A35: Test Section 3

Temperature profiling and the monitoring of equipment movements during construction.

Research report
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Seirgei Miller, Henny ter Huerne and André Dorée
Department of Construction Management & Engineering, University of Twente

Address P.O. Box 217, 7500 AE, Enschede
Tel +31 53 489 4601
Fax +31 53 489 2511
E-mail s.r.miller@utwente.nl
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1. Project description

Temperature profiling and the monitoring of equipment movements during the construction Test section 3 on the A35

The report consists of two main sections:

- Temperature profiling during paving operations; and
- Monitoring equipment movements using GPS.

2. Composition of the research group

<table>
<thead>
<tr>
<th>Names</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ir. S R Miller</td>
<td>PhD candidate</td>
</tr>
<tr>
<td>Prof. Dr. Ir. A.G. Dorée</td>
<td>Professor in procurement &amp; market dynamics</td>
</tr>
<tr>
<td>Dr. Ir. H.L. Ter Huerne</td>
<td>Assistant professor</td>
</tr>
</tbody>
</table>

2.1 Acknowledgments

The contributions of the following persons are gratefully acknowledged:

- UT students Marleen Boenders, Matthijs de Man and Zander Veenstra for their assistance during the on-site data collection;
- UT students Marcel Hiehle and Stephan Bosch for their assistance during the data analysis stage; and
- Marco Oosterveld (BAM Wegen) for organising essential data collection equipment and his assistance in the data analysis tasks.
3. Temperature profiling during construction

3.1 Background

Temperature differentials in the asphalt mat can produce density differentials, which will affect the life of the pavement (Mahoney et al., 2000, Willoughby et al., 2002). Temperature segregation occurs because of differential cooling of portions of the mix on the surface of the mix in the haul truck, along the side of the truck box, and in the wings of the paver (Asphalt-Institute, 1989, NCAT, 1991, Mahoney et al., 2000). Stroup-Gardiner and Brown (2000) defined segregation as a lack of homogeneity in the hot mix asphalt (HMA) constituents of the in-place mat of such a magnitude that there is a reasonable expectation of accelerated pavement distress. Temperature differentials are created when the surface layer of the asphalt cools in the truck during transport. The cooler mix on the surface layer of the load can be near cessation temperature. The amount of material that cools depends on many factors including, but not limited to, the haul length, ambient temperature, and wind speed. This cooler material, when not remixed prior to placement, creates concentrated areas in the mat generally termed temperature differentials.

According to Stroup-Gardiner (2000), Read (1997) is credited with the initial observation that temperature differentials in the HMA during construction was a strong indicator of segregated mix. Several researchers have since used infrared camera images to fully document temperature differentials during all aspects of HMA paving operations and identified infrared camera images as a useful method for determining temperature differentials for detecting, locating, and measuring segregation (Brock and Jakob, 1997, Stroup-Gardiner and Brown, 2000, Stroup-Gardiner et al., 2002, Stroup-Gardiner et al., 2004). Their research showed that areas in the HMA mat with temperature differentials of more than 10°C were potentially segregated areas and areas with temperature differentials of more than 20°C were likely to be highly segregated.

3.2 Objectives

The objective of this part of the research was to determine the extent of temperature variability during the construction of the A35 test section in order to assess the degree of temperature homogeneity.

3.3 Data collection

Infrared camera images were used to fully document temperature differentials during the hot mix asphalt paving operations. Two ThermaCAM™ E320 infrared cameras were used to collect surface temperature data. Thermal images were taken in a predetermined protocol at 10m staked positions (see Table 1). The research team prepared schedules based on paver speeds of between 3m/min and 5m/min since the success of the photographic regime was highly dependent on the speed of the paver.

Figure 1 - Example of a thermal image
The supplied camera software was used to undertake the initial analysis of the thermal images with extensive post processing using Excel and MATLAB software. Figure 1 shows an example of a thermal image taken with possibilities for spot analysis (Sp1), area analysis (Ar1) and line analysis (Li1). The screed of the asphalt paver is clearly visible on the left of the image.

![Table 1 – Typical thermal image schedule](image)

Two operators captured more than 400 thermal images over the two-night period instead of the planned 600 images. The main reason for this was the operational discontinuities encountered (change in the speed of the paver) during construction operations. The average speeds for the various paved lanes are shown in Table 2. These speeds were calculated using data taken from the thermal images since they accurately showed the position of the paver at particular times.

The average speed of the paver for lanes 2 and 3 for the first night of paving is above 5m/min and is clearly much higher than the average for the other three lanes (approximately 3.5m/min). This necessitated an on-site change to the thermographic schedules since it was extremely difficult for the camera operators to stick to the schedule and keep up with the paver.

