300-556 PAVING THE WAY FORWARD: A CASE STUDY IN INNOVATION AND PROCESS CONTROL

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ABSTRACT

Co-operation between clients and the private sector provides significant opportunities to promote innovation in the road construction industry. This paper describes such an innovation project. In 2006, the Dutch ministry of Transport organised an innovation competition, challenging contractors to propose new technologies that might be relevant for the future of roads and road construction. BAM Wegen proposed using a combination of a dual layer paving process with a shuttle buggy for improved homogeneity, and themographic imagery and continuous GPS tracking on the paver and rollers for improved process control during the asphalt paving process. The main objectives were two-fold. Firstly, to work towards a 25% increase in the service life of the porous asphalt by improving the total process from the choice of raw materials and mix design to the monitoring of the finished product. Secondly, to develop innovative monitoring techniques of the asphalt laying process, since major developments in road paving are often hampered by insufficient feedback from finished projects. This proposal was one of the three "winners" that were each granted a project to put their ideas to the test on a short stretch of the A35 highway. This paper explains the idea's behind the proposed innovations, the way they where translated into practice, the actual project and the findings. Evaluation and discussion subsequently focuses on [1] the success of the proposed new technologies, on [2] the way the contractor has dealt with an innovation project in its daily business, and on [3] the effect of monitoring additional process data on quality control. Finally, the introduction of innovation during the construction process is discussed in the context of new trends in contracting i.e. the introduction of performance-based contracts, the move towards longer guarantee periods, risk transfer and new business models.

Keywords: asphalt, innovation, process control, GPS technology, thermographic images

1. INTRODUCTION

There is a wealth of research on the importance of innovation in construction. Several themes are addressed with appropriate business strategies for construction firms initially dominating the knowledge base [1, 2]. Recently, innovation is seen as an important source of competitive advantage [3, 4] and the implementation of innovations in construction has subsequently received much attention [5-7]. The situation is no different in The Netherlands. Pries and Janszen [8] in analysing the innovative behaviour of the construction industry in the country, stresses that innovation creates possibilities for achieving competitive advantage, but only when managed properly. Bremer and Kok [9] suggest that innovation aims can be realised but, only if paid by the whole construction sector and not by individual firms. Bossink [10] found that innovation drivers e.g. technological capability and knowledge transfer, are used by managers of the authorities, clients, architects, consultants and contractors to stimulate and facilitate innovation processes. More significantly, over the last four years since the Dutch parliamentary enquiry into the construction sector, the business environment within the road construction sector has changed dramatically. According to Dorée [11] the collusion structure that regulated competition has fallen apart. Public clients have introduced new contracting schemes containing incentives for better quality of work [12] and therefore play a critical role in the construction innovation process. This prominent role allows them to stimulate and support the implementation of innovative solutions such as process performance [13, 14]. Nam and Tatum [15] suggest that clients' sponsorship is essential for the successful implementation of construction innovation.

New types of contracts, tougher competition and the urge to make a distinction in the market, spur the companies to advance in product and process improvement. These changes have significantly altered the playing field for competition. The companies see themselves confronted with different "rules of the game" than what they were used to. Performance contracting and longer guarantee periods create a new set of risks and business incentives [16]. In general, the companies experience the pressure of new types of competition and other rules and trends, but at the same time, they acknowledge the opportunity to distinguish themselves. Road construction companies, in turn, seek better control over the construction process, over the planning and scheduling of resources and work, and over performance. Improved control would also reduce the risks of failure during the guarantee period. To be able to achieve these goals, the relevant on-site operational parameters need to be known and the relationships between these parameters need to be thoroughly understood. For asphalt paving companies to be able to improve product and process performance, they now

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more than ever acknowledge they need to develop intricate understanding of the asphalt paving process and the interdependencies within the process.

This paper is structured as follows. After the introduction, we explain the background to the Dutch Ministry of Transport sponsored innovation project, BAM Wegen's innovation role and objectives for the project. This is followed by a description of the data collection, the analysis and a discussion of the results. Finally, we present conclusions and recommendations for practice in the context of the introduction of innovation during the construction process.

