Use of the Wehner-Schulze machine to explore better use of aggregates with low polish resistance

1: Capabilities of the Wehner-Schulze machine

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Capabilities of the Wehner-Schulze machine

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Executive Summary

The prediction of in-service skid resistance by measurement of the polish resistance properties of aggregate and asphalt in the laboratory is a key tool for specifying and maintaining a safe highway network. Research has been carried out to investigate a laboratory tool designed for that purpose. The Wehner-Schulze machine has been in development since the 1960s and its use is becoming more widespread in Europe. Its ability to characterise the materials available to highway engineers in the UK is the subject of the research reported here.

A programme of research was carried out under contract to the Highways Agency to compare the polishing applied to the pavement surface course by traffic with the polishing that can be applied in the laboratory using the Wehner-Schulze machine. In addition, provisional investigations of the machine’s precision are reported.

A methodology was developed whereby asphalt prepared using a number of different coarse and fine aggregates, representing the geological range available in the UK, could be subjected to polishing by traffic with minimum risk and disruption to road users. Asphalt slabs were prepared in the laboratory, cored into discs, and embedded in the surface course in three separate sites to sample a range of traffic conditions. The discs were retrieved at intervals over a three year period. Identical asphalt slabs were prepared for testing in the Wehner-Schulze machine to two different test regimes developed by machine operators in Europe.

Friction measurements made after polishing by traffic correlate well with friction measurements made after polishing by the Wehner-Schulze machine. It is shown that polishing applied by the machine does not directly mimic polishing by traffic: rather, it is more severe and results in lower friction, especially for asphalts prepared with coarse aggregate that is susceptible to polishing. It is also demonstrated that the amount of polishing experienced on the road, and therefore the expected skid resistance, is dependent on the average daily volume of traffic rather than cumulative traffic levels.

The repeatability of the machine is satisfactory, but the reproducibility, as measured in a pan-European cooperative study, requires improvement. It is therefore concluded that individual machines are suitable for comparison of surfacing materials or for research purposes and the development of asphalt design but, before it can be used for specification purposes, further work is required. This might include development of the machine itself or collaborative research with other operators of the Wehner-Schulze machine to identify and reduce sources of variability in the operation of the machine.
1  Introduction

This report describes work carried out for Highways Agency under projects called “Evaluation of new laboratory procedure for assessing polishing and skid resistance properties of aggregates in the UK” and “Better use of low PSV aggregate”. Combined, the two projects sought firstly to evaluate the ability of a new laboratory procedure to simulate the polishing action of traffic and its suitability for use in materials specification and secondly to demonstrate its potential for use in research to investigate skid and polish resistant properties of aggregates and asphalts. This report details the experiments carried out to achieve the first of these goals.

The procedure in question uses the Wehner-Schulze (W-S) machine, purchased in 2005 by the Highways Agency. The W-S machine is a commercially available laboratory device designed to apply a controlled amount of polishing to samples of road surfacings or their constituent parts. The machine has an integrated friction measurement device and its purpose is to estimate the specimen’s likely in-service skid resistance performance. The machine’s purchase, installation at TRL and subsequent commissioning are described in published project report PPR144 (Woodbridge, Dunford, & Roe, 2006) and more technical details are reproduced in Chapter 2, below, which also describes the background to the present work.

The methodology used to compare polishing in the Wehner-Schulze machine with polishing by traffic is then presented, followed by a comparison of the visual appearance of specimens subjected to different polishing mechanisms. A detailed analysis in Chapter 5 summarises the implications of the friction measurements made on various specimens in terms of the machine’s performance and its simulative capability. The precision of the machine, which has bearing on the feasibility of using the W-S machine for specification or for future research, was briefly examined; results of experiments carried out to investigate repeatability and reproducibility are described in Chapter 6.

After an account of discussions TRL staff have had with European colleagues about use of the W-S machine and its progress towards European standardisation final chapter of this report reviews the experiments carried out and draws some conclusions about the prospects for use of the W-S machine in the UK.

A second report will describe ancillary investigations carried out under the same projects, where the W-S machine was used as a research tool to investigate the effect of combining coarse aggregates with different polish resistance properties.
2 Background

Aggregates used in the surface course on UK roads are required to meet a pre-defined specification in terms of their resistance to polishing under the action of traffic. The current method of testing this polishing resistance is via the ‘Polished Stone Value’ (PSV) test, in which the skid resistance of small samples of aggregate is tested after they have been subjected to controlled polishing in the laboratory. The experiments described in this report attempt to compare the polishing action of the Wehner-Schulze machine with the polishing action of traffic on in-service highways. It was hoped that the results could be used to determine both the machine’s ability to compliment the PSV test for materials specification and its value as a research tool. The following sections describe the machine’s operation, review other work in the field and introduce the methodology used by TRL.

2.1 Wehner-Schulze machine and alternative test regimes

2.1.1 The machine

The Wehner-Schulze (W-S) test equipment, shown in Figure 2.1, was developed during the 1960s in Germany, at the Technical University of Berlin (TUB), as an alternative laboratory test procedure for assessing the polishing of aggregates in road surfacings. At that time, it was considered that the polished stone value (PSV) test was not satisfactory because it gave relatively small numerical differences between different aggregates used in Germany and had poor reproducibility.

The W-S procedure, similarly to the PSV test, is designed to simulate accelerated polishing on road surfacing materials and test the friction provided by the specimen before and after that polishing. An important difference between the PSV test and the W-S procedure, however, is that the latter uses large, flat specimens (usually 225 mm diameter) that can be obtained from actual road surfaces, asphalt test specimens manufactured in the laboratory or laboratory-manufactured test plates using aggregate alone. The test is carried out using a purpose-designed machine that is available commercially. The UK machine was the twelfth machine to be manufactured.

Polishing is achieved in the Wehner-Schulze machine by lowering three conical rubber rollers so that they are independently forced into contact with the test surface. The polishing head is made to rotate at a speed of 500 rpm while a suspension of silicon dioxide in water is pumped onto the surface to act as a polishing medium. During the polishing operation, each roller is independently forced onto the test surface at a contact
Capabilities of the Wehner-Schulze machine

Pressure of approximately 0.4 Nmm$^{-2}$, equivalent to 4 bar (58 psi), typical of the tyre pressures of a commercial vehicle. The mounting bearings are engineered to provide some friction so that, although the rollers are free to rotate, there is some drag, giving a slight slip of 0.5 to 1.0%. Grooves about 2 mm wide, 2 mm deep and about 20 mm apart are cut in the roller rubber, running from the apex to base of the rollers, to simulate tyre treads.

Friction is calculated from measurements of torque imparted to the surface when the test head, comprising three separate rubber sliders and rotating at a pre-defined speed, is dropped onto the surface and allowed to slide to a halt under its own mass. In the standard test, the measuring head is accelerated until it is rotating at 3000 rpm, which is equivalent to a tangential speed for the rubber sliders of 100 km/h. Just before the head has reached the target speed, water is sprayed on to the test surface to attain a theoretical water film thickness of about 0.5 mm and the assembly is dropped onto the surface from a height of about 10 mm, imparting a pressure of 0.2 Nmm$^{-2}$, equivalent to 2 bar (29 psi) in tyre pressure. The friction test value reported, $\mu_{PWS60}$, is the friction calculated when the friction head has slowed to 60 km/h.

New specimens may require cleaning to remove excess bitumen from the surface prior to testing. For this purpose, a custom-designed grit blasting cabinet is used. The cabinet has several automatic settings which control the duration and evenness of the blasting over the specimen surface. As well as for initial sample cleaning, the grit blasting can be used to ‘roughen’ the specimen surface as a specific test stage to simulate the action of winter weather.

In the initial stages of this programme of work, a review was made of the use of the W-S machine in Europe (Dunford, 2008). It emerged from this that the machine was commonly used with different test regimes: in the experiments described in this report, these are referred to as the TUB method, the LCPC method and the TRL method and they are described below.

### 2.1.2 Test regime - TUB method

Developed at the Technical University of Berlin (TUB), the most commonly used polishing regime can be summarised as follows:

- Test friction
- Polish for one hour (90,000 roller passes)
- Test friction
- Gritblast
- Test friction
- Polish for one hour (90,000 roller passes)
- Test friction ‘to the limit’ (repeat friction tests until subsequent values differ by less than 0.005).

### 2.1.3 Test regime - LCPC method

The second polishing strategy was developed in France at the Laboratoire Central des Ponts et Chaussées (LCPC), which is now part of the French institute of science and technology for transport, development and networks (IFSTTAR). The gritblasting stage was dropped in favour of polishing alone because researchers felt it to be more
representative of the action of traffic and the development of skid resistance on the road. The LCPC method is:

- Test friction
- Polish for 1,000 roller passes
- Test friction
- Repeat until a peak in friction is reached
- Polish until 50,000 roller passes have been applied
- Test friction
- Polish until to 90,000 roller passes have been applied
- Test friction
- Polish until to 180,000 roller passes have been applied
- Test friction

2.1.4 Test regime - TRL method

The third polishing strategy that has been used during the course of the work described in this report has now been adopted by TRL for use of the machine to examine the properties of specimens prepared in the laboratory. It is a shortened version of the TUB method:

- Gritblast
- Polish for one hour (90,000 roller passes)
- Test friction ‘to the limit’ (until subsequent values differ by less than 0.005).

