) but they have covered a wide range of traffic levels and aggregate PSV.

Two major conclusions have been drawn from the study:

- In low-stress situations, thin surfacings provide good low-speed skid resistance well above IL even with lower PSV than would currently be permitted.
- Thin surfacings with an upper aggregate size of 6 mm are able to provide adequate friction at high speeds even though their in-service texture depth may be relatively low when measured by conventional techniques.

As a result, it has been possible to make recommendations for changes to the requirements in HD36 in relation to minimum PSV levels and texture depth, specifically for negatively textured thin surfacings on sites with low traffic stress, that will allow a wider range of aggregates to be used in some circumstances, providing both economic and sustainability benefits. In summary, these are:

- For Site Categories A1, B1 and C, amend the background minimum PSV boundaries to 53, 58, 63 and 68 to more closely match the geology of sources available in the UK.
- For Site Categories A1, B1 and C, reduce the minimum PSV required for traffic levels below 5000 CVD by 7 units, with an underpinning minimum of 50.
- Revise the texture depth requirements for thin surface course systems as follows:
  - For materials with an upper aggregate size of 14 mm, the texture depth (MTD) should be not less than 1.3 mm initially and not less than 1.0 mm after two years in service (this is the same as the current requirement)
  - For materials with an upper aggregate size of 10 mm, the texture depth (MTD) should be not less than 1.1 mm initially and not less than 0.8 mm after two years in service
  - For materials with an upper aggregate size of 6 mm, the texture depth (MTD) should be not less than 1.0 mm initially and not less than 0.7 mm after two years in service
  - Where 0/6 mm materials are to be used on high-speed roads a supplement to current HAPAS (highway authority product approval scheme) certificates will be required that provides evidence from a type approval installation trial (TAIT) to verify adequate high-speed friction performance.

The laboratory studies have demonstrated that current techniques for assessing texture depth do not satisfactorily explain the skid resistance effects observed, especially on surfacings made with smaller aggregates. The programme did not study the performance of these materials in higher-stress locations. Proposals have therefore been included for:

- Extending the understanding of performance to the more difficult higher-stress conditions
• Finding better ways to measure and interpret texture and its influence on skid resistance across the speed range for different surfacing types
• Developing an approach to future skid resistance policy and in-service monitoring that will take high-speed skid resistance more directly into account than is currently possible.
10 Acknowledgements

The work described in this report was carried out in the Infrastructure Division of the Transport Research Laboratory. The authors are grateful to Helen Viner who carried out the technical review and auditing of this report and to Peter Sanders, Christopher Sadat-Shafaee and Derek Meachen who carried out laboratory and site work.

References


Appendix A  Texture depth measurement

A.1 Volumetric Patch method

The volumetric patch test allows the Mean Texture Depth (MTD) to be calculated using a simple test method, set out in BS EN 13036-1 (British Standards, 2010). A known volume of standardised glass beads is spread on the road surface such that it is distributed evenly to form a circular patch, using apparatus similar to that shown in Figure A.1. The diameter of the patch is measured a number of times around the circular patch and a simple formula (Equation A.1) relates the measurements made to the mean texture depth.

\[ \text{MTD} = \frac{V}{d} \]  

where \( V \) is the volume of granular material (sand or glass beads) poured onto the surface and \( d \) is the average diameter of the area covered by the material after it has been spread.

Figure A.1 Glass beads, measurement container and spreading tool for volumetric patch test

This is the technique used by the material suppliers to verify the texture depth on the newly-laid trial sections, making repeated measurements with a sequence of patches along and across the width of the traffic lane.

For the laboratory studies, each core insert was taken in turn and a single patch formed on its surface. The volume of glass beads used was 25,000 mm\(^3\) except on three of the cores whose texture depth was so low that the circle of spread beads was larger than the diameter of the core itself. On these cores, a volume of 12,500 mm\(^3\) was used.

A.2 Sensor-measured texture depth and RMS texture depth

This technique uses a pulsed laser sensor that measures the displacement between the sensor receiver and the road surface at frequent intervals along the road to generate a road surface profile. The algorithm used to summarise the data into a single average value to represent the texture depth is based on the concept of the root mean square (RMS) measure of the texture above and below a mean level.

To take account of larger-scale movement of the sensor on the test vehicle as it travels along the road, measurements are fitted to a quadratic function over a 300 mm length, the values then being aggregated to give an average value for a 10 m section of road. This was called Sensor Measured Texture Depth in order to distinguish it from the older patch method. SMTD is calculated using Equation A.2:

\[ \text{SMTD} = \sqrt{\frac{1}{n} \sum (z_i - \bar{z})^2} \]

Historically, fine-graded sand was used, giving rise to the colloquial name "sand patch" for this test.
where \( n \) is the number of measurements in a 300 mm length and is always forced to be odd, \( y \) is the height measurement measured by the laser and \( x \) is the nominal scaled distance between measurements ranging from \(-\frac{1}{2}(n-1)\) to \(\frac{1}{2}(n-1)\) over the 300 mm length.

This is the technique that has been used in the UK in research and in monitoring in-service roads since the 1980s.

Alternative algorithms for calculating texture depth using a similar principle (often smoothing the data over different lengths) produce measurements that are generically referred to as RMS texture depth.

Texture measurements made during the monitoring period along the trial sites were all made using the SMTD method, with a sensor fitted to the SCRIM. Laboratory measurements of RMS texture on individual cores taken from the trial sites were made with the circular texture meter (see below).