2. THE INNOVATION PROJECT

In 2006, the Dutch Ministry of Transport organized an innovation competition, challenging commercial parties to put forward ideas to extend the mean service life of the dual layer porous asphalt system from seven to nine years. The porous asphalt system consists of a 25 mm thick upper layer with a maximum grain size of 8 mm and a 45 mm thick lower layer with a maximum grain size of 16 mm. It is specially designed for high reductions of traffic noise (5-7 dB (A) at normal traffic speed). BAM Wegen joined forces with the University of Twente and various other parties to enter the innovation competition. The group's focus was on extending the service life of porous asphalt and involved improving the whole process from the choice of raw materials and mix design, to monitoring of the finished product. The aim of this project was to improve the homogeneity of the asphalt mix during production, transport and application. The realisation phase of the project was a 460m long section of resurfacing of the A35 highway in the east of The Netherlands. BAM Wegen developed, planned and carried out the construction of the test section. The scope of the project required the removal of the existing surfacing layer followed by repaving with the dual layer porous asphalt system. The two layers were laid simultaneously with a special paver. The 12m wide highway was divided into three paving lanes viz. 5m, 4m and 3m wide. Construction work was carried out over two nights during April 2007.

The University of Twente research team monitored some key process parameters during construction. The team focuses on innovation and performance in the asphalt paving process, having recently consulted key role players in the industry [11, 17-19] and subsequently publishing a number of conference papers in this research area [20-22]. Their research is aimed at improving quality and consistent reduction of quality variability in the hot mix asphalt (HMA) paving process. Two key research questions are addressed. The first tackles the main causes of variability in the asphalt paving process whilst the second focuses on the effect of revised operational strategies on quality in the paving process.

3. OBJECTIVES

Contractor BAM Wegen set two main objectives for the project. Firstly, to work towards a 25% increase of the service life of the porous asphalt by improving the total process from choice of raw materials and mix design to the monitoring of the finished product. Secondly, to develop innovative monitoring techniques of the asphalt paving process since major developments in road paving are often hampered by insufficient feedback from finished products. The latter objective led to the contractor introducing two innovations for the project viz. to use a combination of a dual layer asphalt paving process with shuttle buggy for improved homogeneity; and to use themographic imagery and continuous GPS (Global Positioning Systems) tracking on the paver and compactor rollers for improved process control during the asphalt paving process. The introduction of monitoring and control mechanisms using temperature profiling and GPS systems in the asphalt paving process is the focus of this paper.

4. DATA COLLECTION

4.1 Temperature profiling

Infrared camera images were used to document temperature differentials during the hot mix asphalt paving operations. Two ThermaCAM™ infrared cameras were used to collect surface temperature data. More than 400 thermal images were taken in a predetermined protocol at 10m staked positions (see **Figure 1). The research team prepared schedules (see the example in** Table 1) 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. 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 right of the image.

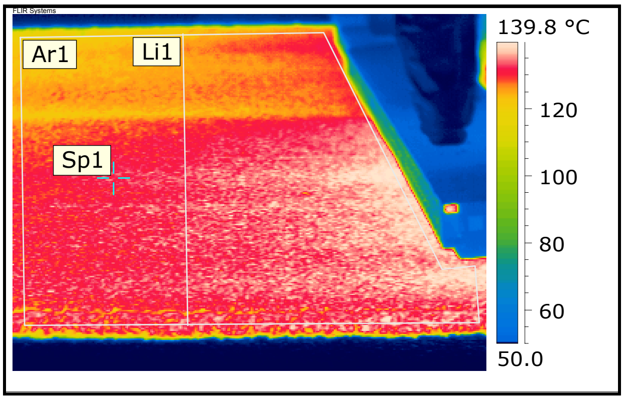


Figure 1: **Typical thermal image**

Staked position on the asphalt lane to be paved - based on the paver speed of 3m/min

	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230
Time an infrared picture is taken (min)	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46
	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55
	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60	62	64	66
	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61	63	65	67	69	71	73	75
										58	60	62	64	66	68	70	72	74	76	78	80	82	84	86
										67	69	71	73	75	77	79	81	83	85	87	89	91	93	95

Table 1: **Typical thermal image schedule**

4.2 Monitoring of equipment movements

A GPS system was used to collect positioning data over the two-night period using a high-end Leica GPS system with 10cm accuracy. The system consisted of a reference station set up next to the highway and roving units mounted on each of the asphalt paver and two roller compactor units. Positioning data was collected at 1-second intervals and was analysed using the MATLAB software.