Experience has shown that friction measurements made on freshly prepared asphalt specimens are generally quite high and do not vary greatly regardless of the asphalt design. Similarly, friction measured immediately after gritblasting is always very high regardless of the asphalt under test. The first polishing period in the TUB method was removed on the basis that the gritblasting carried out immediately afterwards essentially ‘resets’ the microtexture of the surface, eradicating the effects of that initial polishing. For testing aggregate-only specimens, the gritblasting stage is not used.

2.2 Review of other work in the field

A straightforward methodology for comparing the polishing applied by a laboratory mechanism with the polishing applied by traffic, was developed in the 1960s. Hosking (1967), carried out full-scale trials designed to provide information about the performance of a wide range of road stones when used in different types of bituminous surfacings. 58 trial sections were laid, comprising surface dressings, hot rolled asphalts, dense bitumen Macadams, dense tar surfacings and open texture bitumen Macadams with eight different coarse aggregates (with PSVs ranging from 49 to 75) each 65-100 yards long. Skid resistance was measured using two methods and reported as sideway force coefficient (S.F.C.) and skid resistance value (S.R.V.), the latter using the portable skid resistance tester. To supplement the results of the main experiment two 203 mm x 50 mm (8 in x 2 in) specimen blocks of chippings (Figure 2.2), made from each of the eight coarse
aggregates, were inserted in the nearside wheel path, one on each side of the road. The methodology was copied in an experiment to examine the polish resistance of roadstones available in Malaysia (Beaven & Tubey, 1978). This experiment focussed on the polishing of the stones, rather than on their use in bituminous materials. In addition to carrying out PSV testing on a wide range of aggregates, panels of the available granite and limestone chippings were embedded into the surfaces of two roads – a heavily trafficked dual carriageway and a lightly trafficked housing estate road – and skid resistance was measured periodically using the portable skid resistance tester so that the polishing applied by traffic could be compared with the polishing applied during the PSV test.

Hosking showed that a good correlation between skid resistance after traffic and skid resistance after laboratory polishing could be found, albeit with some outlying measurements, while Beaven and Tubey demonstrated equally good, but different, correlations that were dependent on the volume of traffic on the road. The results of these two studies, carried out to investigate the polishing of aggregate alone in the PSV test, are shown in Figure 2.3 on the left and right respectively.

**Figure 2.3 Results from early traffic – laboratory polishing comparisons**

The PSV test is carried out on specimens prepared by arranging aggregate particles into a rectangular, curved, surface, before binding them with epoxy resin. After polishing, the skid resistance of the specimens is measured with a portable skid resistance tester. In the experiments described above it was therefore possible to use the same device to measure skid resistance in the laboratory and on the embedded panels in situ. It is not possible to do this for the Wehner-Schulze procedure because although it has been reported that a transportable version of the W-S machine was manufactured, it is not widely used. The Dynamic Friction Tester (ASTM, 2009) uses a similar principle for friction measurement but aside from requiring correlation with the W-S friction test, access to live roads for stationary testing is not as easy now as it was in the 1960s and 70s. Therefore, experiments to compare W-S polishing to traffic polishing have necessarily brought specimens to the machine or made comparisons with other skid resistance measuring devices.
For example, as part of a larger experiment looking at the performance of various asphalt surface courses, Dames et al. (1997) compared skid resistance measured on site using a full scale survey vehicle (Stuttgarter Reibungsmesser - SRM) with friction measured in the W-S machine. The trial site was trafficked for five years and asphalt specimens, made in the laboratory to the same specification as the trial site sections, were polished in the W-S machine, presumably using the TUB polishing method. A good correlation was found between skid resistance measured on the road after traffic polishing with friction measured in the W-S machine after W-S polishing.

Researchers in France, who obtained a Wehner-Schulze machine at about the same time as the Highways Agency, carried out a polishing comparison experiment by removing cores from full-scale trial sections (Do M.-T., Tang, Kane, & Larrard, 2007). A core was removed from each trial site immediately after construction. This core was subjected to polishing in the W-S machine in stages so that the evolution in friction could be observed throughout the polishing procedure. Further cores were then removed from the trial sites at four or five occasions over a two year period. W-S friction measurements on these cores were compared with the friction evolution curve obtained for the first cores. Researchers noted that a limitation of the trial sites was that it was only possible to test a small range of asphalts, using a limited number of aggregates (PSVs of 51, 53 and 55). However, they determined that the evolution of friction, as measured in the W-S machine on cores taken from the road, had the same form as the evolution of friction as measured on cores polished only in the W-S machine.

### 2.3 Development of TRL methodology

#### 2.3.1 Concept

The TRL methodology was developed to incorporate features of the experiments described above, using additional guidance in an unpublished RRL Technical Note from 1970. Specimen embedment was used in order to maximise the range of aggregates that could be tested, without the need for long trial sites, and to avoid the safety implications of subjecting road users to aggregates known to have very low resistance to polishing (such as limestone). Since it was not possible to measure skid resistance with the W-S machine in-situ, it was necessary to embed several versions of each aggregate so that they could be removed periodically. It may have been possible to embed one specimen of each type then remove, test and replace it within a short period but this would have required twice as much work at site and more disruption to road users. Asphalt specimens were prepared rather than aggregate-only mosaics in order to improve consistency and/or randomise differences between specimens made using the same constituents. Asphalts slabs were prepared in the laboratory and then cut into 225 mm discs to fit the Wehner-Schulze machine.

#### 2.3.2 Pilot testing at TRL

An initial phase of testing was carried out to demonstrate that the method of embedding the asphalt specimens into the road was robust and would not constitute a hazard to road users when trafficked. A series of holes was cored into an existing surface laid in the Pavement Test Facility (PTF) at TRL, which allows a loaded tyre to be repeatedly passed over the surfaces. A brief description of the PTF can be found in Appendix A. The holes were cleaned and dried and then part-filled with a two component adhesive system (Triflex 238 and 239) that is used for bonding frames for cats eyes into road
Capabilities of the Wehner-Schulze machine

surfaces. Sufficient adhesive was poured into each hole so that when a new asphalt disc was lowered in, the mixture was forced up the side of the disc and any gaps around the disc circumference were carefully filled with adhesive. The discs were held level with the surface using a wooden batten, fixed to the disc’s upper surface with a screw and masonry plug, until the adhesive had cured.

To simulate the loading of traffic, the inserted discs were tracked by the PTF dual-wheel carriage for 45,000 passes. The loading was set so that the effective carriage mass was 5.75 tonnes (and therefore an axle mass of 11.5 tonnes is represented) and the number of passes should simulate several days’ trafficking on the most heavily trafficked site to be used in the experiment. Very little damage or deformation was found during this period of simulated trafficking and it was therefore concluded that the risk of the inserted discs becoming loose and causing a hazard to road users was low.

Figure 2.4 shows the discs inserted into the replica pavement. Note that they were inserted in a diagonal pattern so that some were loaded on an edge, and some were loaded across their full diameters.

It was found that the embedded asphalt discs could be removed by coring without excessive damage to their surfaces. The possibility of repairing the holes resulting from removal of the discs by re-inserting the surplus asphalt discs that were removed when the specimens were first embedded was evaluated. However, in practice, a commercially available ready mixed asphalt was used for backfilling the holes because it was quicker.

Figure 2.4 Specimens in the Pavement Test Facility
3  Methodology for road experiment

Following the pilot testing described above, 210 slabs of asphalt were prepared in the laboratory, using one basic asphalt design with fourteen different combinations of coarse and fine aggregates, for use in the various experiments that will be described below. Some of the specimens were just polished the Wehner-Schulze machine, the majority were embedded in road sites to be retrieved after trafficking and some were left outside on the TRL site so as to be subjected only to the effects of weather. The following sections describe the specimens, the polishing carried out in the laboratory, specimen embedment into trial sites and retrieval and testing of the trafficked specimens.

3.1  Description of specimens

The asphalt slabs were prepared using a standard stone mastic asphalt design. Table 3.1 lists the fourteen combinations of coarse and fine aggregates used; for anonymity, aggregate sources are referred to by letter, and the PSV for each is the nominal value allocated by the supplier, where that information was available. All slabs were cored to give a disc of asphalt to fit the Wehner-Schulze machine.

