Making Operational Strategies of Asphalt Teams Explicit to Reduce Process Variability

F. R. Bijleveld[1]; S. R. Miller[2]; and A. G. Dorée[3]

Abstract: The on-site construction process undertaken by asphalt teams has a critical impact on pavement quality. Process improvement and learning require explicit information about the process. However, current on-site operational activities and key parameters are, in general, not systematically monitored and mapped. The lack of process information makes it difficult for contractors and asphalt teams to distinguish between good and poor practices and to improve. Although technologies to make the on-site process explicit are becoming widely available, their adoption has been slow. To overcome this knowledge gap regarding explicit information about the on-site construction process, this paper proposes a framework and utilizes technologies for the systematic monitoring and mapping of on-site activities and key parameters. Various technologies and sensors, such as a global positioning system (GPS), a laser linescanner, and infrared cameras, make it possible to track the on-site movements of machinery and asphalt temperatures during construction. This framework was applied and refined during 29 asphalting projects in the Netherlands, creating an extensive set of on-site process data. Considerable variability was found in the delivered asphalt temperatures, the asphalt cooling, the compaction process and density progression, and the movements of machinery. This variability offers opportunities where action could be taken to improve process quality by reducing process variability. The framework and explicit data can help asphalt teams to verbalize their tacit knowledge and make their own processes and choices transparent and further promotes learning processes. This paper contributes to a deeper understanding of the on-site construction process and highlights how to encourage technology adoption in construction. **DOI: 10.1061/(ASCE)CO.1943-7862.0000969.** *© 2015 American Society of Civil Engineers.*

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Introduction

Given their increasing liability and the risks involved, it is increasingly important for road construction companies to gain deeper insights into the on-site asphalt construction process (Dorée 2004; Ang et al. 2005; Kassem et al. 2008; Miller 2010; Gallivan et al. 2011). However, in general, contractors do not systematically monitor and map their own operational strategies (Miller 2010; Gallivan et al. 2011). In this paper, on-site operational strategies are defined as the activities, the key parameters during the process, and the underlying reasoning employed by asphalt teams that affect key quality parameters. If on-site operational strategies are not explicitly mapped, it is nearly impossible to associate and relate possible premature failures to the initial construction process.

While the quality of the asphalt mixture is well defined through different functional and mechanical properties, such as stiffness and resistance to rutting, very little is known about the quality of the on-site construction process. Miller (2010) concluded that the majority of the research deals with the characteristics of asphalt as a construction material, while only some 5% of asphalt-related journal papers deal with asphalt construction operations. Several important studies have been undertaken that have addressed construction operations in rather fragmented research areas, such as *asphalt temperature* (Faheem et al. 2007; Lavoie 2007; Delgadillo and Bahia 2008; Stroup-Gardiner et al. 2000; Schmitt et al. 2009; Cho et al. 2012; Wang et al. 2014) and *compaction* (Commuri et al. 2011; Beainy et al. 2012; Cho et al. 2013). In both asphalt temperatures and compaction operations, extensive variability has been found, and it has been suggested that this is mainly caused by poor operational practices.

The current construction practices of asphalt paving companies lean heavily on the experience of the asphalt teams and operators on site (Ferrada and Serpell 2014). This results in individualized implicit learning and lengthy learning cycles. To adequately manage and improve the process, it is necessary to move away from implicit learning toward the explicit mapping of operations and key parameters.

To this end, technologies to monitor the on-site construction process are becoming increasingly available (Commuri et al. 2011; Beainy et al. 2012; Cho et al. 2012). These studies indicate that technologies can help contractors make their processes explicit and hence gain more understanding about their own processes. Although some experiments were incorporated into industrial applications, in practice, their adoption has been slow (Hartmann 2006; Miller 2010; Gallivan et al. 2011; Beainy et al. 2012).

In this paper, an operational framework is developed and explained to gain deeper insights into the on-site asphalt construction process and, at the same time, encourage the introduction of technologies into the process. An *operational framework* means that the framework has been validated in practice and is ready for use.

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Methods

Problems and Objectives

The main challenges addressed in this paper are (1) the difficulty in improving process quality because the on-site processes and key parameters are not explicitly monitored and systematically mapped, and (2) the slow and often complete failure to adopt available technologies to monitor the on-site process. In response, the objectives of this research were (1) to develop a framework to systematically monitor and map the on-site construction activities and key parameters using available technologies; (2) to implement the framework, including the technologies, in current construction practice; and (3) to provide deeper insights into the on-site construction process and corresponding variability to improve process quality. The objectives of this paper are to highlight a successful demonstration of the technology and the implementation process in the industry and to demonstrate the opportunities offered by a structured and systematically collected data set with on-site monitored data to enhance learning, reduce process variability, and boost process quality.