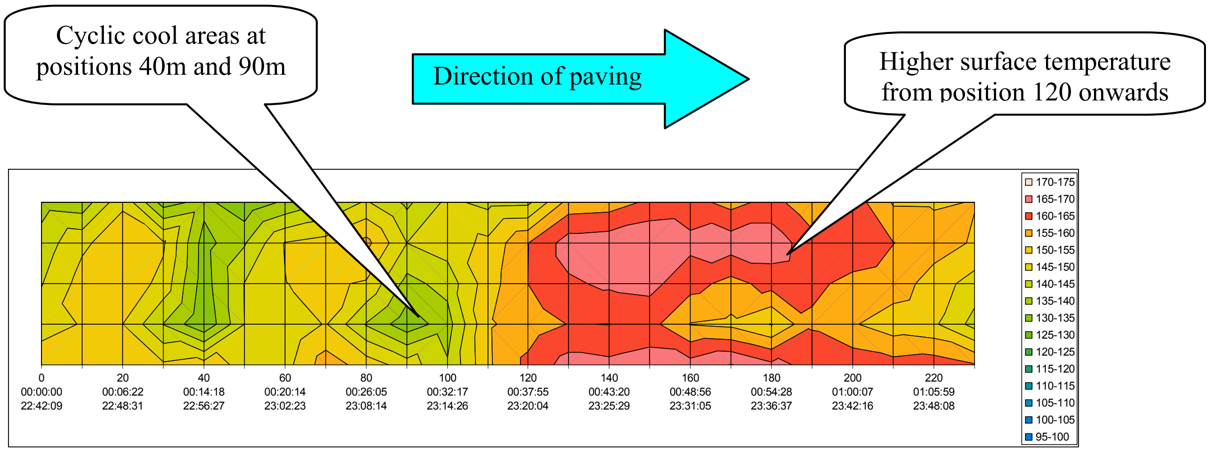
5. ANALYSIS

5.1 Temperature profiling

The temperature data were analysed in two exercises. In the first, we prepared temperature contour maps of the paving operations (as the asphalt mix leaves the paver) and in the second, we compared surface temperature cooling rates with in-asphalt cooling rates.
Figure 2,
Figure 3 and
Figure 4 shows the resultant temperature profiles for three of the five paved lanes. The data are presented on both distance and time axes to highlight key findings. The temperature profiling has highlighted several operational issues. Figure 2 shows a distinct difference in surface temperature in the first half of the section paved compared to the second half. 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 indicates a constant movement of the paver and delivery of asphalt to the surge bin. The rate of cooling of the asphalt mat is clearly visible in
Figure 4 when the paving operations stop as shown at position 140m or when paving operations stop at the end of the paved lane. 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. 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 and 90m. In addition, an analysis of the range in surface temperature across the width of the paved lanes in

Table 2 revealed that all five lanes have significant areas where surface temperature varies across the width of the paving lane. This was used to identify potentially segregated areas.