Note that the speeds of the paver were also calculated using the GPS data. This is shown in the analysis of paver movements in Section 0 of the report.

![Table 2 – Average paver speeds in m/min](image)
3.4  Weather conditions

Weather data was collected using a portable weather station. However, the on-site weather data was lost because of the logger overwriting the data after the construction period.

Historical weather data was then collected from the nearby Vliegveld Twente weather station. Table 3 gives weather details for the two-night period.

The effect of the weather on the cooling of the asphalt mix was not considered given that the weather conditions were stable during paving operations with average temperatures of approximately 16°C and an average wind speed of less than 5 km/h.

<table>
<thead>
<tr>
<th>Vliegveld Twente Weather Station</th>
<th>Temp (°C)</th>
<th>Windspeed</th>
<th>Wind direction</th>
<th>Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night 1  Wednesday</td>
<td>Max. 21.0</td>
<td>6.9</td>
<td>135.0</td>
<td>82.0</td>
</tr>
<tr>
<td>Min. 13.0</td>
<td>1.2</td>
<td>0.0</td>
<td>29.0</td>
<td></td>
</tr>
<tr>
<td>Range 8.0</td>
<td>5.7</td>
<td>135.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average 17.9</td>
<td>4.4</td>
<td>81.7</td>
<td>65.6</td>
<td></td>
</tr>
<tr>
<td>St. Dev. 2.4</td>
<td>1.7</td>
<td>45.8</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>Night 2  Thursday</td>
<td>Max. 23.3</td>
<td>6.9</td>
<td>90.0</td>
<td>87.0</td>
</tr>
<tr>
<td>Min. 9.0</td>
<td>3.5</td>
<td>0.0</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>Range 14.3</td>
<td>3.4</td>
<td>90.0</td>
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<td>67.1</td>
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<td>St. Dev. 5.0</td>
<td>1.1</td>
<td>37.2</td>
<td>19.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 - Weather conditions during construction

3.5  Evaluation of surface temperature differentials

3.5.1  Variability in temperature profiles

The temperature data were used to prepare temperature contour maps of the paving operations (as the asphalt mix leaves the paver). Figure 2 shows an example of typical results viz. the temperature profile for the 5m wide Lane 1 paved on the first night. Note that the asphalt paving is shown to start at position 0. This corresponds to kilometre 60,730 on that A35. The paving of Lanes 2 and 3 using the TAS machine started at position 70m and this in turn corresponds to kilometre 60,800 on the A35. The second night’s paving started at kilometre 60,960. This is referred to as position 0 in the subsequent analysis. Note that the direction of paving is shown on Figure 2 i.e. towards Haaksbergen Straat.

The data in these figures are presented on both distance and time axes to highlight key findings. Also, the two nights’ asphalt paving operations are discussed separately.
The first night’s paving operations are shown in Figure 2, Figure 3 and Figure 4.

Figure 2 - Temperature contour map for Wednesday Lane 1

Figure 3 - Temperature contour map for Wednesday Lane 2
Key findings based on temperature measurements are as follows:

- **Paving on Lane 1** started around 22:30 and finished around 23:50 with an average paver speed of approximately 3.5m/min. The average temperature of the asphalt mix delivered to the site for Lane 1 is significantly different on the first night compared to all the other lanes. Closer inspection of the Wednesday Lane 1 temperature contour map shown in Figure 2 shows a distinct difference in surface temperature in the first half of the section paved compared to the second half. The average surface temperature up to position 110m is approximately 146°C compared to approximately 160°C for the rest of the lane. There are two possible reasons for this viz. a distinct difference in the temperature of the mix delivered to the site or the first trucks were waiting for a long period before paving operations started.

- **Paving on Lane 2** started approximately 4 hours later at about 04:30 and was completed around 05:10. The narrow band of contours between positions 70m and 90m in Figure 3 represents the initial movement of the paver and shows the initial coolness of the mix. The more or less constant pattern in the contours between positions 110m and 190m indicate a constant movement of the paver and delivery of asphalt to the surge bin.

- **Paving on Lane 3** started approximately at about 05:30 and was completed around 06:10. As in Lane 2, the narrow band of contours between positions 70m and 90m represents the initial movement of the paver and shows the initial coolness of the mix.

- **A common temperature characteristic is visible in Figure 2 and Figure 4.** viz. a distinct lack of consistent repetitive temperature contours during continuous paving operations.