### A.3 Mean Profile Depth

Mean profile depth also uses a pulsed laser sensor to measure a surface profile, but the algorithm used is designed to be analogous to the volumetric method by estimating the average depth below the peaks in the profile along the narrow line followed by the sensor.

MPD measures the heights of the highest peaks above the mean level, using Equation A.3:

\[
\text{MPD} = \frac{y_1 + y_2}{2} \quad \text{A.3}
\]

where \( y_1 \) is the height of the highest peak in the first half of a 100 mm length of profile, and \( y_2 \) is the height of the highest peak in the second half of the 100 mm profile. Note that this method relies on either digital high-pass filtering over the continuous profile to remove wavelengths above 100 mm, or subtraction of a least squares fit from the continuous profile to remove the slope and offset.

### A.4 Circular Texture Meter

The Circular Texture Meter (CTM) is a static device to measure texture depth at a fixed location. It uses a laser displacement sensor mounted on an arm that scribes a circle of radius 90 mm. The laser sensor measures the distance to the surface at 1024 points around the circumference of its rotation and uses this to produce an accurate height profile of the pavement surface.

In addition to profile height measurements, the device also outputs values for the average texture of the surface using either of two calculation algorithms to derive RMS texture depth and/or MPD.

The CTM used in this study (owned by Highways Agency) is shown in Figure A.2. This is a variant of the standard commercial device designed specifically to measure within the confines of cores cut for use in the Wehner-Schulze machine: the measured circle coincides with the contact line of the friction test head in the W-S machine.

Measurements on the trial site cores were made by placing the CTM on a custom made table above a hole of diameter 225 mm. Each core was offered up to the hole in turn so that their surfaces were flush with the table top.
## Appendix B  Results of friction tests on extracted cores

Table B.1 Friction measurements made on extracted cores using W-S machine

<table>
<thead>
<tr>
<th>Site</th>
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### Appendix C  Results of texture and profile measurements on extracted cores

#### Table C.1 Texture measurements, pressed area (in mm$^2$) and profile peak counts from extracted cores

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<th>Site</th>
<th>Size (mm)</th>
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## Table D.1 Table 3.1 reproduced from HD36/06

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<tr>
<th>Site category</th>
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<th>IL</th>
<th>Traffic (cv/lane/day) at design life</th>
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<td>A1</td>
<td>Motorways where traffic is generally free-flowing on a relatively straight line</td>
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<td>A2</td>
<td>Motorways where some braking regularly occurs (eg. on 300m approach to an off-slip)</td>
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<td>50 50 50 50 50 50 60 60 60 60 65 65</td>
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<td>B1</td>
<td>Dual carriageways where traffic is generally free-flowing on a relatively straight line</td>
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<tr>
<td>B2</td>
<td>Dual carriageways where some braking regularly occurs (eg. on 300m approach to an off-slip)</td>
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<td>50 50 50 50 50 50 60 60 60 60 65 65</td>
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<td>C</td>
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</tr>
<tr>
<td>G1/G2</td>
<td>Gradients &gt;5% longer than 50m as per HD 28</td>
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<td>60 60 60 60 60 60 65 68+ 68+ 68+ 68+ 68+</td>
</tr>
<tr>
<td>K</td>
<td>Approaches to pedestrian crossings and other high risk situations</td>
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<td>65 65 65 68+ 68+ 68+ 68+ 68+ 68+ 68+ 68+ 68+</td>
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<tr>
<td>Q</td>
<td>Approaches to major and minor junctions on dual carriageways and single carriageways where frequent or sudden braking occurs but in a generally straight line</td>
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<td>60 65 65 68+ 68+ 68+ 68+ 68+ 68+ 68+ 68+ 68+</td>
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<tr>
<td>R</td>
<td>Roundabout circulation areas</td>
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<tr>
<td>S1/S2</td>
<td>Bends (radius &lt;500m) on all types of road, including motorway link roads, other hazards that require combined braking and cornering</td>
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<tr>
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<td>HFS HFS HFS HFS HFS HFS HFS HFS HFS HFS HFS HFS</td>
</tr>
</tbody>
</table>

Notes:
1. Site categories are grouped according to their general character and traffic behaviour. The Investigatory Levels (IL) for specific categories of site are defined in HD 28 (DMRB 7.3.1). The IL to be used here must be that which has been allocated to the specific site on which the material is to be laid, as determined by following the procedures in HD 28.
2. Motorway or dual carriageway slip roads may fit in a number of groups depending on their layout. For example, a free-flowing section close to the main line would be in Group 1 whereas the end of an off-slip approaching a give way line or the point at which a queue develops would be in Group 3. Some slip roads with gradients may be in Group 4. Use the most appropriate Group depending upon the Site Category from HD 28 that was used to determine the IL.
3. Where '68+' material is listed in this Table, none of the three most recent results from consecutive PSV tests relating to the aggregate to be supplied must fall below 68. See paragraph 3.21.
4. Throughout this Table, HFS means specialised high friction surfacing incorporating calcined bauxite aggregate and conforming to Clause 934 of the Specification (MCHW 1) will be required. Where HFS is required on the approaches to a hazard, the minimum treatment length must be 50m. This may be extended where queuing traffic or sightlines indicate that 50m may not be sufficiently long.
5. For site categories G1/G2, S1/S2 and R any PSV in the range given for each traffic level may be used for any IL and should be chosen on the basis of local experience of material performance. In the absence of this information, the values given for the appropriate IL and traffic level must be used.
6. Where designers are knowledgeable or have other experience of particular site conditions, an alternative PSV value can be specified.

Table 3.1: Minimum PSV of Chippings, or Coarse Aggregate in Unchipped Surfaces, for New Surface Courses