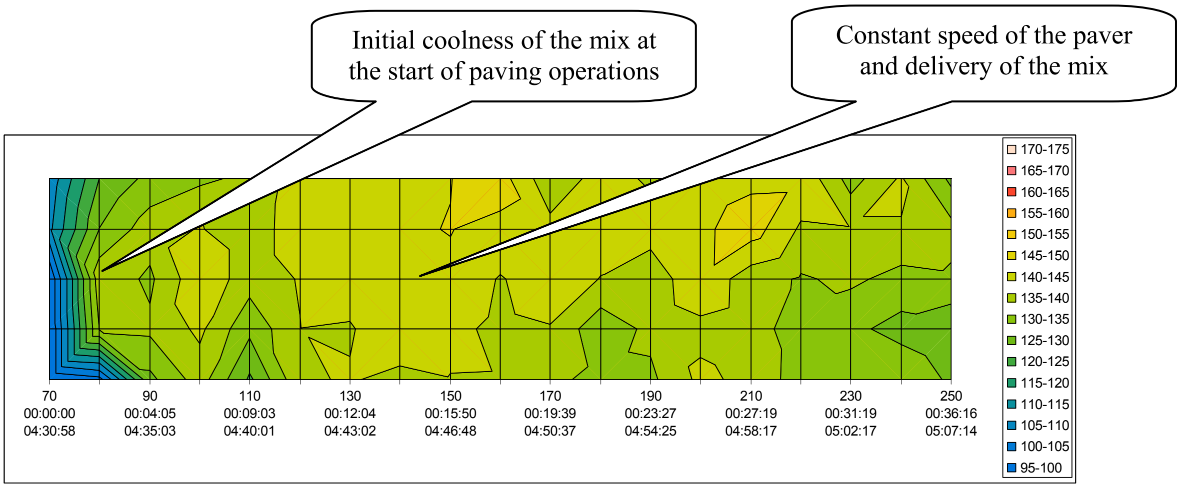


Cyclic cool areas at positions 40m and 90m

Direction of paving

Higher surface temperature from position 120 onwards

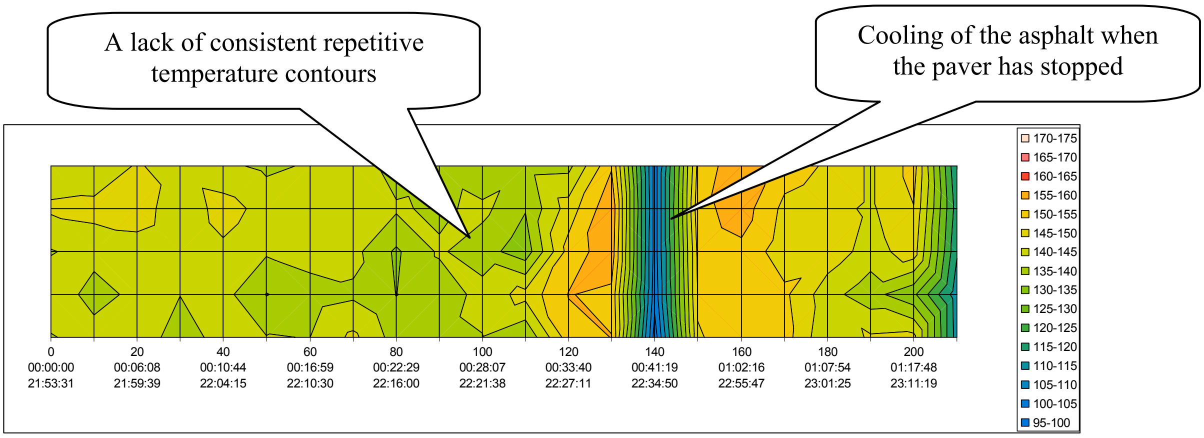
Figure 2: **Temperature contour map for Wednesday Lane 1**



Initial coolness of the mix at the start of paving operations

Constant speed of the paver and delivery of the mix

Figure 3: **Temperature contour map for Wednesday Lane 2**



A lack of consistent repetitive temperature contours

Cooling of the asphalt when the paver has stopped

Figure 4: **Temperature contour map for Thursday Lane 1**

Surface temperature differentials		0-5	5-10	10-15	15-20	20-25	25-30	>30	Total
Wednesday	Lane 1	0	6	6	11	1	0	0	24
	Lane 2	2	9	6	0	1	0	1	19
	Lane 3	0	1	11	5	1	0	0	18
Thursday	Lane 1	2	17	1	1	1	0	0	22
	Lane 2	0	9	11	2	0	0	0	22
Total		4	42	35	19	4	0	1	105

Table 2: Difference in surface temperature across the width of the paved lane

The thermal images were used to produce individual cooling rate curves for the 10m staked positions based on the photographic regime shown in

Table 1 . In-asphalt temperature measurements were then compared with the surface temperature cooling rate curves.

Figure 5 shows the in-asphalt temperature curve at staked position 115m on one of the lanes. 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. These results were typical for all in-asphalt temperature data processed. The in-asphalt temperature readings were compared with the average surface temperature readings 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 6.