Construction companies generally approach variability from the perspective of quality and identify quality as *conformance with requirements*. As such, once a design or specification has been established, any deviation implies a reduction in quality. This rather narrow view of quality leads construction companies to focus on conformance in an *end result* paradigm and not on process parameters and process controls that might lead to a better-quality product. Because there is little focus on monitoring the process, there is little known about the on-site process and any variability within it.

This study characterizes quality and variability using Montgomery's (2005) definition: "quality is inversely proportional to variability." This definition implies that, if the variability in key process characteristics decreases, then the quality of the process increases. Thus, process quality improvement is the reduction in variability of the key process characteristics. The identification and relevance of key process characteristics, such as asphalt temperature, asphalt cooling, and compaction operations, have been studied extensively (Schmitt et al. 2009; Commuri et al. 2011; Beainy et al. 2012; Cho et al. 2013; Wang et al. 2014).

Methodology and Approach

This research is conducted from a pragmatic philosophical perspective. First, the authors believe that meaningful new theories are built upon the existing experimental knowledge of practitioners and that this knowledge needs to be explicated to improve practice. Experience and practical knowledge are best extracted by observing day-to-day practice. Second, to validate whether a theory built on the practitioners' concepts is a good theory or not is only possible if it is tested in a practical setting. This gets to the heart of pragmatic inquiry: pragmatic researchers believe that a system is only good if it works in practice (Rescher 2000). Therefore, the authors' results are to be evaluated and validated according to their efficacy when applied in practice.

The gap between scientific findings and practical application is often very real. Various studies show that practitioners frequently struggle or fail to adopt research findings (Rynes et al. 2001; Dopson et al. 2002; Van Aken 2004; Van de Ven 2007) and demonstrate the difficulties of implementing technological innovations (El-Halim and Haas 2004; Miller 2010). An engaged research approach, combined with the pragmatic philosophical stance, can reduce the gap between theory and practice. Van de Ven's (2007) engaged scholarship and Van Aken's (2004) design science seemed to be the most relevant concepts to apply. Engaged research involves participative forms of research that obtain the perspectives of key stakeholders. This research claims to produce knowledge that is more penetrating and insightful than when practitioners and researchers work apart on the problem. Van Aken's (2004) design science is aimed at designing solutions for an industry's problems rather than generating knowledge solely and argues that design science can mitigate the gap between theory and practice and enhance the research relevance.

An action research approach was adopted, alternating progressive steps of (1) introducing new technologies into the construction process, (2) explicating the on-site construction process, (3) analyzing the on-site process and variability, and (4) evaluating the implemented technologies. The authors' action research approach involved the researcher, innovative technologies, asphalt teams, and operators in the research process. A cooperative network involving 11 Dutch contractors and a university was created to introduce technologies and to explicate and professionalize the on-site construction process. This network is called *ASPARi* (short for ASphalt PAving, Research, and innovation).

Background

Technologies to Monitor On-Site Operational Strategies

Technologies to monitor asphalt temperatures and compaction operations during the construction process have become increasingly available and affordable. Several experiments to map parts of the process have been conducted in recent years. Krishnamurthy et al. (1998), Peyret et al. (2000), Bouvet et al. (2001), and Navon and Shpatnitsky (2005) developed automated paving systems for monitoring asphalt compaction operations. Lei et al. (2013) developed a method for checking crane paths for heavy lifting in industrial projects using a global positioning system (GPS). Gransberg et al. (2004) developed a mathematical method to calculate the required number of roller passes. Akhavian and Behzadan (2013) developed a knowledge-based simulation modeling of construction fleet operations using multi-modal-process data mining. Commuri et al. (2011) and Beainy et al. (2012) developed neural network-based intelligent compaction analyzers for estimating compaction quality, and Cho et al. (2012) assessed the effects of temperature segregation on pavement distress in the early stages of the lifecycle.

These studies show that technologies can help contractors make their processes explicit, learn explicitly what they do, and hence gain more understanding about their own operational strategies.

Technology Adoption and Implementation

While the technologies are available and have become increasingly affordable, in practice, their adoption is slow, and few have become accepted widely by the industry (Pries and Janszen 1995; Mitropoulos and Tatum 2000; Bossink 2004; El-Halim and Haas 2004; Hartmann 2006; Miller 2010; Gallivan et al. 2011; Beainy et al. 2012). Many technologies fail to be adopted commercially because of an insufficient understanding of the nonexplicit operational strategies; as a result, they lack evidence of added value. These barriers to technology adoption for an asphalt compaction innovation were demonstrated by El-Halim and Haas (2004). A vicious circle has prevailed wherein technologies are not often adopted because of the lack of evidence of added value, while evidence of added value is lacking because technologies are not often adopted. The adoption of technology may also be hindered by the skepticism and reluctance of the operators. They may feel that their workmanship is being devalued or that management could use the technology punitively (Miller 2010). So, progress to adopt and fully integrate new technologies into operational strategies will come about only when the evidence of their additional value is made clear and when these innovations are better aligned with the actual needs and workmanship of the operators.