- **The paver speed for lanes 2 and 3 are markedly higher** (faster than 5m/min) than that for the first lane paved. This is probably as a result of the need to complete paving operations before the road had to be opened for traffic.
The second night’s paving operations are shown in Figure 5 and Figure 6 (Thursday evening start).

**Figure 5 - Temperature contour map for Thursday Lane 1**

- A lack of consistent repetitive temperature contours
- Cooling of the asphalt when the paver stopped

**Figure 6 - Temperature contour map for Thursday Lane 2**

- Surface temperature of the last 130m is lower than the first 80m paved
- Temperature dropping as the last material is used from the hopper

**Key findings for the second night of paving are as follows:**

- Paving on Lane 1 started around 21:50 and finished around 23:20 with an average paver speed of approximately 3,3m/min. The rate of cooling of the asphalt mat is clearly visible when the paving operations stop as shown at position 140m in Figure 5.

- Paving on Lane 2 started approximately 4 hours later at around 03:00 and finished around 04:00 with an average paver speed of approximately 4m/min. Figure 6 also shows a distinct difference in surface temperature in the first half of the section paved compared to the second half.

- A common temperature characteristic can be seen in the temperature contour plots for the lanes viz. erratic temperature contours at the end of the paver movements for both lanes paved on the second night. The temperature of the mix is clearly dropping as the hopper’s last material is used.
There is also evidence of a distinct lack of consistent repetitive temperature contours during continuous paving operations.

3.5.2 Potentially segregated areas

An analysis of the range in surface temperature across the width of the paved lanes in Table 4 reveals the following:

- All five lanes have significant areas where surface temperature varies across the width of the paving by between 10 and 15°C. These could be classed as potentially segregated areas.
- Lanes 1 and 3 in the first night of paving show significant temperature differences in the range of 15 to 20°C and therefore could be seen as potentially highly segregated areas.
- There is evidence of some areas where the temperature difference is greater than 20°C across the width of the paved lane.

<table>
<thead>
<tr>
<th>Surface temperature differentials</th>
<th>0-5</th>
<th>5-10</th>
<th>10-15</th>
<th>15-20</th>
<th>20-25</th>
<th>25-30</th>
<th>&gt;30</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Wednesday</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lane 1</td>
<td>0</td>
<td>6</td>
<td>6</td>
<td>11</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>24</td>
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<tr>
<td>Lane 2</td>
<td>2</td>
<td>9</td>
<td>6</td>
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<tr>
<td>Lane 3</td>
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<td>1</td>
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<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>Thursday</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lane 1</td>
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<td>17</td>
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<td>1</td>
<td>1</td>
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<tr>
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<tr>
<td>Total</td>
<td>4</td>
<td>42</td>
<td>35</td>
<td>19</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>105</td>
</tr>
</tbody>
</table>

Table 4 - Difference in surface temperature across the width of the paved lane

3.5.3 Concentrated cooler areas

Few areas were found with surface temperatures below 100°C and therefore close to asphalt compaction cessation temperature. These were limited to the start up of the paver as shown in Figure 3; and when paving operations stop as shown in Figure 5. However, there is evidence of the appearance of cooler areas that could be the result of the cool mix in the surge bin being reworked in the fresh, hotter mix i.e. the cooler asphalt in the outer areas of the surge bins finally moved through the paver. Figure 2 shows examples at positions 40m, 90m and 180m.
3.6 2-layer ZOAB cooling rates

3.6.1 Cooling rate curves

The thermal images were used to produce individual cooling rate curves at 10m intervals viz. the staked 10m positions. Wednesday’s Lane 1 of paving is used for illustration purposes. Table 5 shows the essential data extracted from the thermographic images. As mentioned earlier, it is possible to analyse the images in three ways viz. based on spot temperatures (Sp1), average temperatures over the area (Ar1) and across the section photographed (Li1).

<table>
<thead>
<tr>
<th>Position: 160m</th>
<th>IR: Date Of Creation</th>
<th>IR: Time Of Creation</th>
<th>Time difference</th>
<th>Sp1</th>
<th>Li1: Max</th>
<th>Li1: Min</th>
<th>Li1: Max - Min</th>
<th>Li1: Average</th>
<th>Ar1: Max</th>
<th>Ar1: Min</th>
<th>Ar1: Max - Min</th>
<th>Ar1: Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>23:31:05</td>
<td>23:40:23</td>
<td>23:55:01</td>
<td>00:06:01</td>
<td>43.4</td>
<td>65.4</td>
<td>60.7</td>
<td>4.7</td>
<td>67.8</td>
<td>63.2</td>
<td>55.3</td>
<td>7.9</td>
<td>61.8</td>
</tr>
<tr>
<td>23:31:05</td>
<td>23:40:23</td>
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<td>43.4</td>
<td>65.4</td>
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<tr>
<td>23:31:05</td>
<td>23:40:23</td>
<td>23:55:01</td>
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<td>43.4</td>
<td>65.4</td>
<td>60.7</td>
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<tr>
<td>23:31:05</td>
<td>23:40:23</td>
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<td>43.4</td>
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<td>23:31:05</td>
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<td>7.9</td>
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<tr>
<td>23:31:05</td>
<td>23:40:23</td>
<td>23:55:01</td>
<td>00:06:01</td>
<td>43.4</td>
<td>65.4</td>
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<td>63.2</td>
<td>55.3</td>
<td>7.9</td>
<td>61.8</td>
</tr>
</tbody>
</table>