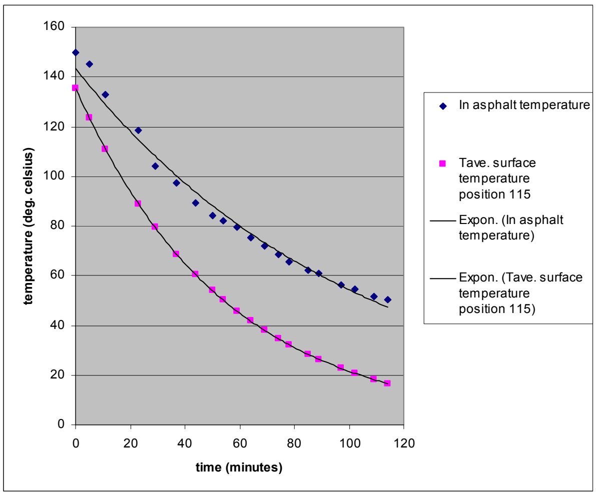


Figure 5: Typical cooling rate curves for in-asphalt and surface temperature

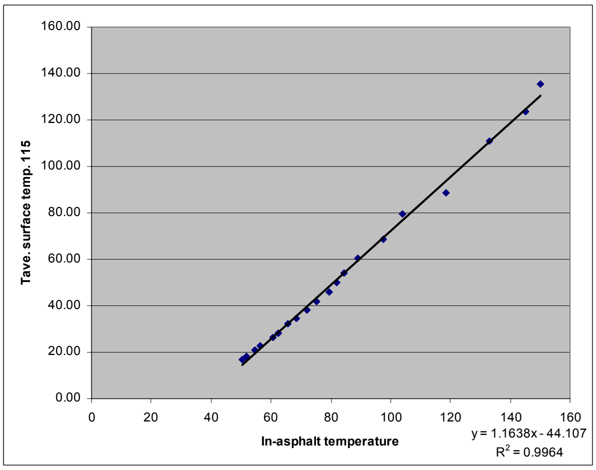


Figure 6: Typical correlation between the in-asphalt and surface temperature

5.2 The monitoring of equipment movements

5.2.1 Paver operations

The paver speeds were derived from the GPS data and is shown in
Figure 7. Note the higher paver speeds for Lane 2 on both nights. This is possibly due to the need to complete paving operations before the highway had to be opened for traffic the next morning. This pressure to complete the work is substantiated in a comparison of the start of paving and subsequent compaction starting times for both rollers shown in
Table 3. Note the early starts of Roller 1 in compacting Lanes 2 and 3 of the first night and Lane 2 on the second night.

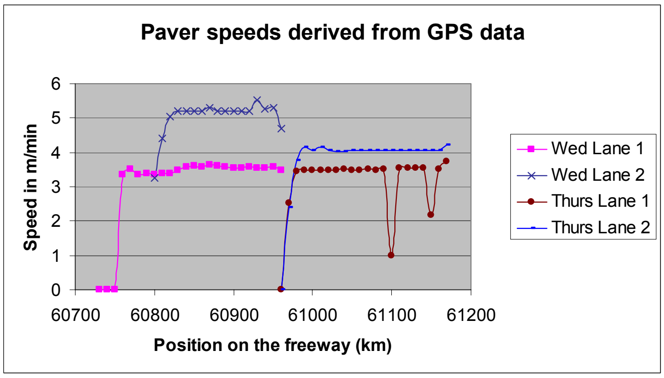


Figure 7: **Paver speeds derived from the GPS data**

Comparison of paving & compaction starting times	Wednesday			Thursday	
	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2
Start of paving	T_0 (22h40)	T_0 (04h30)	T_0 (05h39)	T_0 (21h58)	T_0 (03h07)
Start of roller 1 ($T_{\text{mins later}}$)	T_{41}	T_2	T_2	T_{32}	T_2
Start of roller 2 ($T_{\text{mins later}}$)	T_{85}	T_{35}	T_{28}	T_{60}	T_{45}

Table 3: **Comparison of paving and compaction starting times**

5.2.2 Compaction operations

Animations showing equipment movements were produced from the GPS data 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 example in
Figure 8 shows the position of the machines before the start of construction of Thursday night's Lane 1. The animations provide explicit evidence of all paving and compaction activities on distance and time-lines and the extent of co-operation between the paver and the roller compactors.

