PAVEMENT THICKNESS, SURFACE EVENNESS AND CONSTRUCTION PRACTICE

by

J C McLellan

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ABSTRACT

The structural performance and the riding quality of a road are strongly influenced by the accurate and uniform laying of the pavement materials to the appropriate design thickness. The report describes an investigation into the effectiveness of level-control procedures currently used in road construction to achieve the required thicknesses and surface regularity.

Measurements of surface profile and of thickness of pavement were made, during construction, on 38 randomly selected 100-metre lengths from two flexible and three rigid roads.

Analysis of the measurements showed that the mean layer thicknesses were generally at or near the required thickness but that layer thickness varied considerably along the test lengths, particularly for the concrete pavements. On flexible roads, the results showed that the profiles of the lower layers influenced the evenness of the finished surface. On rigid construction the evenness of the finished surfaces was found to be independent of the profile of the sub-base.

It is suggested that better methods of controlling the laying of pavement materials would improve the uniformity of performance of both flexible and rigid roads and would improve the riding quality of flexible roads.

1. INTRODUCTION

The riding quality and structural performance of a road are related to the accuracy to which the various layers of material are laid. To achieve optimum performance within a given design, the aim should be to have an even surface profile and layers that are as uniform in thickness as possible.

To control the accuracy of laying of material the current Specification for Road and Bridge Works\(^1\) requires that measurements of surface level of each layer be made relative to the design level of the finished road surface. Tolerances for surface levels of each layer and of the formation are also specified.

The achievement of the specified requirements depends on the effectiveness of the existing level control procedures and equipment. An investigation has therefore been undertaken to determine the effectiveness of existing procedures in achieving (a) accurate and uniform pavement thickness and (b) a good riding surface. The report describes the methods used and the results obtained.

2. LEVEL CONTROL OF FLEXIBLE AND RIGID ROAD CONSTRUCTION

Typical cross sections of flexible and rigid roads are shown in Figure 1. The normal practice in flexible construction is to construct the pavement in successive layers and to run the paving machines directly on the surface of the previously constructed layer. The paver design permits layers of variable thickness to be laid; this assists in progressively smoothing out unevenness in each succeeding layer.
Various automatic paver guidance systems are now available to control the level of the paver screeds, and the achievement of a good surface profile is thus less dependent on the skill of the operator than previously.

Concrete can be laid using either a fixed-form paving train or a slip-form paver. The train runs on rails that are usually mounted on steel side forms and the vertical alignment of the rails controls the level of the screeds on the finishing machines. Unevenness in the sub-base profile would not therefore be expected to influence the profile of the finished concrete surface.

Slip-form pavers are mounted on caterpillar tracks that run on the prepared sub-base on either side of the slab being laid. Their vertical and horizontal positions are controlled by automatic guidance systems. The effects of sub-base profile on pavement thickness and riding surface for pavements constructed with both types of paving equipment are examined in the report.

3. THE PAVING OPERATIONS EXAMINED AND MEASURING EQUIPMENT USED

3.1 Sites

Measurements of pavement levels were made on five sites, two of flexible and three of rigid construction; details of the sites, labelled A to E, are shown in Table 1. Contracts A and C were three-lane dual-carriageway motorways. Contract E was a motorway with two-lane dual-carriageways and Contracts B and D were two-lane dual-carriageway all-purpose roads. As shown in Table 1 the finished riding surface had a riding quality that ranged from fair to good and all of the surfaces complied with the surface regularity requirements of the Specification.

3.2 Measuring equipment

The equipment used for levelling is shown in Plate 1. It consists of a rotating laser source capable of generating a datum plane with an effective radius of up to 300 metres and a level staff fitted with a moving optical receiver that is sensitive to the laser light. The receiver travels up or down the staff, which has metric graduations, until it detects and locks on to the laser plane. With the detector locked in position the staff can be lifted and the measurement read from the scale. The accuracy of measurement decreases with increasing distance from the laser source and was found to be within ±2 mm at a radius of 100 metres. The rotating laser source is powered by a 12 volt car battery and the staff has a 12 volt dry battery fitted within it.