<table>
<thead>
<tr>
<th>ID</th>
<th>Coarse aggregate</th>
<th>Coarse aggregate type</th>
<th>Nominal PSV of coarse aggregate</th>
<th>Fine aggregate</th>
</tr>
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<tr>
<td>1</td>
<td>A</td>
<td>Felsite</td>
<td>59</td>
<td>L</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>Porphry</td>
<td>60</td>
<td>B</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>Porphry</td>
<td>60</td>
<td>L</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>Gritstone</td>
<td>65</td>
<td>C</td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>Granite</td>
<td>57</td>
<td>L</td>
</tr>
<tr>
<td>6</td>
<td>E</td>
<td>Basalt</td>
<td>55</td>
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<td>7</td>
<td>F</td>
<td>Gravel</td>
<td>-</td>
<td>L</td>
</tr>
<tr>
<td>8</td>
<td>G</td>
<td>Dolerite</td>
<td>65</td>
<td>L</td>
</tr>
<tr>
<td>9</td>
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<td>Gritstone</td>
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<td>L</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
<td>Gritstone</td>
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<td>L</td>
</tr>
<tr>
<td>11</td>
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<td>12</td>
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</tr>
<tr>
<td>14</td>
<td>M</td>
<td>Limestone</td>
<td>36</td>
<td>L</td>
</tr>
</tbody>
</table>

For each of the fourteen aggregate combinations, fifteen asphalt discs were produced:

- 2 were subjected to polishing in the W-S machine
- 12 were embedded in sets of four into three trial sites, to be subjected to polishing by traffic
- 1 was subjected to the actions of weather.
For the remainder of this report the fourteen aggregate combinations will be referred to as ‘mix’ followed by the appropriate ID (as listed in Table 3.1). Individual asphalt discs will be referred to as ‘specimen’.

### 3.2 Polishing in the laboratory

For each mix, one control specimen was subjected to polishing using the TUB method and one control specimen was subjected to polishing using the LCPC method (see Section 2.1.2). The graph in Figure 3.1 shows the coefficient of friction, $\mu_{PWS60}$, measured by the Wehner-Schulze machine on a pair of specimens as they were tested according to the LCPC and TUB methods, against the number of roller passes applied. The filled red square symbols show the friction measurements made during the TUB method, and the open blue diamond symbols show the measurements made during the LCPC method. It can be seen that where the two polishing methods coincide (at the start, at 90,000 passes and at 180,000 passes), the measurements of friction are similar.

The initial friction measurements are probably associated with the properties of the excess bitumen and fine material present on the surface of the asphalt specimens while the initial increase in friction found during the LCPC method is probably due to a gradual revealing of the underlying coarse aggregate. The results shown are for duplicate specimens of mix 1 but it should be noted that the initial friction measurements for all 14 aggregate combinations were similar (friction measurements range from 0.36 to 0.41), even though measurements made after polishing differed (friction measurements range from 0.30 to 0.43). Also, initial friction measurements were generally higher than the final measurement made after 180,000 polishing passes. Friction measurements made on all of the specimens polished in the W-S machine can be found in Appendix B.
3.3 Trial sites and specimen embedment

In order to investigate a range of levels of trafficking, the asphalt discs were embedded into three different sites. The three sites were well known, having been used as trial sites during a parallel programme of research, and are part of the HA’s trunk road network. The discs were installed in the nearside wheelpath in lane 1 of the A14 near Stanford, in the nearside wheel path of the A5 near Gibbet Hill and in the outside wheelpath of lane 2 of the A5 at the same location. The three sites carry 4500, 1200 and 200 commercial vehicles per day (CVD), according to Highways Agency records and for the remainder of this report will be referred to as sites A, B and C respectively.

At each of the three sites 56 asphalt discs, comprising four specimens from each mix, were embedded during August 2007, according to the methodology described in Section 2.3. The photographs in Figure 3.2 show some of the discs immediately before and after embedment into site C.

3.4 Specimen retrieval and testing

The intention of the experiment was to retrieve one specimen of each mix at six month intervals, during winter and summer periods. However, primarily due to constraints with gaining access to the live road network at the appropriate times, the specimens were removed on a more ad-hoc basis. Table 3.2 shows the timing of retrieval and the number of discs retrieved on each occasion. It was not possible to gain access to the A5 for the second visit and one set of fourteen discs remains embedded in those sites.
Table 3.2 Number of asphalt discs retrieved from sites during each visit

<table>
<thead>
<tr>
<th>Site</th>
<th>April 08</th>
<th>October 08</th>
<th>April 09</th>
<th>August 10</th>
</tr>
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<tr>
<td>A</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>11†</td>
</tr>
<tr>
<td>B</td>
<td>14</td>
<td>0</td>
<td>13*</td>
<td>13*</td>
</tr>
<tr>
<td>C</td>
<td>14</td>
<td>0</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

*one specimen damaged on retrieval
†three specimens damaged by unrelated road works

Specimens retrieved from the road on the first two occasions were tested using the LCPC method (including the initial friction test). The reason for polishing in the machine in addition to the polishing that had occurred on the road was to determine whether an increase in friction could be detected, perhaps due to revealing of aggregate on the surface, as was the case on the control specimens. In general, this was not the case - there were only two instances of an increase in friction with further polishing, once on a specimen retrieved on the first visit, and once on a specimen of a different mix, retrieved on the second visit. The graph in Figure 3.3 shows friction measurements made throughout the LCPC method applied to the duplicate specimens of mix 1 retrieved from site A on visits 1 and 2 (April 08 and October 08). Note that the final friction measurements are very similar to the final friction measurements made on the control specimens that were just polished in the laboratory (Figure 3.1).

Specimens retrieved on the third and fourth visits were not subjected to further polishing in the machine and only a single measurement of friction was made on each. Friction measurements made on all of the retrieved specimens can be found in Appendix B.
4 Visual comparison of polishing processes

Various photographs were taken of the asphalt discs while they were embedded in the trial sites, mainly to serve as a record of their condition as they were polished by traffic. In addition, photographs of the surfaces were taken after retrieval, at various levels of detail, so that a comparison could be made between the different polishing mechanisms: polishing by Wehner-Schulze (via TUB method or LCPC method) vs polishing by traffic (at different levels of trafficking).

4.1 The action of traffic and weather

The photographs in Figure 4.1 show the same specimen, one of the duplicates of mix 8 installed in site A, in August 2007 and in August 2008. After 12 months of service the specimen appearance is significantly altered, largely due to the ageing of the bitumen which gradually lightens in colour. On close inspection, some of the individual aggregate surfaces are revealed but there is still bitumen and fine aggregate present on the surface.

Figure 4.1 Photographs of the same specimen, embedded in site A, taken immediately after embedment (left) and after 12 months of traffic.
The presence of a residual film of bitumen and particles of the fine aggregate used is easier to see by comparing the surfaces of specimens of mix 14, prepared using limestone coarse aggregate, as in Figure 4.2. These photographs were taken in August 2008, 12 months after installation, and it is immediately apparent that the amount of limestone coarse aggregate showing through is proportional to the volume of traffic at the site i.e. there is more limestone visible in the top photograph than in the bottom photograph.
The photographs in Figure 4.3 show duplicate specimens of mix 14 after extraction in August 2010, from sites A, B and C. In all three cases there is more aggregate visible through the bitumen than there was in August 2008, but there are still clear differences between the three sites. It may be of interest to return to the specimens still remaining in the A5 sites (B and C) to see if the bitumen ever fully wears away from the aggregate surface. The effects are slightly exaggerated because limestone coarse aggregate is likely to have a weaker affinity for bitumen than other aggregates more normally used in surface courses. The other specimens demonstrate similar behaviour but, largely because of the aggregate colours, it is not so easy to see.

The friction on each of the specimens shown in Figure 4.3 was 0.272, 0.291 and 0.325, according to the W-S machine, for sites A, B and C respectively (i.e. top to bottom). There is a relationship between friction and the level of traffic but it is not obvious whether this is as a result of the amount of coarse aggregate showing or if the amount of coarse aggregate showing is a symptom of the mechanism that causes the difference in friction or, probably, both.
The photograph in Figure 4.4 shows the mix 14 specimen that was left outside at TRL, subjected to weather for the same length of time as the specimens that were embedded in the road. Note that some of the bitumen has been eroded, possibly after becoming brittle under the action of UV sunlight. The friction measured on this specimen was 0.612 so although coarse aggregate does show through, these surfaces have not been polished.

Figure 4.4 Mix 14 specimen in August 2010 after exposure to weather only
4.2 Comparison of polishing mechanisms

The dominant feature of the specimen photographs so far has been the presence or amount of bitumen and fines remaining on the surface. This is also true when comparing the different polishing mechanisms (machine or traffic).

For example, Figure 4.5 shows specimens of mix 14 after testing in the W-S machine using the TUB and LCPC methods. Figure 4.6 shows specimens of mix 14 after extraction from sites A, B and C in April 2009. The bitumen, including some from the sides and edges of the aggregate particles that might not be affected by vehicle tyres, has been removed by the gritblasting stage of the TUB method and the coarse aggregate has been polished smooth; the surface looks similar to the specimen polished by relatively heavy traffic at site B. After using the LCPC method there are only small areas of coarse aggregate visible through the remaining bitumen; the surface looks more similar to the specimen polished by light traffic at site C.

![Figure 4.5 Photographs of mix 14 specimens polished using TUB method (left) and LCPC method (right)](image)

![Figure 4.6 Photographs of mix 14 specimens after polishing by traffic in site A (left), site B (middle) and site C (right)](image)
Another example of these comparisons is shown in Figure 4.7 and Figure 4.8, with photographs of mix 1 specimens (felsite coarse aggregate with nominal PSV 59). In this example the LCPC method has removed considerably less bitumen than is the case for the specimen retrieved from the lightly trafficked site; only the uppermost parts of the aggregate particles are visible.