Date and time stamp

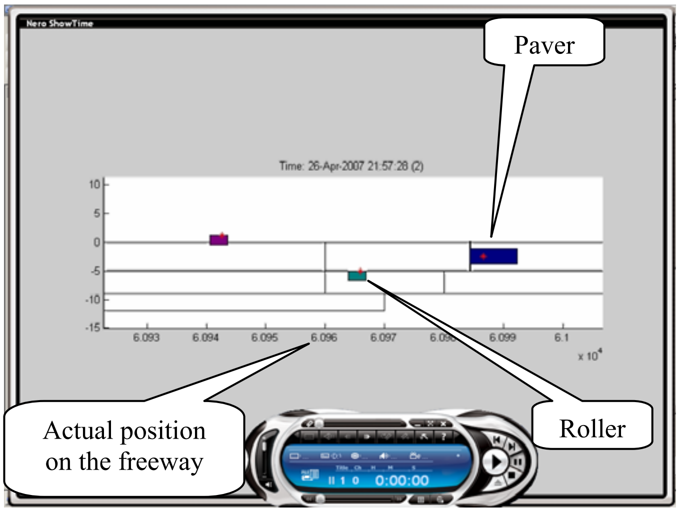


Figure 8: **Animation for Thursday Lane 1**

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. The process followed was to initially determine the compaction coverage separately for each roller and then calculate the overall compaction coverage for the lane. This was compared with the core density results for the lane. Lastly, we conducted a comparison of the overall compaction coverage for all lanes. To illustrate the process followed, **Figure 9 to** Figure 12 show examples of typical results for Wednesday's Lane 1. It appears that Roller 1 (shown in Figure 9) applied most of the compaction effort to Lane 1 on the first night of paving with a large percentage of the area covered with between 5 and 10 roller passes. In Figure 10, 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 five roller passes. The two roller operators appeared to work in a complimentary way with one roller concentrating on compaction duties on the left of the lane and the other on the right. However, scrutiny of the overall number of passes in **Figure 11 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. The density results on the right of the lane tend to be lower in places where less roller passes have been applied (** Figure 12).

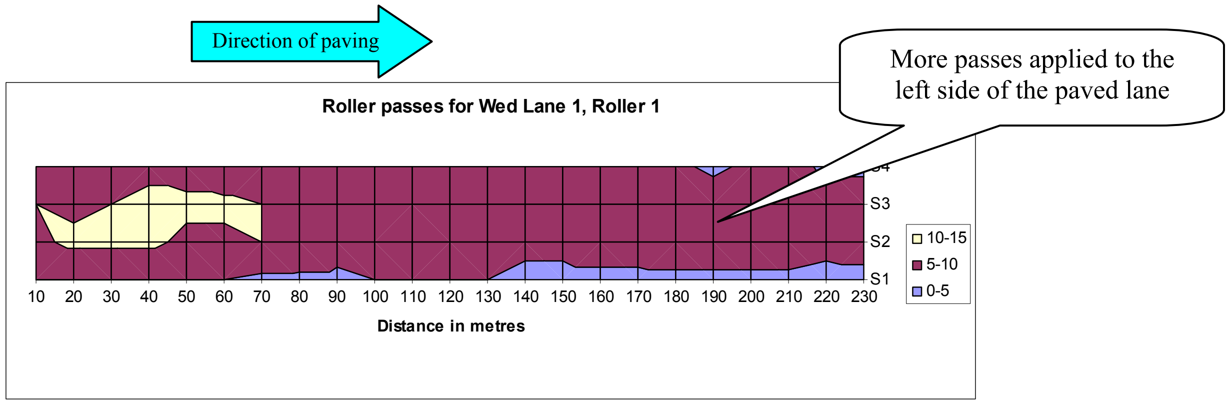
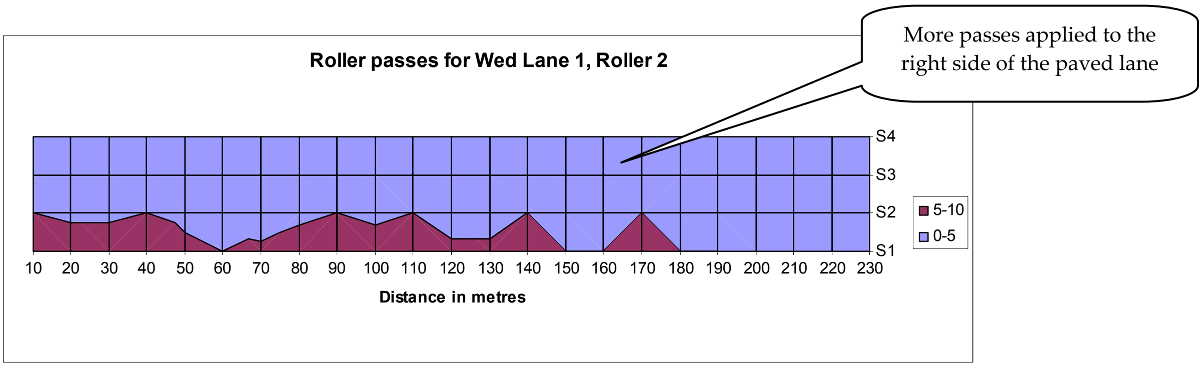
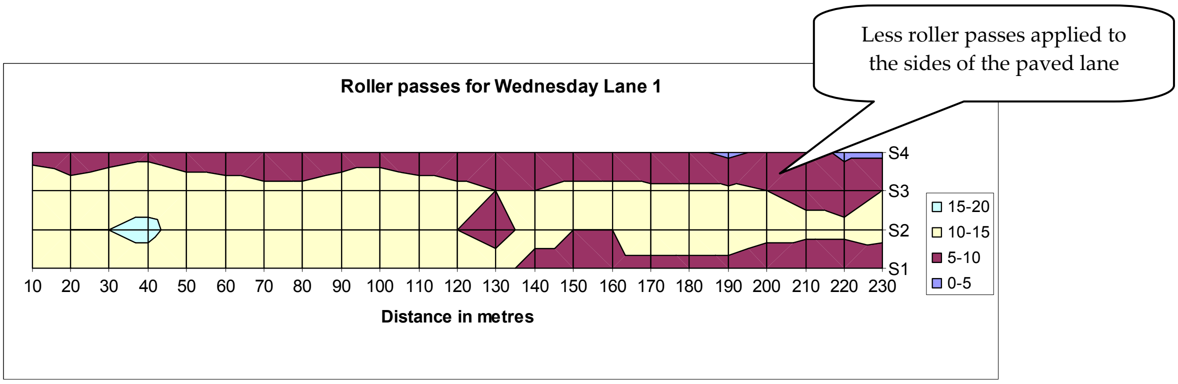