Framework to Systematically Explicate the On-Site Construction Process

Miller (2010) initially developed the basis of the measurement framework—called process quality improvement (PQi)—which aims to improve process quality by closely monitoring on-site asphalt operations and making key parameters explicit. The PQi framework evolved through various implementation phases. First, the technologies were introduced and tested. Having identified the useful technologies, a structured framework was developed to collect systematically the same set of variables. Finally, this framework was implemented by 11 contractors in the Netherlands.

Technology Introduction

Table 1 lists the technologies introduced in the PQi framework. In general, the focus is threefold: monitoring the movements of all machinery, asphalt temperatures, and density progression during the process. Also, data were collected about the weather and essential events to aid better understanding and to place the monitored data in context.

The authors worked closely with the construction industry to manage the new technologies. They were introduced to and aligned with the operators' needs, and the authors involved the operators directly by obtaining their feedback. The research network tested these technologies on their merits, and the results were fed back to the industry.

Framework Development

The same parameters were monitored in a structured and systematic way to compare the same parameters of different projects. A framework (cycle) was developed to work gradually toward improvements where the monitoring and analysis of processes and key parameters could be reproduced for future projects and facilitate learning from one project to another. The data collected were used to produce a series of visualizations and animations that makes operational behavior explicit (Miller et al. 2011). However, hard data alone do not explain the causes of variability and the logic and reasoning that operators use. Therefore, feedback sessions were conducted with asphalt teams, providing them with the explicit data and asking them to reflect on their work, discuss and analyze the results, and propose improvements to their future operational strategies. The typical PQi framework consists of the following phases:

1. Phase 1: Preparation—Check site design, undertake site calibration, record site conditions, and hold a preparatory meeting with the asphalt team.
2. Phase 2: Data collection—Asphalt temperature profiling; monitoring machine movements, weather conditions, density progression, and noteworthy events.
3. Phase 3: Data analysis—Analyze all data and prepare visualizations and animations.
4. Phase 4: Feedback—Discuss the measurements, visualizations, and animations with the asphalt team, laboratory technicians, and others involved in the project.
5. Phase 5: Improve—Create a short memo and assign improvements for the asphalt team and the researchers, including learning aspects for future data collections.

Implementation of the Framework

After developing the framework, it was important to upscale the number of experiments to make the process variability explicit. The ASPARi research network assisted with the contractors committing themselves for 4 years (2011–2014). Research focused on minimizing the cycle time to analyze the data and give feedback to asphalt teams. Researchers from the university wrote manuals and procedures to use the equipment and analyze the data. Next, a working group was formed, consisting of one or two representatives of the 11 contractors to form a team to implement the framework. Two-day courses were held to educate the contractors on using the equipment and to analyze the data. Using the technologies and the manuals, the contractors aimed to monitor two projects per year, share the collected data, and collectively work out improvements for the on-site process.

Data Set to Systematically Map On-Site Construction Processes

The 29 projects monitored using this framework created a broad adoption base and an extensive set of data. Fig. 1 provides an

Table 1. Instruments Introduced in the PQi Framework

Instrument	Task	Method	Variables
Weather station (Vantage Pro, Hayward, California)	Monitor weather conditions	Set up a weather station at the construction site	Temperature, wind speed, humidity, sun radiation (every minute)
Laser linescanner (Raytek, Santa Cruz, California)	Measure initial surface temperature behind the screed	Mount the scanner behind the screed of the paver	Surface temperature behind the screed in 20 zones (every second)
Infrared cameras	Measure cooling surface temperature at fixed positions	Cameras on tripod at fixed positions	Thermographic picture (every minute)
Thermocouples	Measure cooling in-asphalt temperature at fixed positions	Insert thermocouples in the middle and at the bottom of the asphalt layer	In-asphalt temperatures (every minute)
GPS receivers + base station (Trimble, Sunny Vale, California)	Monitoring machinery at the construction site	Set up a base station and put receivers on top of the machines	Position of machines to an accuracy of less than 2 cm (every second)
Density measurements (nuclear and electromagnetic)	Measure density progression at cooling measurement locations	Measure density after every roller pass	Type of roller pass and density
Memo recorders (Sony)	Record circumstances	Record circumstances during the process	Observations of circumstances in a logbook (stopping places, lunch, delays in transport, and so forth)

overview of the seven technologies adopted, the data collected, and the insights inspired by the data. The insights relate to the consistency of paving and compaction; the initial asphalt temperature behind the paver combined with the cooling rates of both surface temperature and in-asphalt temperature determined at fixed points; and the influence of weather and other conditions on these parameters.