It is possible that, although the W-S’s polishing rollers come into contact with a relatively large area on the specimen surface and their polishing action is sufficient to polish the aggregate (as in Figure 4.5 left), the polishing action in the machine or the conformation of the rollers to the surface is not sufficient to remove substantial amounts of the residual film of bitumen and fines. The additional bitumen and fine aggregate left on the surface does not completely mask the friction delivered by the different coarse aggregate types though: this will be demonstrated later by the good correlation between friction measured after testing in the machine with the TUB and LCPC methods. However, the residual film may contribute to the reduced range of friction measurements observed after testing with the LCPC method (Figure 5.5).

Figure 4.7 Photographs of mix 1 specimens polished using TUB method (left) and LCPC method (right)

Figure 4.8 Photographs of mix 1 specimens after polishing by traffic in sites A, B and C
There is an additional concern regarding the polishing mechanism delivered by the two machine test regimes. The images in Figure 4.9 are close-up photographs of individual aggregate particles shown in the photographs in Figure 4.5. It is immediately obvious that the polishing delivered by the LCPC method has affected the aggregate differently. The tops of the particles that have come into contact with the polishing rollers have been worn completely flat. This may be because the rollers do not conform to the surface profile so that the aggregate peaks bear the whole weight of the polishing head; in the case of the limestone aggregate used in mix 14, the coarse aggregate is softer than the enveloping bitumen/fine aggregate film that protects the slightly lower parts of the surface - the effect is therefore exaggerated in this example. However, it can be seen that, on other specimen surfaces polished using the LCPC method, the coarse aggregate peaks and the remaining bitumen film form a surface with continuous height rather than allowing the coarse aggregate to stand proud as is the case for the TUB method, and for real trafficking.

![Figure 4.9 Photographs of aggregate surfaces in specimens of mix 14 after testing with TUB method (left) and LCPC method](image1)

![Figure 4.10 Aggregate surfaces in specimens of mix 1 (left) and mix 13 after testing in the W-S machine using the LCPC method](image2)
5 Analysis

In this chapter the friction measurements made on the asphalt discs are used first to establish that the polishing experienced by those embedded in the road sites is representative of the polishing that would normally be expected on the road, then to compare the test regimes used in the W-S machine and finally to compare polishing by traffic to polishing by machine.

5.1 Polishing by traffic

The concept of an equilibrium level of skid resistance suggests that a road surface is continually polished and roughened by traffic, but the underlying level of skid resistance reaches an equilibrium which is dependent on the average daily volume of traffic. It is a well documented phenomenon that skid resistance is lower during the summer months due to the polishing action of traffic with the presence of fine detritus and, conversely, higher in the winter due to the presence of coarser detritus (Hosking & Woodford, 1976).

As described in Section 3.3, asphalt discs were embedded in trial sites used for another research programme. That research included making measurements of skid resistance on site, using SCRIM (Sideway-force Coefficient Routine Investigation Machine), from construction until the skid resistance had reached an equilibrium level (i.e. stopped decreasing). The graph in Figure 5.1 shows skid resistance measured during the summers, over a period of almost four years on sites B and C. It can be seen that an equilibrium level of skid resistance, within normal year to year variation, has been reached at both sites by the time the surfacings were two years old.

![Figure 5.1 Skid resistance measurements on A5 trials sites](image)

Once skid resistance has reached equilibrium, the value measured on site C (carrying less traffic) is always slightly higher than the value measured on site B. The pattern of reduction in skid resistance to an equilibrium level is similar on site A but different
coarse aggregate was used in construction of the pavement in which the discs are embedded.

For further comparison, the graph in Figure 5.2 shows friction measured in the W-S machine on cores taken from in-service roads constructed using the same coarse aggregate as one another (and the same asphalt design) that carry heavy, medium and light traffic. The heaviest traffic is estimated as 4,500 CVD rather than 4,050 as on site A, and the medium and light traffic sites are sites B and C with 1200 CVD and 200 CVD respectively. Results from skid resistance testing on these sites are presented in detail in PPR324 (Roe, Dunford, & Crabb, PPR324, 2008).

![Figure 5.2 Friction measurements on cores from in-service roads with heavy, medium and light traffic](image)

The graph in Figure 5.3 shows the average friction measured across all fourteen discs retrieved from the three sites on all four occasions. The error bars indicate the range of friction measurements on individual specimens. It is clear that, by August 2010, the average level of friction on discs retrieved from the site with the lowest traffic (site C) is higher than on discs retrieved from the sites carrying more traffic. The ranges of measurements made on individual specimens overlap and so a brief statistical analysis was carried out – summarised below the graph. The results should be considered in the context of expected physical phenomena of equilibrium skid resistance and seasonal variation.
A statistical test (Student’s t-test with paired samples and assumed two-tail distribution) confirms that:

- The equilibrium level of skid resistance on the site carrying less traffic (site C) is higher than on sites carrying more traffic (A and B) but it took longer than eight months to reach that condition (discs were embedded in August 2007)
  - The average friction measured on all discs retrieved from site A in April 2008 is not significantly different from that measured on discs retrieved from site C at the same time (probability value 0.16)
  - The average friction measured on discs retrieved from site A in April 2009 and August 2010 are significantly different from those measured on discs retrieved from site C at the same times (probability values 0.002 and 0.003 respectively)

- Skid resistance across all sites is higher in the winter than it is in summer
  - The average friction measured on all discs in April 2008 is not significantly different from that measured on all discs in April 2009 (probability value 0.38)
  - The average friction measured on all discs is significantly lower in August 2010 that it is in April 2008 and April 2009 (probability value 0.00 in both cases).

It should be borne in mind that these measurements can only serve as a snapshot of skid resistance condition. However, the observations are consistent with measurements made at other sites and with the expected physical phenomena. It is likely that the levels of friction measured on discs extracted from site C will never drop, in the future, to the levels of friction currently observed on the discs extracted from sites A and B, even after the same cumulative amount of traffic has passed. This could be shown using the discs that remain embedded in that site.
5.2 Comparison of W-S test regimes

The differing appearance of specimens undergoing W-S procedure following the TUB and LCPC methods has already been discussed in Section 4.2. The differences can also be shown by comparing friction measurements. The graphs in Figure 5.4 and Figure 5.5 show the relationships between friction after LCPC and TUB methods at 90,000 and 180,000 roller passes respectively. Each point on the graph is labelled with the mix ID corresponding to a pair of specimens made using the same aggregate combination; a dashed line of unity is shown for reference.

After 90,000 polishing passes, there is generally a good relationship between the two sets of friction measurements. The measurements made on the pair of gravel specimens (ID 7) may be outlying because the properties of rounded gravel particles are likely to be different to the other coarse aggregates used. However, the same is not true for the measurements made on the pair of dolerite specimens (ID 8) which also appear to be outlying – inspection of the surfaces reveals no obvious explanation. The relationship is clearly not one to one – the action of stopping the polishing process to carry out multiple friction measurements results in a different degree of polishing.

![Graph showing friction measurements after 90,000 roller passes for LCPC and TUB methods.]

Figure 5.4 Friction after 90,000 roller passes – LCPC method vs TUB method

It is possible that, at this stage, the LCPC method, because of the aggressive action of friction testing, has removed more of the bitumen/fines layer to reveal the underlying coarse aggregate. This results in a higher friction after the LCPC method than after the TUB method at 90,000 roller passes for those mixes using highly polish resistant coarse aggregate.

After 180,000 passes there is a good relationship between the two sets of friction measurements (Figure 5.5). The two outlying points are no longer outlying and there is a wider spread of friction measurements after completion of testing using the TUB method (the range on the x-axis from 0.27 to 0.46 compared with the range on the y-axis from 0.30 to 0.43).
The graph in Figure 5.6 is identical to the one in Figure 5.5 with the addition of arrows that mark the translation of each point from 90,000 to 180,000 polishing passes.

There are several cases where completion of testing using the TUB method has resulted in an increase in friction – it is mostly due to this effect that mix 7 is no longer an outlying point. For the four specimen pairs with friction measurements greater than...
0.39 after the completion of the TUB method (mixes 1, 4, 9 and 10) friction has increased between 90,000 and 180,000 roller passes during the TUB method but decreased during the LCPC method. On the majority of the remaining pairs completion of either method of testing has resulted in a decrease in friction.

Changes to the relationship between the two sets of friction measurements (LCPC vs TUB) that occur between 90,000 and 180,000 passes generally result from large changes in friction caused by testing with the remainder of the TUB method (i.e. points move further on the x-axis than they do on the y-axis of the graphs above). It is likely that the divergence of the two test methods is mainly caused by inclusion of the gritblasting stage and that the bitumen/fines layer has a moderating effect on the friction measured. Indeed, the increase in friction during the TUB method for some of the specimens is probably due to additional revealing of high PSV coarse aggregate surfaces by the gritblasting process: these coarse aggregate particles resist polishing more than the remaining bitumen/fines and therefore increase the overall skid resistance.

With hindsight a third control specimen could have been prepared for each mix in order to compare results from testing with the TRL method. However, this shortened method of testing was only developed after commencement of the project.

5.3 Comparison of traffic and W-S polishing

The main purpose of the experiment was to determine the machine’s ability to predict in-service performance. In addition to the qualitative comparisons made by inspection of the asphalt disc and coarse aggregate surfaces (Section 4.2) it is possible to compare friction measurements made on the discs retrieved from each of the trial sites with friction measured after testing in the W-S machine.