Figure 9: **Compaction coverage for Wednesday Lane 1 - Roller 1**



More passes applied to the right side of the paved lane

Figure 10: Compaction coverage for Wednesday Lane 1 – Roller 2



Less roller passes applied to the sides of the paved lane

Figure 11: Overall compaction coverage for Wednesday Lane 1

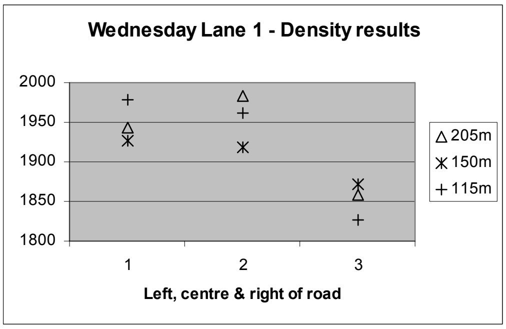


Figure 12: Core density results for Wednesday Lane 1

6. RESULTS

The temperature profiling has enabled the contractor to measure the extent of variability in surface temperature and hence draw a number of conclusions about temperature homogeneity. There is evidence of a distinct lack of consistent repetitive temperature contours during continuous paving operations for all lanes and the surface temperature varies appreciably both longitudinally and transversely leading to extensive variability in temperature homogeneity. Also, several operational discontinuities affecting the paving process were identified. The rate of cooling of the asphalt mat is clearly visible when the paver stops during continuous paving operations and at the end of paved lanes; and the initial movement of the paver and subsequent initial coolness of the mix are clearly visible through narrow bands of contours at the start of paving operations.

The monitoring of equipment movements using GPS systems has highlighted a number of operational issues. The paver speeds vary considerably for certain lanes. The time between the start of paving and the start of compaction varies significantly. Also, 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 distinctly different outcomes in terms of overall compaction coverage.

7. DISCUSSION

The use of thermographic imaging and GPS technology in the asphalt paving process is not new. According to Stroup-Gardiner [23], Read [24] 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 in determining temperature differentials for detecting, locating, and measuring segregation [25-28]. Also, 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. Li et al. [29] 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. Krishnamurthy et al. [30] developed an Automated Paving System (AUTOPAVE) for asphalt compaction operations. Peyret et al. [31] 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). Oloufa [32] described the development of a GPS-based automated quality control system for tracking pavement compaction. Hence, it appears that several thermographic imaging and GPS experiments to map the asphalt paving experience were conducted in recent years. However, although some of these technological experiments were developed into industrial applications, it appears that it is not yet part of operational strategies and working practice in asphalt processes [18, 19].