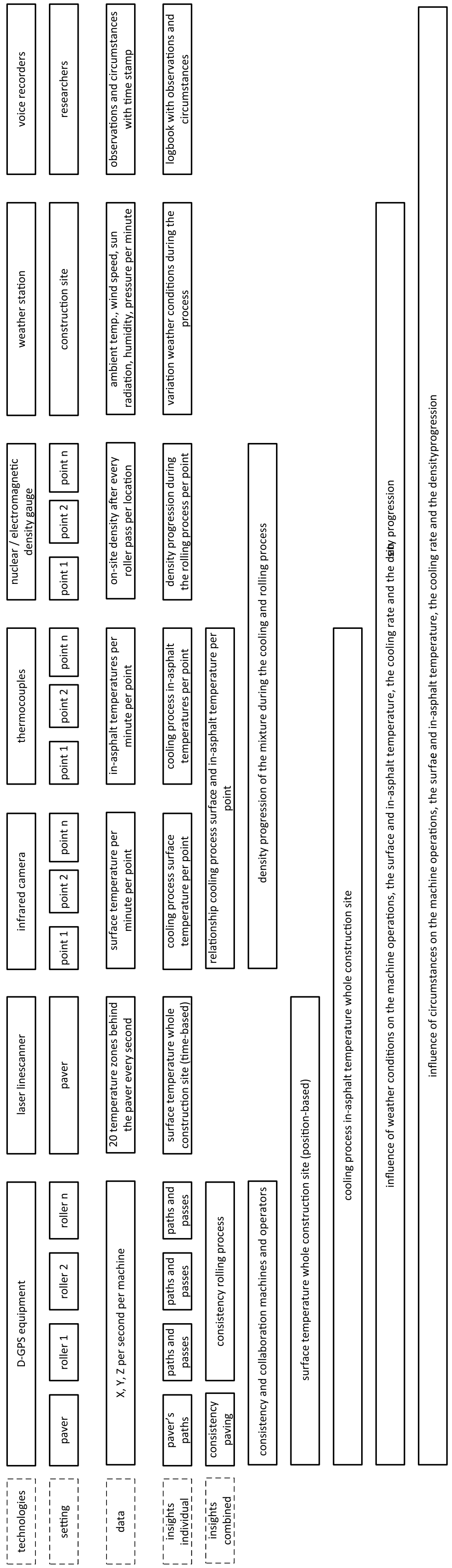


Fig. 1. Technologies included in the process quality improvement (PQi) framework and the resulting data and insights

Demonstration of the Insights from the Monitored Projects

From 2007 to 2013, the framework was applied in 29 projects covering a broad spectrum of projects and asphalt mixtures in varying weather conditions. Measurements were taken at highways, secondary roads, and company grounds. This diversity of situations made it difficult to extract statistical relationships and models. However, several phenomena were observed, and these are described in the next sections.

Delivered Asphalt Surface Temperature

Using the laser linescanner behind the screed of the paver, the effects of truck changes and short and longer stopping places of the paver on the surface temperature became explicit. Depending on the asphalt mixture, corresponding layer thickness, and ambient circumstances, the asphalt mixture will cool down during the paver's stops, possibly creating premature failure in the future. The data collected with the laser linescanner are visualized in temperature contour plots (TCPs). Fig. 2 shows a TCP with examples of paver stops and the resulting temperature differentials.

Table 2 gives a summary of the monitored paver stops and the temperature drops due to short and longer stops of the paver when categorized by asphalt mixture. Stops of 0–3 min are considered truck changes, 4–9 min are considered short paver stops, and 10 min and longer are considered hiccups with the plant or the logistical process. From the data, the authors drew the following conclusions:

1. One hundred forty paver stops were observed from the 29 projects constructing 35 asphalt layers. Of these stops, 50 were between 0 and 3 min with an average temperature drop of 24°C, 61 stops were between 4 and 9 min with an average temperature drop of 32°C, 11 stops were between 10 and 15 min with an average temperature drop of 45°C, and 18 stops were longer than 15 min with a temperature drop between 40 and 100°C.
2. During truck changes, the temperature drop is in the range of 5–40°C. During the short stops (3–9 min) and longer stops (>10 min), the temperature drops are larger and more variable. This variability is related to the changing influence of the ambient conditions, the asphalt mixture, and the layer thickness.
3. Substantial temperature drops were observed for both base/bind and surface mixtures not only at longer paver stops but also at truck changes. Temperature drops of 25°C should be expected during paver stops of 0–3 min.
4. The cooling rate of the asphalt mixture depends on the thickness of the layer. Substantially slower cooling rates were observed with thicker mixtures (base/bind) than with thinner mixtures, especially during paver stops from 4 to 15 min.
5. For warm mix asphalt (WMA), short paver stops (0–3 min) have only a minor impact on the cooling of the asphalt mixture because the temperature is already relatively low and the changes are hardly noticeable.