Table 5 – Surface temperature data for Wednesday Lane 1 at Position 160

Figure 7 shows the calculated cooling rate curve for position 160 (kilometre 60890) based on the average cross section temperatures. The average surface temperature dropped from 156°C to approximately 62°C over a 53-minute period giving a cooling rate of approximately 1.8°C/min.
The data was also used to produce an overall cooling rate curve that could be used to determine the surface temperature profile with time in the multi-layer ZOAB arrangement. The resultant temperature profile is shown in Figure 8.

![Surface temperature cooling rate curve](image)

*Figure 8 - Surface temperature profile with time*

### 3.7 Evaluation of in-asphalt temperature differentials

In-asphalt temperature measurements were taken in order to compare in-asphalt cooling rates with the surface temperature cooling rates.

#### 3.7.1 In-asphalt temperature differentials

The in-asphalt temperature was measured at all positions where cores were scheduled to be taken. Figure 9 shows the in-asphalt temperature measurements and the corresponding extended surface temperature curve for Wednesday Lane 1. The measurements shown are those taken at staked position 115m (Kilometre 60,845). The rate of cooling of the surface temperature, as expected, is higher than the in-asphalt rate of cooling. This is normal given that the surface of the asphalt is exposed to ambient weather conditions and that some mix segregation occurs during transport and paving. These results were typical for all the in-asphalt temperature data processed.
3.7.2 Correlation between surface temperature and in-asphalt temperature data

The in-asphalt temperature readings were compared with the average surface temperature readings at the proposed core sampling positions to determine the extent of correlation. All five lanes showed a strong correlation, based on $R^2$ values, with all values above 0.9. A graphical representation of the strong relationship for the same position 115m (Kilometre 60,845) is shown in Figure 10.

$$y = 1.1638x - 44.107$$

$R^2 = 0.9964$
3.8 Temperature profiling conclusions

Key findings based on the temperature profiling are:

- There is evidence of a distinct lack of consistent repetitive temperature contours during continuous paving operations for all lanes.
- The surface temperature varies appreciably both longitudinally and transversely leading to extensive variability in temperature homogeneity.
- The rate of cooling of the asphalt mat is clearly visible when paving operations stop during paving operations and at the end of the paved lane.
- The initial movement of the paver and the initial coolness of the mix are clearly visible through narrow bands of contours at the start of paving operations.

The temperature profiling has highlighted several operational issues and discontinuities that require attention. These include but are not limited to the following:

- The practice of using a crane to feed asphalt has led to extensive variability in temperature homogeneity. This is illustrated by the distinct lack of consistent repetitive temperature contours during continuous paving operations.
- A result is the occurrence of areas where the temperature differences are greater than 15°C across the width of the paved lane and which could be classed as potentially segregated areas and highly segregated areas.
- No insight could be gained from the use of the shuttle buggy given the discontinuities experienced by using the crane for the loading operation.
- The paver speed for lanes 2 and 3 on the first night are markedly higher (faster than 5m/min) than that for the other lanes. The need to put productivity interests viz. to complete paving operations before the road had to be opened for traffic, ahead of quality interests deserves attention.
- The high paving speeds in Lanes 2 and 3 of the first night of paving resulted in the research team having to deviate from the prepared protocols. The result is that cooling rate curves could not be produced for some individual positions.
- The third thermal camera (operated by BAM) was not used in a prepared protocol. This meant that very little could be deduced from the images collected with it.
- The paving team was not completely familiar with the operational characteristics of the paving machine. This possibly led to variability in the paving operations.