BAM Wegen, through this innovation project, has shown a conscious desire to adopt and integrate temperature profiling and the monitoring of equipment movements into their operational strategies and methods. Explicit knowledge, systematic and easily communicated in the form of hard data [33], may provide support for and a deeper understanding of the operational 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.

A number of benefits are apparent. The consequences of on-site operational behaviour and discontinuities are made explicit. The temperature profiling highlights the resultant variability in temperature homogeneity and identifies potentially segregated areas. Temperature contour maps and compaction coverage plots are digitally “georeferenced in layers” and saved in permanent records (see **Fejl! Henvisningskilde ikke fundet.**). Thus, future reviewing and matching with on-site pavement distress and failure is possible. Logging the movements of the equipment using GPS captures the results of the operational choices made by the paver and roller operators. The animations provide evidence of the rolling patterns and of how rolling is undertaken during the construction process. Mapping the heuristics the operators use allows a deeper understanding of the on-site paving process. This systematic analysis and mapping of the asphalt paving process should lead to firstly, addressing the important issue of reducing variability in operational behaviour and secondly, to an improvement in consistency and quality in the final product.

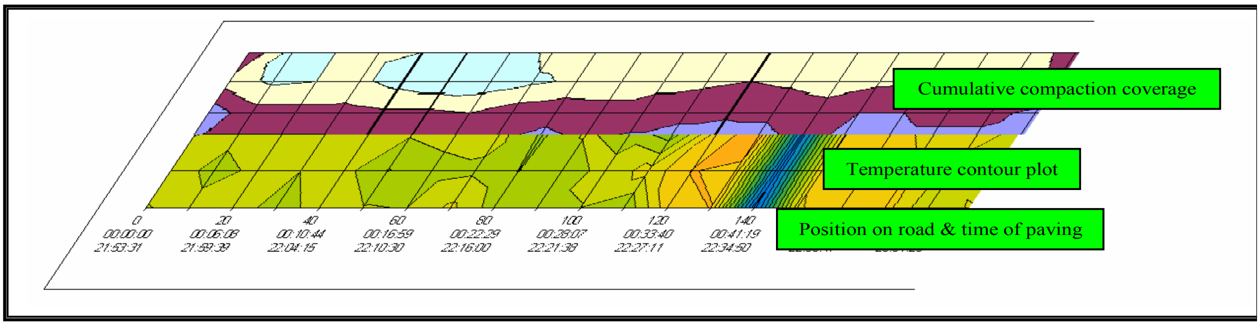


Figure 13: **Example of "georeferencing" for permanent records**

8. CONCLUSIONS

The Dutch road construction industry is in transition. The policy and conduct of the Ministry of Transport actively stimulates innovation and development in two ways. On the one hand, they reshape the business environment for the contractors through performance contracting, longer guarantee periods and risks transfer. On the other hand, contractors are challenged to invest in Research, Technology and Design. In innovation, newly developed products and processes can be tested and demonstrated. This paper described an innovation project in The Netherlands. This project (although relatively small) provided several valuable outcomes and insights:

- Systematic monitoring of surface temperature provides insight in the variability of asphalt temperature, and the shape of the cooling process. This type of monitoring can be useful for improving process and quality control;

- Surface temperature measurement can be used as a reliable indicator of in-asphalt temperature;
- GPS monitoring of the paver and the rollers maps the actions of the machine operators. The generated animations provide valuable insight into the number and spread of compactions during the process. The compiled data can be compared with the density measurements (nuclear gauge and drilled cores);
- The generated animations can be a good evaluation tool for the operators and teams, speeding up process learning and continuous improvement;
- The full array of registered data can be used to develop new strategies for maintenance and product/process improvement; and
- The more data-rich approach to road construction opens up new strategies for combined technology and skills development, enhancing the effectiveness and adoption of new technologies in the road contraction.

Overall, the conclusion is that the new contracting policies (performance contracting, longer guarantee periods, risk transfer) create a more challenging business environment and incentive to innovate. The contractors are aware of this and reshape their competitive strategies. Innovation projects as described in this paper are valuable for experimenting with new technologies. Above all, this project made clear that - with new monitoring technologies in place – a great deal can be gained in quality, process control and process improvement.

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