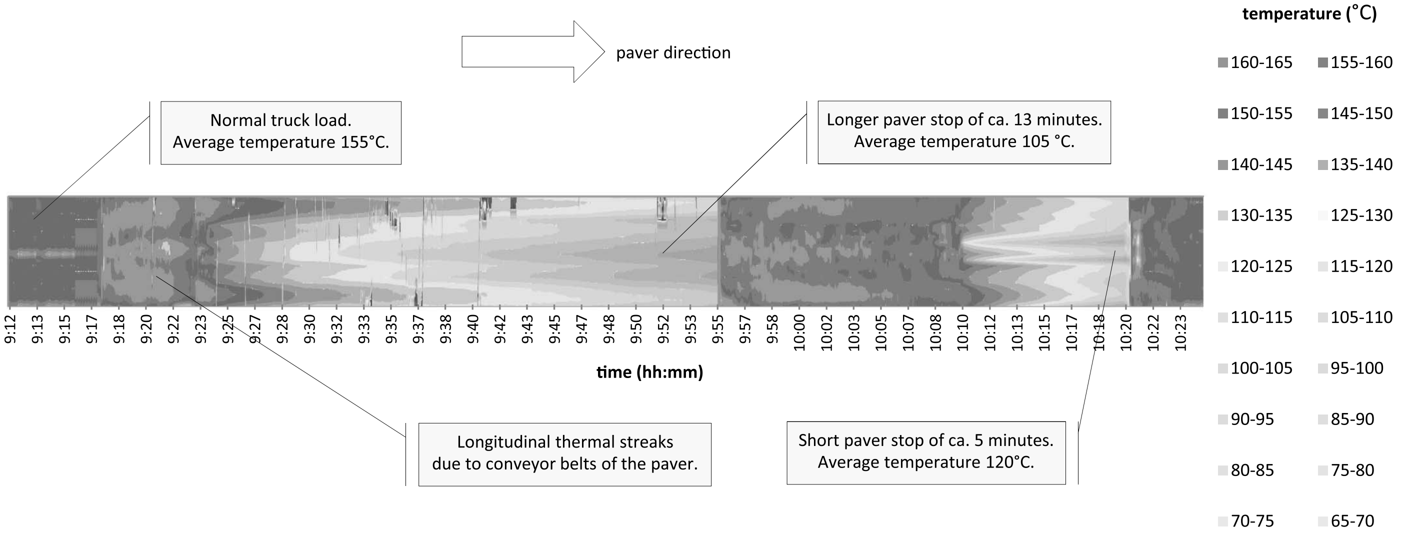


Fig. 2. Temperature contour plot (TCP) and temperature differentials

Table 2. Summary of Paver Stops and Temperature Drops

	Surface layer (30–50 mm)		Base/bind (50–80 mm)		WMA (60–80 mm)	
	Twelve layers		Twenty layers		Three layers	
Paver stops (min)	Number of stops	Average temperature drop (°C)	Number of stops	Average temperature drop (°C)	Number of stops	Average temperature drop (°C)
0–3	21	25	28	22	1	Hardly noticeable
4–9	17	40	34	33	10	18
10–15	3	55	7	46	1	30
15–50	5	63	12	62	1	50

The existence of temperature differentials has been previously acknowledged in the literature (Stroup-Gardiner et al. 2000; Cho et al. 2012) and had been confirmed in practice (ter Huerne 2004; Miller 2010). In response to temperature variability, material transfer vehicles (MTVs) can be a solution for reducing temperature differentials (Stroup-Gardiner et al. 2000). The MTV allows continuous paving through uninterrupted delivery of material to the paver and creates an extra buffer capacity. The use of the laser line-scanner made it possible to systematically monitor and map the temperature variability.

MTVs were used during three monitored projects, where some short stops (0–3 min) and mainly stops longer than 15 min (i.e., huge logistical hiccups) were measured. The surface temperature of the asphalt mixture ultimately cooled down to 120°C during the short stops. This was mainly caused by geographical conditions or communication between the paver and MTV. Fig. 3 shows that the MTV successfully reduces the temperature differentials behind the screed of the paver but that the average temperature slightly drops (approximately 5–20°C). In this example, the average temperature drops from 150 to 145°C, and the standard deviation falls from 15°C to less than 5°C.

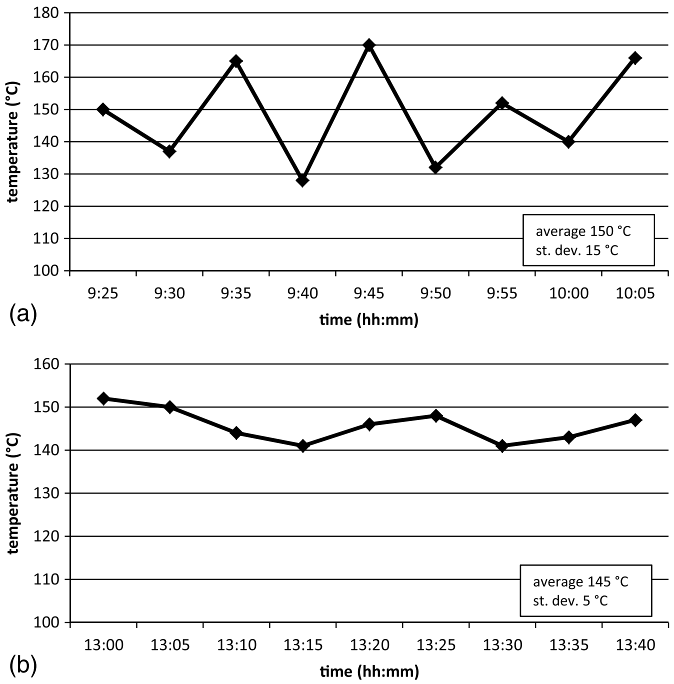


Fig. 3. (a) Average surface temperature behind the paver without MTV; (b) average surface temperature behind the paver with MTV