5.3.1 The polishing action of traffic

It is generally agreed that the skid resistance of the surface course is affected by the action of traffic in the presence of some polishing medium (usually the detritus that builds up on the road). The precise mechanism of polishing is not fully understood and work has been undertaken to examine the influence of load distribution and the complicated behaviour of rubber as it is forced into contact with the surface. The pavement’s response to traffic is considered either in terms of the average daily volume of traffic or in terms of the cumulative amount of traffic.

In the first case, as mentioned in Section 5.1, after the initial period of wearing in, road surfaces reach an equilibrium state of polishing. For roads where average daily traffic volume is constant, the skid resistance will then fluctuate through seasonal variations, weathering and polishing cycles but will usually remain at about a constant level for many years. If the traffic volume subsequently increases or decreases, the position of the equilibrium may shift so that a lower or higher overall level of skid resistance is observed, but with the same seasonal fluctuation superimposed (Design Manual for Roads and Bridges, 2004). This is the model used in the UK.

In the second case, the seasonal effects are often recognised but considered secondary to an overall reduction in skid resistance that follows a pattern related to the theory that the vehicles passing over the surface have a cumulative wearing effect, for example: $\mu = a(N+b)^c$ where N is the number of vehicles and a, b and c are constants (Do, Tang, Kane, & Larrard, 2009).
5.3.2 Average daily volume of traffic

It is possible to demonstrate that the relationship between friction after machine polishing and friction after traffic polishing is dependent on the average daily traffic volume, as was observed in the experiment by Beaven and Tubey (1978), Figure 2.3: the graph in Figure 5.7 shows a very similar pattern to the results in the earlier work. The graph shows friction measured on specimens retrieved in August 2010 from sites A, B and C, against friction measured after testing in the W-S machine with the TUB method. The broken lines are lines of best fit, excluding the measurements made on mix 14 specimens which seem to be outlying points. Although the correlation is not very strong in either case, it is clear that specimens from sites A and B have been polished by traffic to a greater extent than those from site C. This is as expected given the average results presented in Figure 5.3.

![Graph showing relationship between friction on extracted discs and control discs](image)

**Figure 5.7 Relationship between friction on extracted discs and control discs**

5.3.3 Cumulative traffic

The graph in Figure 5.8 shows the friction measurements made on the mix 1 control specimen during testing with the LCPC method, overlaid with the friction measurements made on the specimens of the same mix retrieved from site A. The W-S polishing progress is tracked in terms of the number of roller passes on the x-axis at the bottom of the graph and the traffic polishing progress is tracked in terms of the number of months since embedment on the x-axis at the top of the graph.
The final measurement of friction is similar for both polishing mechanisms. The intermediate friction measurements on the specimens retrieved from the road are considerably higher than those made on the specimen polished in the laboratory. Friction measurements on other specimens show a similar pattern but with varying offset between friction measured on road specimens and friction measured on W-S control specimens. The graph in Figure 5.9 shows the comparison for mix 4, which used coarse aggregate with a higher nominal PSV. It is therefore not possible to derive a simple relationship between the number of polishing roller passes and the amount of time (or traffic) passed without implying that no change occurs on the road until after 20 months, which does not reflect measurements made on the sites in which the specimens were embedded (Figure 5.1 for example).

To make a proper comparison between friction measured and the cumulative amount of traffic would require more than four discrete measurement points but the indication from results with the asphalt discs used is that no such relationship exists. It would also be informative to study a greater range of traffic levels – if all three sites are used for the above comparison, the results are dominated by measurements made on discs extracted from site A. This is because, by the time of the first extraction, site A had carried more traffic than the site B had carried by the end of the experiment.

**Figure 5.8 Friction measurements during LCPC method and after extraction from site A - mix 1**
5.3.4 Potential for a predictive model

Some researchers, including Szatkowski and Hosking (1972), Roe and Hartshorne (1998), Do et al (2009), have attempted to derive models for prediction of in-service skid resistance using results from testing carried out in the laboratory. For completeness, a similar treatment has been attempted using the results from this experiment. In-service skid resistance will be dependent on the susceptibility of the asphalt (and in particular the coarse aggregate) to polishing by traffic, the amount of traffic, the amount of stress applied by the traffic and the weather.

Excluding mix 14 specimens, friction measured on discs extracted in August 2010 correlates linearly with friction measured after testing control specimens with the TUB method (Figure 5.7). The slope and intercept of the lines of best fit seem to be dependent on the site, and therefore possibly on the daily volume of traffic at the site. It may be possible to develop a relationship such as:

\[ \text{Equilibrium friction on road} = f(\text{volume of traffic}) \times \mu_{PWS60}(\text{TUB}) \pm f(\text{volume of traffic}) \]

This is developed further in Appendix C.

The correlations between road and W-S polishing are weak and would benefit from measurements on additional specimens, the number of traffic levels is small and the effect of seasonal variation has been shown to be significant. The specimens were installed in the surface course at straight, non-event, locations so the relationship cannot take account of any additional stress that might be experienced at more challenging locations (bends or traffic light, roundabout and junction approaches).

If a relationship could be developed, the fact that the correlations do not work for specimen 14 might be mitigated by introduction of a friction lower threshold. Introduction of threshold levels (which is the current method for specification of coarse
aggregate) for determination of asphalt suitability based on friction measured after polishing in the W-S machine might be a more pragmatic approach to these results. To further extend the applicability of the test it would be useful to measure friction on specimens made from coarse aggregate in addition to the asphalts made using it.

### 5.3.5 Practical implementation of experimental results

The correlation between friction after polishing by road or W-S machine (TUB method) is improved by use of the average friction measured on all specimens of the same mix retrieved from all three sites, as shown in Figure 5.10.

![Figure 5.10 Average friction on all retrieved discs vs friction after TUB method](image)

There is a wider distribution of friction measured on the specimens polished in the machine. This might improve its ability to differentiate between alternative surfacing solutions for non-stress locations.

The graph in Figure 5.11 shows friction after W-S polishing (TUB method), average traffic polishing and weathering action, ranked in order of increasing friction measured on the W-S control specimens. Broken lines of best fit (excluding the specimens from mix 14) are shown and it can be seen that, as would be expected given the correlation in Figure 5.10, a similar rank order is achieved for machine and traffic polishing. So, if one asphalt performs better than another after polishing in the W-S machine, it will probably also give better in-service performance. Assuming that the asphalt discs from the same mix all started with similar friction, it appears that the reduction in friction caused by polishing is much greater in the W-S machine than it is on the road, especially for polish-susceptible materials.

The action of weathering alone had removed some of the bitumen from the surface of the discs and had left the aggregate particles with rough surfaces (Section 4.1), which is further indicated by very high friction measurements. The correlation is weaker and the level of friction measured after weather is similar to that measured after the gritblasting
stage of the TUB test method. This perhaps adds credence to the inclusion of the gritblasting stage as a simulative measure for the action of weather.

Figure 5.11 Friction measurements on specimens polished by W-S ranked in order of increasing value and average friction on all road specimens

The polishing state, or limit of polishing, achieved in the W-S machine is more severe than at non-event in-service locations even under heavy traffic, especially for those materials that are not resistant to polishing. This work could be developed further by considering locations where polishing by traffic is also harsher, such as at junction, roundabout and crossing approaches or on bends. This could be achieved either by use of the specimen insertion techniques used here or through a long term programme of testing asphalt samples collected during construction of new surfaces for later comparison against in-service performance.
6 Precision and specimen preparation

In addition to its ability to simulate the polishing action of traffic, the machine’s suitability for use as a research tool or for material specification relies on consistency of results either from the same machine or from more than one machine. This section describes experiments that were carried out to determine repeatability and reproducibility as well as a brief investigation of the importance of specimen preparation.

6.1 Repeatability

Nine asphalt specimens were prepared in the laboratory for each of three coarse aggregate sources: 1, 2, and 3. Nine aggregate-only specimens were prepared using aggregate particles from two different sources (4 and 5), arranged in a mosaic and held together with epoxy resin. Three additional mosaic specimens were also prepared using source 3. The asphalt specimens were grit blasted and then polished for one hour in the Wehner-Schulze machine before friction was tested on their surfaces. The mosaic specimens were also polished and tested but were not grit blasted.

The asphalt specimens all used the same fine aggregate and the mix design was kept as constant as possible with only small adjustments for bitumen requirement. The mosaic specimens using aggregate sources 4 and 5 were prepared in three sub-sets by three different operators.

Friction measurements made after polishing are presented in Table 6.1; three decimal places are reported, as from the machine.