The following methodological and analyses issues are important:

- Accurate temperate profile data can be collected during normal HMA construction by using thermal image cameras.
- The images can be used to obtain a temperature image profile of contour that is a reasonable approximation of the temperature homogeneity of the paved lane.
- The infrared camera, although quite accurate for temperature measurements, is labour intensive and subject to operator choices, such as distance, angle and focal length. Although the analysis can be completed using the camera software, extensive post-processing must be undertaken after the construction has been completed.
- The temperature profile data can be used to predict the theoretical cooling curve for the asphalt mix. In addition, establishing threshold temperatures for the ZOAB asphalt mixture, viz. optimal compaction time and optimal compaction temperatures, is critical in effectively using the cooling rate information. However, establishing threshold temperatures was...
beyond the scope of the project since the primary focus was to determine the temperature profile with time in the multi-layer ZOAB arrangement.

The excellent correlation between the cooling rate obtained from the surface temperature data and the in-asphalt temperature data provides further validation of the accuracy of the temperature measurements.

The thermal images provide opportunities for further data analysis using Excel and MATLAB.

The thermal images can be transferred to ArcGIS using the Georeferencing tool. This means that the permanent thermal imaging records and the equipment movement data can be stored in the same location/records.
4. Monitoring equipment movements using GPS

4.1 Background

To monitor the coverage of the compaction compactor and the asphalt paver, its precise location needs to be known at all times. This can be done using global positioning systems (GPS). The GPS receiver is a passive device that receives signals from orbiting satellites. The receiver is able to triangulate its two-dimensional position and altitude anywhere on the surface of the earth using a minimum of three satellites.

GPS technology has become quite common since the introduction of satellite-navigation systems in automobiles. Before GPS became so mainstream, there have been several organized industry-aided research efforts for the development of state-of-the-art technologies for real-time locating and positioning systems for construction operations (Abourizk and Shi, 1994, Pampagnin et al., 1998, Bouvet et al., 2001, Hildreth 2003). Some of these include efforts to develop automated methods for monitoring asphalt laying and compaction using GPS and other IT technologies.

Li et.al (1996) reported on a system to map moving compaction equipment, transform the result into geometrical representations, and investigated the use of Geographic Information System (GIS) technology to develop a graphical illustration depicting the number of compactor passes. The system uses automated real-time positioning through the use of differential GPS which can have an accuracy of better than 100mm. A positioning device placed on the compactor records positioning information and uses wireless technology to transmit the information to a remote computer. Software written using Microsoft Visual Basic™ derives a graphical depiction of the number of passes executed over the length of the roadway using a GIS overlay technique.

Peyret (1998) defined positioning systems in the context of road construction sites and emphasizes the advantages offered by the new generation of systems, making specific reference to the use of GPS. The system is made up of a fixed station reference receiver and a mobile receiver (rover) linked to a microprocessor to perform real-time processing. The major drawbacks of GPS application in the field of road construction equipment positioning are highlighted, namely the accuracy limits, the initialization time after blind periods that increase the gaps in positioning and the fragility of the real-time radio link.

Krishnamurthy et.al. (1998) developed an Automated Paving System (AUTOPAVE) for asphalt paving compaction operations. The system was developed using GPS technologies and included developing a semi-automated path-planning and real-time guidance system to automate the paving operation. The system accepts relevant paving project inputs, generates path plans, presents a graphical visualisation of the generated path plan and offers real time guidance capabilities. The system offers an interactive, user-friendly, graphical interface with real-time tracking and path guidance features, incorporating visual and audio guidance capabilities.

Peyret et.al. (2000) reported on their Computer Integrated Road Construction (CIRC) project. This aims to develop Computer Integrated Construction systems for the real-time control and monitoring of work performed by road construction equipment, namely compactors (CIRCOM) and pavers (CIRPAV). It is based on a methodology of sharing common numerical geometric data from design, through all site operations up to the quality control of the geometry of the structure. It relies on CAD software tools, automatic control, short-range wireless data communication and
real-time positioning. The main objective of CIRCOM is to assist the compactor operator, so that he can perform exactly the required number of passes, at the right speed, everywhere on the surface to be compacted. A second objective is to record the actual work achieved in the trajectory followed and the number of passes achieved on every point of the trajectory, in order to feed the site database and to perform global quality control at the site level.

Oloufa (2002) described the development of a GPS-based automated quality control system for tracking pavement compaction. The research team proposed using a system consisting of positioning devices, hardware and software, and experimented with vector and raster-based algorithms to develop a Compaction Tracking System (CTS). The design allows multiple compactors to be tracked since the main processing tasks are done at the base station. A graphical depiction shows the number of passes executed over a length of roadway. The architecture also allows the simultaneous creation of an independent record of the compaction process.