Readings can be taken rapidly over a relatively wide area without changing the laser datum setting, measurements can be taken by one man without an assistant and the laser instrument is self-levelling. The equipment is therefore a considerable improvement on conventional optical levelling techniques.
### TABLE 1
Details of constructions observed

<table>
<thead>
<tr>
<th>Contract</th>
<th>Pavement layers</th>
<th>Construction equipment</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>WC - 40 mm RA</td>
<td>{ Wheeled pavers }</td>
<td>{ PLC:— averaging beam }</td>
</tr>
<tr>
<td></td>
<td>BC - 60 mm DBM</td>
<td>{ S-W rollers }</td>
<td>{ PLC:— wire guided }</td>
</tr>
<tr>
<td></td>
<td>RB - 150 mm RA</td>
<td>Grader, S-W roller</td>
<td>riding quality:— fair</td>
</tr>
<tr>
<td></td>
<td>S-B - Crushed limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>WC - 40 mm RA</td>
<td>{ Wheeled paver }</td>
<td>{ PLC:— averaging beam }</td>
</tr>
<tr>
<td></td>
<td>BC - 90 mm DBM</td>
<td>{ S-W roller }</td>
<td>{ PLC:— wire guided }</td>
</tr>
<tr>
<td></td>
<td>RB - 180 mm LC</td>
<td>Wheeled paver, VIB rollers</td>
<td>riding quality:— fair</td>
</tr>
<tr>
<td></td>
<td>S-B - Crushed limestone</td>
<td>Grader, S-W roller</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>CS - 280 mm or 305 mm unreinforced Granular (type 2)</td>
<td>Fixed-form paving train including joint-forming machines and diagonal finisher</td>
<td>MW - 3 lanes</td>
</tr>
<tr>
<td></td>
<td>S-B - Granular (type 2)</td>
<td>Grader, VIB roller, S-W roller</td>
<td>riding quality:— good</td>
</tr>
<tr>
<td>D</td>
<td>CS - 225 mm unreinforced Granular (type 2)</td>
<td>Fixed-form paving train similar to that on Contract C</td>
<td>MW - single lane</td>
</tr>
<tr>
<td></td>
<td>S-B - Granular (type 2)</td>
<td>Grader, VIB roller, S-W roller</td>
<td>riding quality:— fair</td>
</tr>
<tr>
<td>E</td>
<td>CS - 280 or 305 mm unreinforced soil cement</td>
<td>Conforming-plate slip-form paving train</td>
<td>PLC:— wire guided</td>
</tr>
<tr>
<td></td>
<td>S-B - soil cement</td>
<td>Mix-in-place soil stabiliser VIB roller, S-W roller</td>
<td>riding quality:— good</td>
</tr>
</tbody>
</table>

WC - wearing course  S-W - smooth-wheeled  VIB - vibrating  PLC - paver level  MW - machine width  CJ - contraction  P - concrete laid on polythene

### 4. MEASUREMENT PROCEDURE

On each site, a number of test lengths of 100 metres were randomly selected. On each length level measurements were taken on the surface of each construction layer at a spacing of 0.5 metres along a line 1 metre from the nearside edge of the nearside lane.

A steel tape was used to locate the points for measurement along the test length. The laser level was then positioned so that, where possible, the beam was within the vertical working range of the sensing staff over the 100 metre test length. If this was not possible, the laser level was repositioned during the sequence of measurements. The rotating laser source required a period of not more than two minutes to stabilise before measurements could be made.

At each site, a convenient temporary bench mark, consisting of a steel pin set in concrete, was used as a reference point. The same bench mark was used when measurements were taken on subsequent layers and it also provided a means of relating measurements when the laser level was moved to a new position.
On Contracts A, B and D, 19, 6 and 3 test lengths respectively were investigated; on each of Contracts C and E, 5 lengths were examined.

5. ANALYSIS AND DISCUSSION OF DATA

5.1 Method of analysis

The level data from each 100-metre test length were processed by computer to give the thicknesses and profiles of each layer in the test length. Layer thicknesses were obtained from the difference of corresponding level measurements on successive layers. The mean and the standard deviation of the thicknesses of each layer were computed and histograms of the distribution of thickness were also produced by the computer. Surface profiles of the layers were characterized as deviations from a 25 metre moving-average datum; wave lengths greater than 25 metres have little effect on vehicle ride. As stated in Section 3.1 the achieved riding quality on the test surfaces ranged from fair to good.