<table>
<thead>
<tr>
<th>Coarse aggregate 1</th>
<th>Coarse aggregate 2</th>
<th>Coarse aggregate 3</th>
<th>Coarse aggregate 3</th>
<th>Coarse aggregate 4</th>
<th>Coarse aggregate 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.360</td>
<td>0.508</td>
<td>0.538</td>
<td>0.539</td>
<td>0.144</td>
<td>0.307</td>
</tr>
<tr>
<td>0.358</td>
<td>0.482</td>
<td>0.514</td>
<td>0.532</td>
<td>0.148</td>
<td>0.313</td>
</tr>
<tr>
<td>0.361</td>
<td>0.475</td>
<td>0.513</td>
<td>0.518</td>
<td>0.150</td>
<td>0.309</td>
</tr>
<tr>
<td>0.365</td>
<td>0.466</td>
<td>0.524</td>
<td></td>
<td>0.158</td>
<td>0.316</td>
</tr>
<tr>
<td>0.369</td>
<td>0.497</td>
<td>0.487</td>
<td></td>
<td>0.154</td>
<td>0.339*</td>
</tr>
<tr>
<td>0.353</td>
<td>0.472</td>
<td>0.506</td>
<td></td>
<td>0.149</td>
<td>0.306</td>
</tr>
<tr>
<td>0.353</td>
<td>0.459</td>
<td>0.495</td>
<td></td>
<td>0.116*</td>
<td>0.320</td>
</tr>
<tr>
<td>0.379</td>
<td>0.468</td>
<td>0.467†</td>
<td></td>
<td>0.146</td>
<td>0.317</td>
</tr>
<tr>
<td>0.396</td>
<td>0.470</td>
<td>0.464†</td>
<td></td>
<td>0.143</td>
<td>0.312</td>
</tr>
</tbody>
</table>

*values excluded from calculations of σ and r by Dixon’s test for outliers
†specimen surfaces showed signs of damage which may contribute to low friction measurement

Dixon’s test, a method for identifying outlying measurements in precision tests, (British Standards, 1994), was used to discount any measurements of friction that should not be included in calculations of repeatability. Note that only two outlying points were identified, one from the measurements on mosaics with coarse aggregate 4 and one
from the measurements on mosaics with coarse aggregate 5. Table 6.2 shows, for each set of specimens: the mean friction, the standard deviation of the measurement set and repeatability (which is approximately 2.8 times the standard deviation). For the mosaic specimens prepared with coarse aggregates 4 and 5, two values are shown for standard deviation and repeatability. The value in normal type is calculated by considering all nine specimens as part of the same group; the value in brackets and italics is an average after considering separately each of the subsets prepared by different operators.

Table 6.2 Basic statistics for duplicate specimen sets

<table>
<thead>
<tr>
<th>Coarse aggregate 1</th>
<th>Coarse aggregate 2</th>
<th>Coarse aggregate 3</th>
<th>Coarse aggregate 4</th>
<th>Coarse aggregate 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>0.366</td>
<td>0.477</td>
<td>0.501</td>
<td>0.530</td>
<td>0.149</td>
</tr>
<tr>
<td>σa1</td>
<td>σa2</td>
<td>σa3</td>
<td>σm3</td>
<td>σm4</td>
</tr>
<tr>
<td>0.014</td>
<td>0.016</td>
<td>0.025</td>
<td>0.011</td>
<td>0.005 (0.003)</td>
</tr>
<tr>
<td>r_a1</td>
<td>r_a2</td>
<td>r_a3</td>
<td>r_m3</td>
<td>r_m4</td>
</tr>
<tr>
<td>0.039</td>
<td>0.045</td>
<td>0.071</td>
<td>0.031</td>
<td>0.014 (0.010)</td>
</tr>
</tbody>
</table>

On average, for asphalt specimens, the repeatability of the Wehner-Schulze procedure is 0.05. This is the maximum difference one would expect to see between identical specimens in 95% of tests carried out in the same laboratory under identical conditions. The value is quite high but it does refer to the repeatability of the entire process: asphalt manufacture (including aggregate sampling, weighing, mixing and compacting), gritblasting, polishing and friction testing in the Wehner-Schulze machine.

For mosaic specimens the repeatability is considerably better. When mosaic specimens prepared using the same aggregate are each considered as a single set, the average repeatability is 0.02. When the sub-sets of mosaics prepared by three different operators are considered separately, the average repeatability is still 0.02. Sources of variability include aggregate sampling, mosaic manufacture, polishing and testing in the Wehner-Schulze machine, but the variability induced by preparation by different operators is minimal.

6.2 Reproducibility

At the beginning of the study, the Highways Agency’s Wehner-Schulze machine was included in a round-robin test organised on behalf of the German Federal Highway Research Institute (BAST) by Asphalta, a research laboratory near Berlin. There were fourteen participants, representing almost all examples of the Wehner-Schulze machine in operation at the time. The results are summarised below.

Each laboratory was requested to prepare two mosaic specimens and two mastic specimens using the three coarse aggregate samples sent by Asphalta: limestone, quartzite and basalt (kalkstein, quartzit and basalt in German). The nominal PSVs for the three aggregates are 42, 52 and 61 respectively.

Instruction was provided at Asphalta’s facilities for specimen preparation. The mosaic specimens were prepared in the same way as has previously been described, although
considerably more time and attention was requested than would be normal at TRL: other European laboratories reportedly spend several hours preparing each individual mosaic. The mastic specimens were prepared by filling a metal cylinder (Figure 6.1) with coarse aggregate, bitumen and limestone filler. The mastic cylinder was allowed to cool and, once set, was sliced into discs which were gritblasted until aggregate surfaces were proud of the surrounding bitumen. The preparation method for mastic specimens has the advantage of randomising the aggregate placement and takes less time than the prescribed mosaic preparation method but the resultant aggregate faces are cut rather than crushed.

![Figure 6.1 Mastic cylinder formwork](Image)

The results reported by Asphalta and distributed to the participating laboratories revealed considerable variability; in some cases there is overlap between the highest measurement made on a limestone mosaic and the lowest measurement made on a quartzite mosaic. There is similar overlap between the quartzite and basalt specimens. Table 6.3 summarises the average friction measured across all laboratories for each aggregate source, the standard deviation and reproducibility for each source and the average standard deviation and reproducibility for the whole experiment. The reproducibility is an estimate of the maximum difference, to be expected in 95% of cases, between identical specimens tested under identical conditions in different laboratories. No attempt has been made to validate the calculations and they appear to be representative of the reported measurements.

### Table 6.3 Summary of results from tests on mosaic specimens

<table>
<thead>
<tr>
<th></th>
<th>Limestone</th>
<th>Quartzite</th>
<th>Basalt</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average $\mu_{\text{PWS500}}$</td>
<td>0.1437</td>
<td>0.3970</td>
<td>0.2911</td>
<td></td>
</tr>
<tr>
<td>Standard deviation between laboratories</td>
<td>0.0209</td>
<td>0.0345</td>
<td>0.0459</td>
<td>0.034</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.0580</td>
<td>0.0956</td>
<td>0.1271</td>
<td>0.094</td>
</tr>
</tbody>
</table>

The results for testing on the mastic specimens are shown in Table 6.4. Friction measured on the mastic specimens was approximately 0.05 lower than for the mosaic specimens and there is very similar variability in the results. The consistent reproducibility may indicate that variations are due to the machines themselves rather than to the specimen preparation method. The organisers of the round-robin suggest
that the range of experience – some laboratories using the machine regularly, others not – as a possible cause for additional variability.

Table 6.4 Summary of results from tests on mastic specimens

<table>
<thead>
<tr>
<th></th>
<th>Limestone</th>
<th>Quartzite</th>
<th>Basalt</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average $\mu_{PWS60}$</td>
<td>0.0968</td>
<td>0.3538</td>
<td>0.2253</td>
<td></td>
</tr>
<tr>
<td>Standard deviation between laboratories</td>
<td>0.0182</td>
<td>0.0398</td>
<td>0.0464</td>
<td>0.035</td>
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<tr>
<td>Reproducibility</td>
<td>0.0505</td>
<td>0.1102</td>
<td>0.1285</td>
<td>0.096</td>
</tr>
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</table>

Each machine that took part in the round-robin experiment tested two specimens of each type. It is possible to calculate the repeatability for each machine by using the absolute difference in friction measured on each pair of specimens in place of standard deviation. On average, repeatability was 0.03 and 0.04 for mosaic and mastic specimens respectively, which compares well with the calculations made earlier.

6.3 Specimen preparation

Although one of the Wehner-Schulze machine’s primary advantages is its ability to test asphalt specimens, it is possible that it will be used in place of the PSV test to measure the polish resistance of aggregate alone (in the mosaic format). Repeatability is very good for this type of specimen (Section 6.1). However, there is clearly a desire to increase the speed of specimen manufacture – the anecdotal suggestion that each specimen can take several hours to prepare makes the test undesirable in the context of routine or commercial testing, although experience at TRL suggests that it should take no longer than two hours even for an inexperienced operator.

Additionally, the effect on test results of PSV test specimen preparation by different operators has been a matter of debate – the skid resistance measured on a specimen depends on the arrangement of the aggregate particles. Since the W-S mosaics are circular it is not so easy to arrange the particles in a regular fashion, and it has been shown that the repeatability is good even with the inclusion of variability due to different operators, but it is feasible that, with practice, the specimens could be prepared with some subjectivity.

To these ends a small experiment was carried out to compare friction measurements after polishing made on the set of mosaic specimens tested in Section 6.1 with measurements on mosaic specimens prepared in a less systematic way. Most of the time required for specimen preparation is spent placing aggregate particles on their flattest faces on a circular board in order to form a neat mosaic. An attempt has therefore been made to prepare specimens by randomly placing the aggregates on the board. Using the same coarse aggregates (labelled 3, 4 and 5 above), two sets of nine and a further set of three mosaic specimens were prepared by three operators using the following method, illustrated in Figure 6.2 and Figure 6.3.