Overall, we can conclude that the idea of using GPS and other technologies in asphalt paving processes is not a step in the dark. Several experiments have been conducted in recent years. However, although some of these experiments were developed into industrial applications, it appears that few have been accepted widely by industry and are frequently used on the construction sites. Although some equipment manufacturers now provide GPS as an option for clients, GPS is not yet part of operational strategies and working practice in compaction processes.

4.2 Objectives

The objective of this part of the research was twofold. Firstly, to evaluate the application of GPS technology in the asphalt paving and compaction processes and secondly, to evaluate the application of the technology in investigating operational behaviour.

4.3 Data collection

Two GPS systems were used to collect positioning data over the two-night period. Firstly, a high-end Leica GPS system with 10cm accuracy. The system consisted of a reference station and roving units mounted on each of the asphalt paver and two roller compactor units. Positioning data was collected at 1-second intervals. The point and line data conversions were then input into ArcGIS and MATLAB for further analysis.

The second, a prototype low-end system currently under development, was also used to collect positioning data over the two-night period. The system consists of a GPS receiver and data logger combination. The ‘off-the-shelf’ GPS receiver’s accuracy is between 3m and 5m. Two receivers each were mounted on the paver and the two roller compactors. Data was logged continuously throughout the paving and compaction operations at 1-second intervals.

The objective of using a combination of high-end and low-end technology was to determine whether the accuracy of the prototype system could be improved through extensive post processing. This work is ongoing and will not be discussed in this report.
4.4 Results

The paver and roller movements were analysed using GPS data. Animations showing equipment movements, were produced using the MATLAB software. The animation has been converted from the MATLAB file to an .avi file and can be visualised using a media player. The given examples show the initial stages of the construction of Thursday night’s Lane 1:

- The stationary paver and rollers before the start of paving at 21h57 is shown in Figure 11; and
- The movement of the paver and the start of Roller 1 compacting the asphalt about 32 minutes later are shown in Figure 12.

![Figure 11 - Animation example 1 for Thursday Lane 1](image-url)
4.4.1 Rolling patterns

The rolling patterns (method specifications) employed by the operators were not analysed in detail since the analysis of compaction coverage provided greater insight into the operational behaviour and how it affected the compaction of the various lanes.

Nevertheless, the animation does provide explicit evidence of the following:

- The start of paving and a comparison of the compaction starting times for both rollers since all activities are shown on distance and time-lines.
- Rolling patterns showing how rolling was accomplished during the paving process.
- The extent of co-operation between the paver and the rollers and that between the two rollers.

4.4.2 Analysis of paver movements

The paver speeds were derived from the GPS data and is shown graphically in Figure 13. The speed plot for Wednesday’s Lane 3 is not shown since the data was found to be erroneous. The speeds were then verified with data taken from the thermal images since the images were taken in a specific distance regime and the time is visible on the image. The average paver speeds derived from the thermal images are shown in Table 6.
It is evident that the average speed of the paver for Lanes 2 and 3 for the first night of paving is above 5m/min and is clearly much higher than the average for the other three lanes (approximately 3.5m/min). This is probably as a result of the need to complete paving operations before the road had to be opened for traffic.

![Paver speeds derived from GPS data](image)

Figure 13 – Paver speeds derived from the GPS data

<table>
<thead>
<tr>
<th>Paver speed in m/min</th>
<th>Wednesday</th>
<th>Thursday</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lane 1</td>
<td>Lane 2</td>
</tr>
<tr>
<td>average</td>
<td>3.4</td>
<td>5.1</td>
</tr>
<tr>
<td>st. dev.</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 6 – Average paver speeds calculated from thermal image data

4.4.3 Movement of paver in relation to the compaction rollers

The start of paving and a comparison of the compaction starting times for both rollers are given in Table 7. The pressure to complete the paving and compaction of certain lanes before the road was to be opened to traffic is highlighted by the early starts of Roller 1 in compacting Lanes 2 and 3 of the first night and Lane 2 on the second night.

![Comparison of paving & compaction starting times](image)

Table 7 - Paving starting and compaction starting times
4.4.4 Analysis of compaction coverage

In addition to being able to observe and analyse the operational behaviour of the compaction rollers using the animation video, the GPS data were used to prepare compaction coverage contour maps showing the number of passes applied to specific areas of the paved lanes. This resulted in a more detailed analysis of the compaction process.

Figure 14 and Figure 15 shows examples of typical results viz. the spread of roller passes for both roller compactors for Wednesday’s Lane 1. The data in these figures are presented on a distance scale to highlight key findings. Also, the two nights’ compaction operations are discussed separately.