The influence of the profiles of the lower layers on the evenness of the finished surface was examined using the cross-correlation between the profiles of the various layers defined relative to their 25 metre moving-average datum lines.

5.2 Correlation of layer profiles

Typical examples of the profiles for 30 metre lengths obtained from flexible and rigid construction are shown in Figure 2. For flexible construction it is apparent that there is a correspondence between the profiles of successive layer surfaces. In contrast, the rigid construction shows little or no correspondence between the profiles of the sub-base and of the finished road surface.

The range of correlation coefficients obtained for the different comparisons between layers is shown in Figure 3. In flexible construction, there is generally a high correlation between the profiles of the wearing course and basecourse layers; a lower correlation exists between the basecourse and roadbase, roadbase and sub-base and between wearing course and roadbase layers. These correlations confirm the visual evidence in Figure 2 that the profiles of the lower layers of flexible construction influence the profile of the wearing course. The correlation between the concrete surface and the sub-base surface is low, showing that the sub-base profile has little influence on the finished pavement surface.

The influence of the unevenness of the lower layer surface on the correlation between the upper and the lower layer surfaces is shown in detail in Figure 4. Unevenness is represented by the standard deviation of the deviations of the layer profile relative to a 25 metre moving-average datum. The correlation is shown to be generally independent of layer unevenness.

Figure 5 shows that, for flexible construction, the correlation between layer surfaces decreases as the mean layer thickness increases; for rigid construction the correlation is independent of layer thickness.
5.3 Layer thickness

5.3.1 Level tolerances and thickness: Tolerances for thickness are not given in the Specification for Road and Bridge Works. However, from the tolerances for the surface level of the layers and the minimum thickness requirements, it is possible to derive tolerances for thickness. Relevant details of the tolerances in surface levels and thickness for flexible construction are given in Table 2 and for rigid construction in Table 3. The flexible roads investigated were constructed to the amended 1969 specification (Table 2).

<table>
<thead>
<tr>
<th>Specification edition</th>
<th>Surface</th>
<th>Level tolerances (mm)</th>
<th>Derived tolerances for thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974 amendment to 1969</td>
<td>Wearing course</td>
<td>±6</td>
<td>+12, −6*</td>
</tr>
<tr>
<td></td>
<td>Basecourse</td>
<td>±6</td>
<td>±19</td>
</tr>
<tr>
<td></td>
<td>Roadbase</td>
<td>±13</td>
<td>±33</td>
</tr>
<tr>
<td></td>
<td>Sub-base</td>
<td>±20</td>
<td></td>
</tr>
<tr>
<td>1976</td>
<td>Wearing course</td>
<td>±6</td>
<td>+12, −5**</td>
</tr>
<tr>
<td></td>
<td>Basecourse</td>
<td>±6</td>
<td>±21</td>
</tr>
<tr>
<td></td>
<td>Roadbase</td>
<td>±15</td>
<td>+45, −25</td>
</tr>
<tr>
<td></td>
<td>Sub-base</td>
<td>+10, −30</td>
<td></td>
</tr>
</tbody>
</table>

* A clause was included that stated that the combination of permitted surface level tolerances shall not result in a reduction in the thickness of the wearing course by more than 6 mm below the specified thickness.

** A reduction of more than 5 mm in the wearing course is not permitted.
A clause was also added stating that the thickness of the whole pavement above the sub-base shall not be more than 15 mm below the specified thickness.

Table 3

<table>
<thead>
<tr>
<th>Surface</th>
<th>Specification edition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road surface</td>
<td>±¼ in</td>
</tr>
<tr>
<td>Sub-base</td>
<td>+0, −1 in</td>
</tr>
<tr>
<td>Derived tolerances</td>
<td>+28, −3</td>
</tr>
<tr>
<td>of concrete slab (mm)</td>
<td></td>
</tr>
</tbody>
</table>

* A clause was included that stated that the combination of permitted surface level tolerances shall not result in a reduction in the thickness of the concrete slab by more than 15 mm from the specified thickness.
5.3.2 Flexible construction: The deviations of the averages of the measured layer thicknesses from the specified thickness for each 100 metre test length are shown in Figure 6. The combined wearing and basecourse mean thickness levels show that the great majority of the results fall below or on the specified thickness level. The corresponding thickness levels of the roadbase show that 5 of the 7 test lengths were below or on the specified level.