1. Scoop a handful of the aggregate particles (having been appropriately graded) and place them on the board

2. Use a flat-based implement (a plastic coffee cup was used here) to lightly tamp and simultaneously roll the aggregate particles until they are spread out to only one-aggregate-layer thick
3. Taking care not to displace already tamped aggregate particles, repeat the process with another handful of aggregate particles until the board is evenly covered

4. Carefully fill any gaps using single aggregate particles, taking care not to create a second layer

5. After all gaps are filled, lightly tamp the aggregate layer again to knock all aggregates to rest on their flattest side, without making the particles so closely packed that they rest on each other with sharp edges facing down

6. Pour sand to fill interstices and apply the epoxy base mixture as for normal mosaic specimen preparation.

Figure 6.2 Tamping aggregate particles for random mosaics (left to right) one handful, several handfuls and after gaps filled with single stones

Figure 6.3 Completed mosaic specimens after systematic (2 hours) and random (25 minutes) preparation

The graph in Figure 6.4 shows the friction measurements made on the systematically and randomly prepared mosaic specimens. None of the results from random specimens were identified as outlying measurements and the outliers for systematic specimens are not shown on the graph. There is a small amount of additional variability arising from the quicker, random, specimen preparation method and the average friction measurement is 0.015 higher, possibly because of the presence on the surface of more edges and angular faces. Table 6.5 gives the average standard deviation and repeatability calculated for each set of specimens. As before, the values in brackets and italic have been calculated by considering separately the sub-sets prepared by different operators.
Figure 6.4 Friction measurements on randomly and systematically prepared mosaic specimens

Table 6.5 Summary of friction measurements on randomly and systematically prepared mosaic specimens

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<tr>
<th></th>
<th>Random mosaics</th>
<th>Systematic mosaics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate 3</td>
<td>Mean 0.556</td>
<td>Mean 0.149</td>
</tr>
<tr>
<td>Coarse aggregate 4</td>
<td>Mean 0.166</td>
<td>Mean 0.149</td>
</tr>
<tr>
<td>Coarse aggregate 5</td>
<td>Mean 0.314</td>
<td>Mean 0.313</td>
</tr>
<tr>
<td></td>
<td>σ_r3 0.009</td>
<td>σ_m3 0.011</td>
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<tr>
<td></td>
<td>σ_r4 0.017 (0.007)</td>
<td>σ_m4 0.005 (0.003)</td>
</tr>
<tr>
<td></td>
<td>σ_r5 0.019 (0.016)</td>
<td>σ_m5 0.005 (0.005)</td>
</tr>
<tr>
<td></td>
<td>r_r3 0.025</td>
<td>r_m3 0.031</td>
</tr>
<tr>
<td></td>
<td>r_r4 0.048 (0.020)</td>
<td>r_m4 0.014 (0.010)</td>
</tr>
<tr>
<td></td>
<td>r_r5 0.053 (0.047)</td>
<td>r_m5 0.014 (0.014)</td>
</tr>
</tbody>
</table>

The average repeatability of the test using systematically prepared specimens is 0.02 as previously discussed. The average repeatability of the test using randomly prepared specimens is 0.04 or 0.03 depending whether or not operator variability is included: in 95% of cases, the difference between tests on a pair of specimens will be between 50% and 100% greater if those specimens have been prepared randomly. On this basis, the same accuracy would be obtained from testing up to four times as many specimens prepared using the random methodology. The small amount of time saved in specimen preparation does not outweigh the additional time required to actually test the additional specimens. However, there may be scope to speed up the mosaic specimen preparation process, especially by development of the aggregate arrangement strategy (vibrating plates are used to prepare specimens in some aggregate tests), without increasing variability beyond the requirement of the test.
7 European development

Details of the initial discussions TRL had with colleagues in France and Germany are reported in PPR366 (2008). Since then, results from these and other research programmes have been published, for example those described by Do et al. (2009) and Kuijper (2010). Although the research efforts are similar in scope and the results could be applicable to the goals of each country, it is evident that requirements for the use of the Wehner-Schulze machine are quite diverse. The differences are due to local skid policy, availability of natural resources and differences in skid resistance theory. For example, in most of Europe:

- It is not as common to use coarse aggregate with PSV greater than 60 because the broad range of natural aggregate available in the UK is not matched in Europe
- Skid policy is often less elaborate – on heavily trafficked roads skid resistance (and therefore aggregate polishing) is either good or bad rather than being dependent on road geometry and accident risk
- Skid resistance is thought to reduce over time under the cumulative action of passing traffic rather than to reach an equilibrium value related to the average daily traffic volume.

Discussions with the equipment manufacturer have revealed that the state of development of the machine is at odds with the various institutions’ desires to use it as a specification tool. When the Highways Agency’s machine was purchased it became the twelfth commercial machine in operation. Although further machines will have been built since then, the number is still small and it is understood that each machine has been improved or changed since the previous one built. Furthermore, there are a number of features of the machine’s operation that are not yet well understood. Not least of these is the amount of torque imparted to the specimen during the polishing cycle – it is measured continuously but no research has been undertaken to determine the sensitivity of subsequent friction measurements to changes in the torque resulting, for example, from differences or faults with bearings in the polishing rollers.

Attempts have been made to define a Standard document to regulate the use of the machine and several workshops have taken place to discuss potential future research. It has been recognised that this is required before the machine can be used widely as a specification tool. The name of the procedure for this purpose has been altered to “Friction After Polishing” or FAP. There are two main work strands, as in the scoping studies reported here: to determine a stable set of $\mu_{PWS60}$ threshold values for asphalt or aggregate so that in-service performance can be predicted and to determine the causes for between-machine variability and improve reproducibility.
8 Summary

The results of experiments carried out to evaluate the ability of the Highways Agency’s Wehner-Schulze machine to simulate the action of traffic are summarised below, along with comments about the success of the experimental methodology and the implications of some of the results.

8.1 Methodology

In general, the technique of embedding cores into in-service roads has been shown to be a sound method for assessing the direct effects of traffic. Inspection of the specimen surfaces and measurements of friction have demonstrated that they have experienced some polishing action and it is assumed that it is representative of the polishing experienced in the wheelpaths of the surface course in low-stress situations.

Access to the trial sites to install and then retrieve the asphalt discs was more difficult than anticipated at the outset of the project. However, the same difficulty would have been experienced for coring of any sort and the advantage of minimising the number of sites required to test a variety of aggregate combinations, through use of the insertion technique, is clear. A further complication that was not anticipated led to damage of several of the inserted specimens when the channels for a traffic counting loop were sown through one of the trial sites.

Extension of the methodology to examine the polishing experienced by the surface course in higher stress situations (bends, roundabout and junction approaches) is desirable but may be more difficult. Although the principle of embedding a series of discs into the wheel paths would no doubt result in some polishing it would be necessary to carefully assess the behaviour of traffic in the location to ensure each specimen is polished to the same degree.

8.2 Surface appearance

A visual comparison of the polishing effect of different levels of traffic and the different test regimes used in the W-S machine was carried out by examination of photographs of specimen surfaces. It was observed that the amount of bitumen and fine aggregate remaining on the surface was the dominant feature and it was possible to differentiate the specimens taken from sites with three levels of traffic using this feature alone. This is consistent with observations, made in other studies (Roe, Dunford, & Crabb, PPR324, 2008), of the condition of various asphalt surfacings and suggests that the polishing experienced by specimens was representative of the polishing experienced by the surface course in general.

An initial inspection suggested that the LCPC method for testing in the W-S machine (involving frequent friction tests and no gritblasting) resulted in a degree of polishing consistent with a low volume of traffic. Conversely, the TUB method (including a gritblasting stage and fewer friction tests) appeared to result in a specimen resembling one that had experienced a greater volume of traffic. However, it was also shown that the bitumen/fine aggregate layer is eroded by weathering, with no traffic action at all, so its presence is not a good indicator of the degree of polishing, only of aggregate exposure.
Examination of more detailed photographs of the specimen surfaces revealed a divergence in the apparent polishing mechanisms involved during the different W-S test regimes. For the softest coarse aggregate, repeated friction tests and failure to remove the bitumen with gritblasting apparently resulted in wearing localised regions completely flat, which did not appear to be representative of the action of traffic (where aggregate particles stand slightly proud of the bitumen/fines matrix).

### 8.3 Friction measurements

Friction measurements made on specimens extracted from the trial sites conform to the behaviour expected for surface courses in general and can be explained by the well documented physical phenomena of equilibrium skid resistance and seasonal variation. Skid resistance remains higher on specimens extracted from the site carrying the least traffic. Skid resistance is lower in the middle of the summer than it is after the winter period. In addition to the photographic evidence this suggests that the polishing experienced by the embedded discs is representative of polishing by traffic on the surface course in general.