![Figure 14 – Compaction coverage for Wednesday Lane 1 – Roller 1](image)

![Figure 15 – Compaction coverage for Wednesday Lane 1 – Roller 2](image)
Key findings based on compaction coverage for the first night of paving are as follows:

- It appears that Roller 1 (shown in Figure 14) applied most of the compaction effort to Lane 1 on the first night of paving with a large percentage of the area being covered with between 5 and 10 passes.
- Roller 2 applied a significantly less amount of compaction effort to the lane with more than 90% of the area being covered with less than 5 roller passes.
- The two roller operators appeared to work in a complimentary way. However, an analysis of the overall number of passes in Figure 16 shows a compaction inconsistency. Most roller passes have been applied to the centre of the lane. The outer edges show areas where less passes have been applied.

![Figure 16 – Overall compaction coverage for Wednesday Lane 1](image)

Core density results were plotted as shown in Figure 17. The density on the right side of the lane is lower in places where less roller passes have been applied. Two examples are evident at positions 115m and 205m.

![Figure 17 - Core density results for Wednesday Lane 1](image)
The compaction effort appears somewhat different for Lane 3 on the first night of paving. Roller 1 applied less than 5 passes over 75% of the lane (see Figure 18).

![Figure 18 – Compaction coverage for Wednesday Lane 3 – Roller 1](image)

This is in stark contrast to Roller 2 applying between 5 and 10 passes over 85% of the lane (Figure 19). The result of both operators applying a higher number of roller passes to the section is that between 10 and 15 roller passes are applied to most of the narrowest 3m wide Lane 3.

![Figure 19 – Compaction coverage for Wednesday Lane 3 Roller 2](image)

Key findings based on compaction coverage for the second night of paving are as follows:

- The operational behaviour for Thursday Lane 1 mirrors that of Wednesday Lane 1. It appears that Roller 1 applied most of the compaction effort with most of the area being covered with between 5 and 10 passes. Roller 2 applied a significantly less amount of compaction effort to the lane with approximately 60% of the area covered with less than 5 roller passes. The overall compaction in terms of rollers passes is shown in Figure 20. It shows that less passes have consistently been applied as you move from the left to the right side of the lane. This has possibly contributed to the lower densities as shown in Figure 21.
The overall compaction effort for Thursday Lane 2 shows that there are two distinctly different zones of compaction. The first 120m has been compacted with 10 or more roller passes and the last 60m mostly with between 5 and 10 passes. This is illustrated in Figure 22.
4.5 Equipment monitoring conclusions

Key findings based on the monitoring of equipment movements using GPS systems are:

- The paver speeds vary considerably for lanes 2 and 3 on the first night when compared to the other paved lanes.
- The time between the start of paving and the start of compaction varies significantly. The pressure to complete the paving and compaction of certain lanes before the road is to be opened to traffic is highlighted by the early starts of Roller 1 in compacting Lanes 2 and 3 of the first night and Lane 2 on the second night.
- It appears that roller operators attempted to work in a complimentary manner with one roller concentrating on compaction duties on the left of the paved lane and the other the right. However, the result of the operational behaviour shows three distinctly different outcomes in terms of overall compaction coverage. Firstly, in two instances, the centre of the lane receives more compaction attention than the outer areas (see Figure 16). Secondly, in one instance, the number of roller passes tend to decrease as you move from the left to the right of the lane (see Figure 20). Thirdly, in two instances, two distinctly different zones of compaction are visible when analysing the length of the paving (see Figure 23 below).

The analysis of equipment movements has highlighted several operational issues and discontinuities that require attention. These include but are not limited to the following:

- Operational behaviour varies considerably. Differences were observed during the construction of the various lanes. Lane 1 on the first night was milled, tack coat applied, paved and then compacted after the asphalt was allowed to cool down. However, in the case of the second and third lanes paved on the night, compaction started almost immediately after the asphalt paving operation had started.
- Rolling patterns vary considerably. It is clear from the animation that in some cases, roller operators follow specific rolling patterns i.e. method specifications. However, the operators tend to pay little attention to providing equal compaction effort across the width of the paved lane.
- There is a tendency to apply more compaction passes to the narrower lanes. The 1680mm wide compactor roller covers a greater area (percentage wise) of the 3m wide lane compared to its coverage on the 5m wide lane. The result is that the percentage of compaction passes greater than the average for each lane, is higher with the narrower lanes. This is shown in Table 8.
<table>
<thead>
<tr>
<th>Roller coverage on lanes (number of passes)</th>
<th>ave. passes</th>
<th>std. dev.</th>
<th>no &gt; average</th>
<th>n</th>
<th>% &gt; ave. passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wednesday Lane 1 (5m)</td>
<td>8.0</td>
<td>2.4</td>
<td>36.0</td>
<td>92.0</td>
<td>39.1</td>
</tr>
<tr>
<td>Wednesday Lane 2 (4m)</td>
<td>9.1</td>
<td>2.8</td>
<td>40.0</td>
<td>72.0</td>
<td>55.6</td>
</tr>
<tr>
<td>Wednesday Lane 3 (3m)</td>
<td>10.6</td>
<td>2.7</td>
<td>50.0</td>
<td>68.0</td>
<td>73.5</td>
</tr>
<tr>
<td>Thursday Lane 1 (5m)</td>
<td>9.9</td>
<td>3.4</td>
<td>48.0</td>
<td>84.0</td>
<td>57.1</td>
</tr>
<tr>
<td>Thursday Lane 2 (4m)</td>
<td>10.0</td>
<td>2.7</td>
<td>61.0</td>
<td>84.0</td>
<td>72.6</td>
</tr>
</tbody>
</table>