The specification tolerances shown in the figure do not apply to averaged thickness levels but to individual thickness measurements. Consequently, for the wearing course 76 per cent of the individual measurements were within the tolerances. For the basecourse, combined wearing course and basecourse, and the roadbase, 93 per cent, 85 per cent and 95 per cent respectively were within the tolerances. For the wearing course 22 per cent of the thicknesses were below the requirement of the lower thickness limit (see Table 2).

In Figure 7 the correlation between layer surfaces is shown to increase as the variation in the layer thickness decreases; as expected, the more uniform the thickness, the higher is the correlation.

5.3.3 Rigid construction: The effect of sub-base unevenness on the variation in thickness of the concrete slab is shown in Figure 8. Here, the sub-base unevenness for each complete 100 metre test length is considered, rather than the unevenness relative to a 25 metre moving-average datum. This approach was adopted because the thickness variation is influenced by all wavelengths within the 100 metre test lengths and not just those that affect riding quality, i.e. those less than 25 metres. The strong influence of the sub-base unevenness on the variation in thickness is shown by the very high correlation between the unevenness and thickness in Figure 8.

The deviations of the mean slab thickness from the specified thickness for each 100 metre test section on the three rigid contracts C, D and E are shown in Figure 9(a). The figure shows that the mean thicknesses exceed or equal the specified thickness and that 91 per cent of the individual measurements are within the tolerances. Five per cent of the thicknesses were below the lower thickness limit defined in Table 3.

The corresponding deviations for the total data from each site are shown in Figure 9(b) and are compared with the results from a previous study in which the contracts were constructed to earlier editions of the Specification for Road and Bridge Works. Relevant details of tolerances in surface levels are given in Table 3. Figure 9(b) shows that the change in the tolerances for the sub-base levels in the 1969 Specification from a negative value only, to plus or minus values resulted in mean thicknesses being less than the design thickness. After an amendment had been issued in 1974, that limited the possible reduction in slab thickness, the mean thicknesses were again greater than specified.

The overall distribution of the differences between the measured slab thicknesses and the specified thickness for Contracts C, D and E is shown in Figure 10 together with the lower thickness limit requirements.

Although the mean thicknesses of the concrete slabs in these contracts were found to be satisfactory, the variability in the thickness is likely to lead to non-uniform structural performance, especially in Contracts C and D.
5.4 Construction practice

5.4.1 Flexible construction: In the two contracts in flexible construction (A and B), guide wires, erected along the edges of the road, were used to control the vertical alignment of the roadbase and, on Contract B, also the alignment of the basecourse. Averaging beams were used to control level on the basecourse and wearing course in Contract A and in the wearing course only for Contract B.

Examples of the profiles obtained with both guidance systems are shown in Figure 11. The basecourse and wearing course shown in the upper diagram were laid using an averaging beam and the profiles of the surfaces of both layers closely follow the surface of the roadbase. Shown in the lower diagram, the basecourse and roadbase were laid using a wire-guidance system, which provides a fixed reference. A comparison of the profiles shows that the basecourse is less uneven than the underlying roadbase and also that factors other than the guidance system have influenced the achieved surface evenness. The averaging beam used for the wearing course on this second contract also resulted in the wearing course profile following that of the basecourse.

It appears therefore that the method of paver guidance can influence the surface profile but that other factors are also involved; the thickness of the layer has already been considered in Figure 5. The low correlation between the profiles of a lean concrete roadbase and sub-base is in contrast to the relatively high correlation between the asphalt roadbase and the sub-base shown in Figure 2: this suggests that different types of road materials also influence the profile achieved. Compaction procedures, although not studied in this investigation, are also likely to have a significant effect.