When comparing friction measurements made after polishing in the W-S machine using the two different test regimes it was shown that the range of measurements is greater if a gritblasting stage, and less frequent friction testing, is included. This may be because the gritblasting reveals more of the coarse aggregate, allowing it to become polished. If the coarse aggregate is more susceptible to polishing than the bitumen/fines layer then this could result in a reduction in friction. Conversely, if the coarse aggregate is less susceptible to polishing than the bitumen/fines layer then gritblasting and further polishing could result in an increase in friction. Additionally, there may be a cumulative polishing effect owing to a build up of the polishing medium during the TUB method that does not occur during the LCPC method because the quartz flour is washed away by frequent friction tests.

Friction measurements made on specimens after polishing in the W-S machine correlate well with friction measurements made on specimens with the same asphalt mix after polishing by traffic. The correlation is improved by using average measurements across all extracted discs. With hindsight, given information about the precision of the test (summarised below), more than one specimen of each mix could have been extracted on each occasion, to better characterise traffic polishing.

It may be possible to use average daily volumes of traffic to predict the skid resistance on the surface course in straight, non-event locations, using measurements of friction made after polishing in the W-S machine. However, the amount of data collected here is insufficient to develop this fully. The most useful prediction, i.e. for performance in more stressful locations (e.g. bends, roundabout and junction approaches), cannot be attempted. The good correlation between friction after W-S polishing and friction after traffic polishing does indicate that if one asphalt exhibits better skid resistance than another after polishing in the laboratory, it will probably also have better skid resistance in service.

### 8.4 Precision and specimen preparation

Sets of asphalt and aggregate-only specimens were prepared in the laboratory and tested in the W-S machine in order to estimate the repeatability of the test. Sources of variation for tests on asphalt specimens include aggregate sampling and grading,
weighing of materials, mixing, compaction, uniformity of bitumen. Sources of variation for aggregate-only specimens also include aggregate sampling and grading and it was expected that the operator would have a greater influence on variability than was actually observed. It was found that the repeatability of the test for asphalt is 0.05 and the repeatability of the test for aggregate-only is 0.02 regardless of whether preparation by different operators is included.

The reproducibility of the test was investigated by round-robin testing, organised by German consultancy Asphalta. The results of these tests, which included fourteen different laboratories suggest that the reproducibility of the machine is relatively poor, with a value of 0.09. It is possible that variability is increased by the range of experience the participating laboratories had with the machine at the time. Alternatively, it is possible that small physical differences in the machines may lead to a constant offset in the measurements and therefore to the apparent variability. If this latter explanation can be demonstrated it may be possible to implement a correction factor that could be used to harmonise results across all machines.

The reported repeatability and reproducibility of the PSV test are 3 and 6. An exact comparison is not possible without direct correlation of the friction measurement used in the PSV test with the friction measurement used in the W-S machine. However, superficially, the repeatability of the W-S machine compares favourably (0.02) and its reproducibility (0.09) does not. For research, or for in-house material comparison, a low value for repeatability is desirable and it is likely that individual W-S machines are already suitable for these purposes. However, for material specification, where results from different laboratories are necessarily used against a single standard or specification, the poor reproducibility suggests that further development is required.

8.5 European and future development

Correspondence with European colleagues has revealed similar programmes of research and a desire to use the W-S machine as a specification tool for surface course materials. Variation in local skid policy and available resources (which contributes to skid policy variation) is likely to result in slightly different final usage of equipment like the Wehner-Schulze machine. However, with careful planning it should be possible to develop collaborative research that will achieve the goals of all parties.

To progress towards a specification for materials tested in the W-S machine, related to prediction of in-service performance, a collaborative programme of research would need to:

- Prepare, and test in the W-S machine, aggregate-only specimens using coarse aggregate sampled before mixing into an asphalt
- Collect samples of the mixed asphalt from pavers as new surface courses are laid
- Prepare asphalt specimens and test in the W-S machine
- Measure skid resistance on site (using full scale test device) either throughout the pavement lifecycle or after 3 years’ service to ensure equilibrium has been reached
- Take cores from trial sites in a range of locations to sample low and high-stress situations and test friction in the W-S machine.
A successful research programme would thereby allow investigation of relationships between aggregate tested in the laboratory and in-service performance, asphalt tested in the laboratory and in-service performance and full scale and laboratory measurements of friction.

Given the relatively poor reproducibility of the W-S machine it would be necessary to carry out this research on each machine individually unless a more satisfactory explanation, and mitigation, for the between-machine variability can be realised. This might be achieved by carrying out the above research programme with samples distributed to every machine operator. Alternatively, further structured round-robin testing could be carried out in conjunction with ongoing accreditation of all machines in Europe.

**Acknowledgements**

The work described in this report was carried out in the Infrastructure Division of the Transport Research Laboratory. The authors are grateful to David Whiteoak and staff at TRL who organised and carried out the experimental work, to Min-Tan Do of IFSTTAR and Michael Rohleder of BASt for their input during the review of European practice and to Andreas Freundl of BPS Wennigsen for his technical expertise with the machine.

**References**


Kuijper, P. M. (2010). *Validation of the Wehner/Schulze test.* NL: Rijkswaterstaat, Department of Transport and Shipping.


Appendix A  Pavement Test Facility

The PTF, shown in Figure A.1, is capable of applying successive wheel passes either along the same transverse position across the pavement (canalised trafficking) or at pre-programmed increments either side of the centreline within the range ± 450mm. The vertical loading, direction of travel, speed, and lateral position of the wheel may be selected as required. In addition, the pavement temperature can be raised above ambient using an infra-red pavement heating system controlled by thermocouples installed in the pavement. For flexible pavements temperature is a critical factor in pavement wear as the characteristics of asphalt change with temperature. Pavements in the PTF can either be trafficked at ambient temperature or at maintained temperatures above ambient up to 45 °C.

Pavements are built within the test pit and can be of granular, asphalt or cementitious construction and are typically 10 m long by 2.4 m wide. In addition to assessing the performance of different pavement construction materials the machine can also be used to traffic utility chambers, buried pipes and road marking materials and products.

Wheel load, tyre inflation pressure and tyre type can influence the behaviour of a pavement because they alter the stresses applied to the pavement and the contact area over which these stresses are applied. The PTF can be fitted with a range of tyre types mounted either singularly or as a pair and the load and inflation pressure can be varied in order to assess their effects. Pavement engineers base their designs on the anticipated loading the pavement is expected to see in its lifetime in terms of million standard axles (msa), where a standard axle is a load of 8.16 tonnes. This equates to a wheel load of 40 kN for the single wheel or wheel pair and this loading can be varied over the range 23-100 kN.

Figure A.1 Pavement Test Facility
### Appendix B  Friction measurements on polishing method comparison specimens

#### Table B.1 W-S friction ($\mu_{pWS60}$) during polishing with TUB method

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<th>Mix ID</th>
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<th>90*</th>
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*after gritblasting

#### Table B.2 W-S friction ($\mu_{pWS60}$) during polishing with LCPC method

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Table B.3 W-S friction (μ\textsubscript{PWS60}) on specimens retrieved from trial sites

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Appendix C  Development of a friction prediction formula

The following simple calculations are based on the relationship between the friction measured on specimens extracted from the sites during August 2010 and friction measured on specimens polished in the W-S machine. Any formula developed is valid for equilibrium skid resistance, as measured during the summer, at non-event locations. It should also be noted that the correlations between road and W-S specimens are relatively poor, relying on measurements on a single pairs of specimens, and that the number of traffic levels assessed is not sufficient to allow accurate determination of the formula coefficients.

A similar treatment, for prediction of in-service skid resistance from results of laboratory tests after simulated polishing, is detailed by Roe and Harsthorne (1998). Crucially, that work looked at the laboratory polishing of coarse aggregates alone (the PSV test), and compared in-service performance of various asphalt surfaces in which they were used. This work has the advantage of comparing like for like asphalt specimens, using the same friction measurement technique, but it is limited by its sample size.

The volumes of traffic at the three sites are nominally 4500, 1200 and 200 commercial vehicles per day (CvD) for sites A, B and C respectively. Figure 5.7 shows the comparisons between friction measured on road specimens and friction measured on W-S specimens for each of the three sites. Table C.1 gives the slope, intercept and $R^2$ for each of the linear best-fit lines shown on that graph.

<table>
<thead>
<tr>
<th>Site</th>
<th>Nominal traffic (CvD)</th>
<th>Slope</th>
<th>Intercept</th>
<th>$R^2$</th>
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<td>A</td>
<td>4500</td>
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<td>1200</td>
<td>0.38</td>
<td>0.28</td>
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<td>C</td>
<td>200</td>
<td>0.64</td>
<td>0.22</td>
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</table>

These slopes and intercepts are plotted against the nominal traffic level in Figure C.1 and a logarithmic relationship can be demonstrated for each. A formula for prediction of friction in-service (as measured by W-S machine) given measurements of friction after simulated polishing could therefore be expressed as:

$$\mu_{PWS60}(\text{road}) = [1.33 - 0.13\ln T]\mu_{PWS60}(\text{TUB}) + 0.033\ln T + 0.048$$

where $T$ is the volume of traffic at the site in terms of the number of commercial vehicles per day and $\mu_{PWS60}(\text{TUB})$ is friction measured by the Wehner-Schulze machine after polishing using the full TUB regime.
Figure C.1 Relationship for slopes and intercepts of road/W-S correlation with traffic level