Cooling of the Asphalt Mixture

Thermocouples measuring the in-asphalt temperature and infrared cameras measuring the surface temperature over time made the asphalt cooling process explicit and helped to determine a relationship between the surface temperature and the in-asphalt

Table 3. Asphalt Mixtures and Monitored Cooling Times in Minutes

Project and cooling information	Base/bind (80 mm)	Base/bind (50–60 mm)	Surf (40–50 mm)	Surf (30–35 mm)	WMA (80 mm)	WMA (60 mm)
Number of projects measured	6	14	4	8	1	2
Number of curves measured	14	45	8	24	2	13
Start: 60°C (min)	84	72	54	46	72	49
Start: 120°C (min)	15	11	6	7	—	—
120–90°C (min)	21	20	11	9	15	17
90–60°C (min)	48	41	37	31	57	33

temperature. The asphalt cooling of the whole paved stretch can be predicted, combining this relationship with the continuously measured surface temperature behind the paver using the laser linescanner. For more information on this data fusion, see Vasenev et al. (2014).

The asphalt cooling process measured over time generates cooling curves. The analysis divides the data into three assumed phases of compaction: breakdown, intermediate rolling, and finish rolling represented by the following temperature windows: (1) starting temperature down to 120°C, (2) 120–90°C, and (3) 90–60°C [Shell 1990; National Center for Asphalt Technology (NCAT) 1996; Asphalt Institute 2007]. The measured cooling curves are also compared with the predicted cooling curves of *PaveCool* (Chadbourn et al. 1998) and *CalCool* (Timm et al. 2001). Table 3 gives the monitored information about the various asphalt layers and layer thicknesses, combined with cooling information for all the projects.

From the data, the authors drew the following conclusions:

1. The asphalt cooling takes longer for thicker mixtures. The base/bind mixtures and WMA cooling take approximately 15–30% longer. For the surface layers, this is appproximately 15%. This means that if roller operators want to operate within a certain temperature window, the layer thickness and corresponding cooling time should be made known and communicated in advance.
2. The cooling process from the starting temperature until 120°C for surface layers is very fast. So, if a certain number of roller passes are conducted within this temperature window, there is limited time available. Thus, more attention by roller operators is necessary.
3. WMA logically cools faster down to 60°C. However, several researchers postulate that WMA can be compacted until 40°C (Prowell and Hurley 2007; Silva et al. 2010). Five WMA cooling curves made it clear that it took approximately 32 min until the mixture cooled down to 40°C, while the cooling of the hot mix asphalt (HMA) laydown temperature until the WMA laydown temperature took much less time. This means that, if the mixture can be compacted until 40°C, there is more compaction time available for WMA than for HMA. However, if the same number of roller passes should be conducted between 120 and 90°C for both HMA and WMA, there is less time available. So, adjustment of the rolling procedures is required.
4. The predicted cooling curves derived from *PaveCool* and *CalCool* correspond well with the measured cooling curves on site. However, this is during postprocessing, where the exact layer thickness and weather conditions are known. However, it is difficult to predict the curves accurately before construction.

The measured cooling curves seem to be highly influenced by the wind speed and solar radiation (Asphalt Institute 2007; Wang et al. 2014). Therefore, the influence of these parameters on cooling rates was analyzed in more detail but not for the WMA projects because of insufficient information. Tables 4 and 5 provide the cooling times (in minutes) of projects when there is practically no wind and projects when there is a wind speed of 5 m/s or stronger. From the data, the authors drew the following conclusions:

1. High wind speeds increase the cooling rate significantly and thus decrease the time available to compact the asphalt mixture. Higher cooling rates are observed in all windows of the cooling curve.