Table 8 - Average roller coverage on all paved lanes

The operator of the roller compactor equipped with the Asphalt Manager appeared to be unfamiliar with the equipment.

The following methodological and analyses issues are considered important:

- Accurate GPS data (accuracies to within 10cm) can be collected during normal HMA construction operations using high-end GPS equipment. However, the purchasing cost for such equipment is high. The research team is currently assessing the viability of the low-end GPS equipment trialed during the A35 Test section. The data collection using the prototype GPS data loggers was successful. The next step is evaluating whether (back) corrections could be applied to the data to significantly improve its accuracy. The work is on-going and will be reported on shortly.

- GPS data can be used to develop a deeper understanding of the on-site compaction process through mapping the heuristics the operators use.

- The rolling patterns employed by the operators were not analysed in detail since the analysis of compaction coverage provided greater insight into the operational behaviour and how it affected the compaction of the various lanes. Nevertheless, the animation does provide explicit evidence of the rolling patterns and of how rolling was accomplished during the paving process. This should be used to reduce variability in rolling procedures.
5. Overall conclusions

5.1 Variability

This study has highlighted the variability in operational practices and the outcomes as a result of those practices. A distinct lack of consistent temperature contours has highlighted the extensive variability in temperature homogeneity. The differences in compaction practices have resulted in significant differences in overall compaction coverage.

5.2 Operational behaviour

Several operational issues and discontinuities have been highlighted in this report. The practice of using the crane, the variation in paver speeds, the time between the start of paving and the start of compaction are a few issues that require attention since they may have contributed to the variability highlighted in 5.1.

5.3 Methodology

Explicit process knowledge may provide support for and a deeper understanding of the process being followed. Improving control over the asphalt paving process is an essential step towards improving control over pavement quality. The first step towards insight into temperature homogeneity, paving, compaction and operational strategies is documentation of the operations on site. Capturing and analysis of the thermal images leads to greater insight into temperature homogeneity. Logging the movements of the equipment captures the results of the operational choices made by the operators. The documented operations will therefore provide the lever to discuss and confront the operational choices made by management and more importantly, those choices made by the paving team during construction operations.

6. Reflection

Some operational issues made measurement difficult. These include the following:

- It is difficult to draw inferences about the use of the shuttle buggy and temperature homogeneity because the crane was used to load the shuttle buggy.
- The research team had to deviate from the protocol for measuring the surface temperature because of the increase in the paver speed.
- The high-end thermal camera was used without protocol leading to uncertainty and a lack of usable thermal imaging data.
- The width of the paver ended up being a stumbling block because of the chosen construction widths.
- The paver personnel did not appear altogether familiar with the operations of the paver.
- The Bomag Asphalt Manager was not fully operational at the time and therefore could not be used for measuring incidents during compaction activities.
- The testing of mix segregation was not carried out.
Notwithstanding the problematic operational issues raised, the research team was able to learn from the experience. Valuable lessons include the following:

- Consistent and controlled compaction processes will contribute to consistency and quality of the paving. This entails developing an understanding of the relationship between the compaction grade, motion patterns, coverage patterns, temperature differentials and density differentials during the compaction process. Since the operators cope with these factors on a day-to-day basis, seems highly valuable to start with mapping the heuristics the operators use, and unravelling the logic and tacit knowledge about the do’s and don’ts in the asphalt paving process.
- The systematic analysis and mapping of the asphalt paving process should lead to an improvement in consistency and quality of asphalt paving.
- The study has highlighted the usefulness of temperature profiling using thermographic images and the monitoring of machine movements using GPS. However, the key to the extent of its usefulness lies in its adoption and integration in operational strategies and methods.
7. References