5.4.2 Rigid construction: The results from Figure 8 suggest that concrete pavements of a more uniform thickness could be constructed if sub-bases were constructed to tighter tolerances. Over a particularly uneven section of sub-base, shown in the upper diagram in Figure 12, the slab thickness ranges from 279 mm to 335 mm over a distance of 12 metres.

In the two contracts C and D, where fixed-form paving trains were used, the final trimming of the granular sub-bases was carried out after the side forms had been laid. With this method of construction the achievement of a uniformly accurate sub-base surface level should be relatively straightforward. However, the investigation has shown that the sub-bases were not constructed with a uniformly even surface.

In Contract E, where a wire-guidance system was used for level control, a more uniform sub-base was achieved than in the contracts where fixed forms were used.

Because of the particular joint construction method used in Contract E a more uniform sub-base was required than in Contracts C and D. In Contract E, contraction joint assemblies were fixed to the sub-base and, to meet the tolerances required for the positions of the dowel-bars, the assemblies had to be supported on an even sub-base. In Contracts C and D, because the dowel-bars were inserted into the wet concrete, joint assemblies were therefore not required.

Over some short sections in the slip-form paver contract, there was some correlation between the surface profiles of the slab and sub-base. One example is shown in the lower diagram in Figure 12.
The greatest unevenness in all the profiles examined occurred at end of day construction joints.

6. CONCLUSIONS

1. In the three rigid paving contracts examined, the mean thicknesses of the pavement layers were all at or above the specification thickness. Though the thicknesses vary considerably along the test lengths, 91 per cent of the thicknesses were within the derived tolerances. Five per cent of thicknesses were below the lower thickness limit requirement.

2. In flexible construction, unevenness in the lower layers can result in unevenness in the finished road surface. There is a good correlation between the surface profiles of the wearing course and those of the basecourse and some correlation between the basecourse and roadbase and between the roadbase and sub-base. The proportion of the thicknesses of the individual layers within the derived tolerances ranged from 76 to 95 per cent. For the wearing course 22 per cent of thicknesses were below the lower thickness limit requirement. Since this investigation, the specified tolerances for layer thicknesses have been reduced.

3. In rigid construction the variation in the thickness of concrete slabs is closely related to the unevenness of the sub-base. Consequently this unevenness is not reflected in unevenness of the finished concrete surface.

4. Better control of the surface levels of sub-bases would improve the riding quality of flexible roads and the uniformity of performance of both flexible and concrete roads.

7. FUTURE WORK

The economics of constructing sub-bases to a more accurate surface level is being examined. In this work the effect of achieving more accurate levels on the road material, construction control and road performance costs will be studied. Improved equipment, based on the use of lasers, for the more accurate control of laying processes is under development.

8. ACKNOWLEDGEMENTS

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The assistance of Mrs M H Burtwell in the collection of site data and in the computer programming is appreciated.

The cooperation of the RCUs, County Councils and Consulting Engineers in carrying out the site studies is gratefully acknowledged.
9. REFERENCES


Fig. 1 Typical flexible and rigid road constructions
Fig. 2 Examples of layer profiles from (a) flexible and (b) rigid construction
(Profile features longer than 25m have been removed)
Fig. 3 Correlation between surface profiles of various pavement layers
Fig. 4 The effect of lower layer unevenness on the correlation between the surface profiles of layers.
Fig. 5 The effect of upper layer thickness on the correlation between the surface profiles of layers
Fig. 6 Deviation of mean layer thickness from specified thickness for flexible construction
Fig. 7 The effect of the variation in thickness of the upper layer on the correlation between the surface profiles of layers.
Fig. 8 The relation between variation in the thickness of concrete slabs and the unevenness of the sub-base surface
Fig. 9 Deviation of mean slab thickness from specified thickness (a) results from contracts C, D and E (b) results from earlier work showing effect of specification changes
Fig. 11 Examples of layer profiles from flexible construction obtained with different control methods (Profile features longer than 25m have been removed)
Fig. 12 Examples of layer profiles from rigid construction (Profile features longer than 25m have been removed)
Plate 1 Laser levelling equipment, showing rotating laser source, horizontal laser plane reflected on the background and optical receiver on the staff.
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