Table 4. Cooling Times in Minutes for a Wind Speed Higher Than 5 m/s

Cooling times with wind of <5 m/s	Base/bind (80 mm)	Base/bind (50–60 mm)	Surf (40–50 mm)	Surf (30–35 mm)
Start: 60°C (min)	95	80	63	57
Start: 120°C (min)	16	13	7	8
120–90°C (min)	25	21	12	10
90–60°C (min)	55	46	44	39
Difference between surface temperature and in-asphalt temperature (°C)	6	8	7	5

Table 5. Cooling Times in Minutes for a Wind Speed Lower Than 5 m/s

Cooling times with wind of >5 m/s	Base/bind (80 mm)	Base/bind (50–60 mm)	Surf (40–50 mm)	Surf (30–35 mm)
Start: 60°C (min)	80 (16% less time)	40 (50% less time)	40 (37% less time)	31 (46% less time)
Start: 120°C (min)	15 (3% less time)	6 (55% less time)	6 (9% less time)	5 (33% less time)
120–90°C (min)	20 (20% less time)	15 (28% less time)	10 (21% less time)	7 (33% less time)
90–60°C (min)	45 (20% less time)	19 (59% less time)	26 (41% less time)	19 (52% less time)
Difference between surface temperature and in-asphalt temperature (°C)	15	16	13	8

2. The higher cooling rate makes a major difference, especially for the thinner asphalt layers (30–35 mm)—namely, a decrease of 40–50% in the time available for compaction. Cooling to 60°C takes only 31 min, and 120°C is reached after only 5 min. Thus, the construction of thin surfaces seems very critical if there is a wind speed of more than 5 m/s.
3. The difference between the surface temperature and the in-asphalt temperature is highly influenced by the wind speed. This difference is doubled for asphalt layers thicker than 60 mm when there is a wind speed of 5 m/s or higher—up to differences of 20°C between the surface temperature and in-asphalt temperature.

The literature also highlights the significant influence of solar radiation on the cooling rate (Chadbourn et al. 1998; Timm et al. 2001; Mieczkowski 2007). Tables 6 and 7 provide information on the effect of solar radiation on cooling times for various mixtures. From the data, the authors drew the following conclusions:

1. At high solar radiation (more than 100 W/m^2), the asphalt mixture cools very slowly in the 80–60°C temperature range. However, the influence of solar radiation at high temperatures (on the cooling time from 160 to 120°C) is relatively small.
2. From the feedback sessions, it was clear that asphalt teams often overestimate the influence of high solar radiation during the higher temperature range and, as a result, are often too late for breakdown rolling.

Density Progression during Compaction

During the asphalt cooling process, roller passes are conducted by several roller types, each having different effects on the density and mechanical properties of the asphalt. Data were gathered for each roller type, including the number of passes, the temperature and time windows in which each roller compacts, and the impact of the roller passes at certain temperatures on the density.

The monitored projects demonstrated the extent of the many changing variables and the different operational strategies for asphalt compaction well. Table 8 provides an example where the following variabilities were apparent:

1. The number of passes of the tandem roller ranged from 7 to 11 and between 10 and 17 passes for the three-drum roller, with a standard deviation of between two and three passes. The total number of roller passes per location varied from 14 to 28 roller passes.
2. The time and temperature windows in which the roller passes were conducted varied considerably. The total compaction time of the three-drum roller ranged from 53 to 90 min, and the temperature compaction window of the tandem roller varied from 145 to 100°C and from 120 to 65°C. Interestingly, the standard deviations in compaction time and in asphalt temperature at the start of compaction were higher for the three-drum roller, whereas the standard deviation in asphalt temperature when compaction was finished was higher for the

Table 6. Cooling Times in Minutes for Solar Radiation Higher Than 100 W/m^2

Cooling times with solar radiation of >100 W/m^2	Base/bind (80 mm)	Base/bind (50–60 mm)	Surf (40–50 mm)	Surf (30–35 mm)
Start: 60°C (min)	91	81	67	59
Start: 120°C (min)	16	14	7	7
120–90°C (min)	23	21	14	12
90–60°C (min)	51	45	47	39

Table 7. Cooling Times in Minutes for Solar Radiation Lower Than 100 W/m^2

Cooling times without solar radiation	Base/bind (80 mm)	Base/bind (50–60 mm)	Surf (40–50 mm)	Surf (30–35 mm)
Start: 60°C (min)	76 (17% less time)	61 (26% less time)	50 (26% less time)	39 (34% less time)
Start: 120°C (min)	14 (11% less time)	8 (47% less time)	6 (2% less time)	5 (27% less time)
120–90°C (min)	18 (23% less time)	18 (16% less time)	11 (22% less time)	7 (40% less time)
90–60°C (min)	43 (15% less time)	35 (23% less time)	34 (28% less time)	26 (33% less time)

Table 8. Variability in Key Parameters of Operational Roller Strategies with an 80-mm AC 22 Base

Mixture and weather condition	Point	Roller type and sequence	Number of roller passes	Compaction time (min)	Temperature start compaction (°C)	Temperature finish compaction (°C)	Time between paver and first roller pass (min)
HMA: AC 22 base (80 mm), 15–17°C, solar radiation of 100–200 W/m^2, wind of 8–13 m/s	1	Tandem	10	38	130	85	5
		Three-drum	15	53	115	60	14
	2	Tandem	11	30	145	100	2
		Three-drum	17	62	120	65	19
	3	Tandem	7	43	120	75	7
		Three-drum	17	90	110	70	10
	4	Tandem	7	43	120	65	9
		Three-drum	15	54	110	65	17
	5	Three-drum	10	65	140	70	10
		Tandem	11	30	125	60	32
	6	Three-drum	14	65	140	65	5
Summary of variability in operational strategies' rollers	Average	Tandem	9	37	128	77	11
		Three-drum	15	65	123	66	13
	Standard deviation	Tandem	2	7	10	16	12
		Three-drum	3	18	14	4	5

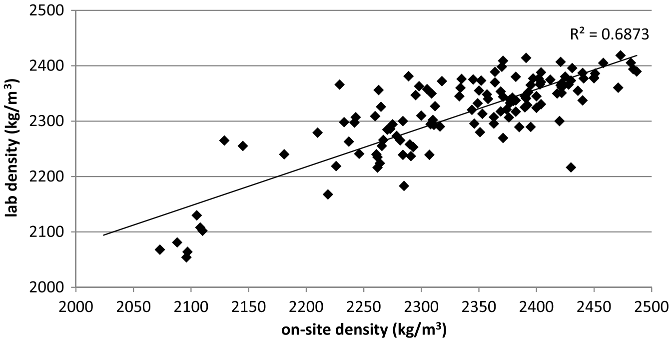


Fig. 4. Correlation between on-site density and lab density

tandem roller. In other words, it seems difficult for the operator of the three-drum roller to determine when to start compaction and for how long to compact and for the operator of the tandem roller to determine when to stop.

3. The sequence of the rollers was changed twice. At Locations 1–4, the roller sequence was first the tandem roller and then the three-drum roller. At Location 5, first the three-drum roller started and then the tandem roller started. Only the three-drum roller was used at Location 6.
4. The time interval between the paver and the first roller pass—and with that the temperature of the mixture at the first roller pass—varied substantially. For instance, the tandem roller started rolling between 2 and 9 min after the paver had laid the mixture. Relating this time difference to the cooling curve, the temperature difference for the first roller pass is approximately 25°C. The standard deviation in the timing of the first roller pass behind the paver is much higher with the tandem roller than with the three-drum roller.

This pattern of variability was highlighted in only one project. However, considerable variability was also found between projects, such as with the use of different sets of rollers for similar asphalt mixtures.

Cores were extracted to determine the lab density at the locations where the cooling and density progression were monitored. This was compared with the on-site measured density. However, this is not desirable for thin surfaces, and no cores were extracted. Fig. 4 shows the correlation between the on-site measured density and the density determined in the laboratory for 130 cores from 23 projects. The relationship between the measured density on site and the core density determined in the laboratory is weak ($R^2 = 0.69$). The differences vary from $+137$ to $-213\ \mathrm{kg/m^3}$. The on-site measurement devices seem useful to determine whether density progression is achieved. However, the current devices are imprecise in determining the absolute density. The results show much variability and therefore are difficult to use.

Movements of the Machinery on the Construction Site

The movements of the machinery on site were analyzed using high-accuracy differential global positioning system (D-GPS) equipment attached to the machinery. These data were used to produce (1) animations of the construction process; (2) visualizations of how often a roller passed a certain point on the construction site; and (3) graphs of the speed of the paver, as shown in Fig. 5.

The animation allows operators to look back at the construction process as a team and to reflect on their own operational strategies. The animation visualizes where the machines are working in respect to other machines and what the rollers do when there are discontinuities in the process—for instance, when the paver stops. The animation also shows the teamwork between different rollers—for instance, when one of the rollers needs to refill the water tank.

How often a roller passes a certain location was analyzed using the GPS data of the rollers and was visualized in compaction contour plots. The analysis shows a great deal of variability in the number of roller passes. For almost all monitored projects, the variability becomes visible at the beginning and at the end of the process, when these locations actually need extra attention. The stopping places of the paver and special road constructions, such as driveways, are also locations where inadequate compaction takes place. The animations show clear evidence of consistent textbook patterns. However, the variability is caused mainly by the operators unintentionally applying the same patterns, regardless of the changes in circumstances. Also, operators tend to continue compaction even after the target density is reached. This practice of starting too late or too early with compaction highlights operators' behavioral problems of not knowing when to start and finish compaction.

The analysis of various paver speeds for the different asphalt mixtures shows that the paver speed during the construction of base/bind layers is higher and more variable than for surface and WMA mixtures. The paver speed during the construction of surface layers is between 4 and 9 m/min, while the paver speed during the construction of base/bind layers is between 4 and 14 m/min. The speed of the paver appears to be a good measure for the continuity of the whole construction process. If the paver can work at a constant speed, the first roller can conduct a consistent rolling pattern. Also, the next rollers for intermediate and finish rolling can conduct their planned rolling patterns. However, if the paving process is inconsistent, the whole construction process becomes inconsistent—causing, for example, delays in the asphalt supply, manual work around the paver, or changes in the speed of the paver.

Validation of the Framework in Practice: Contractors' Perspectives

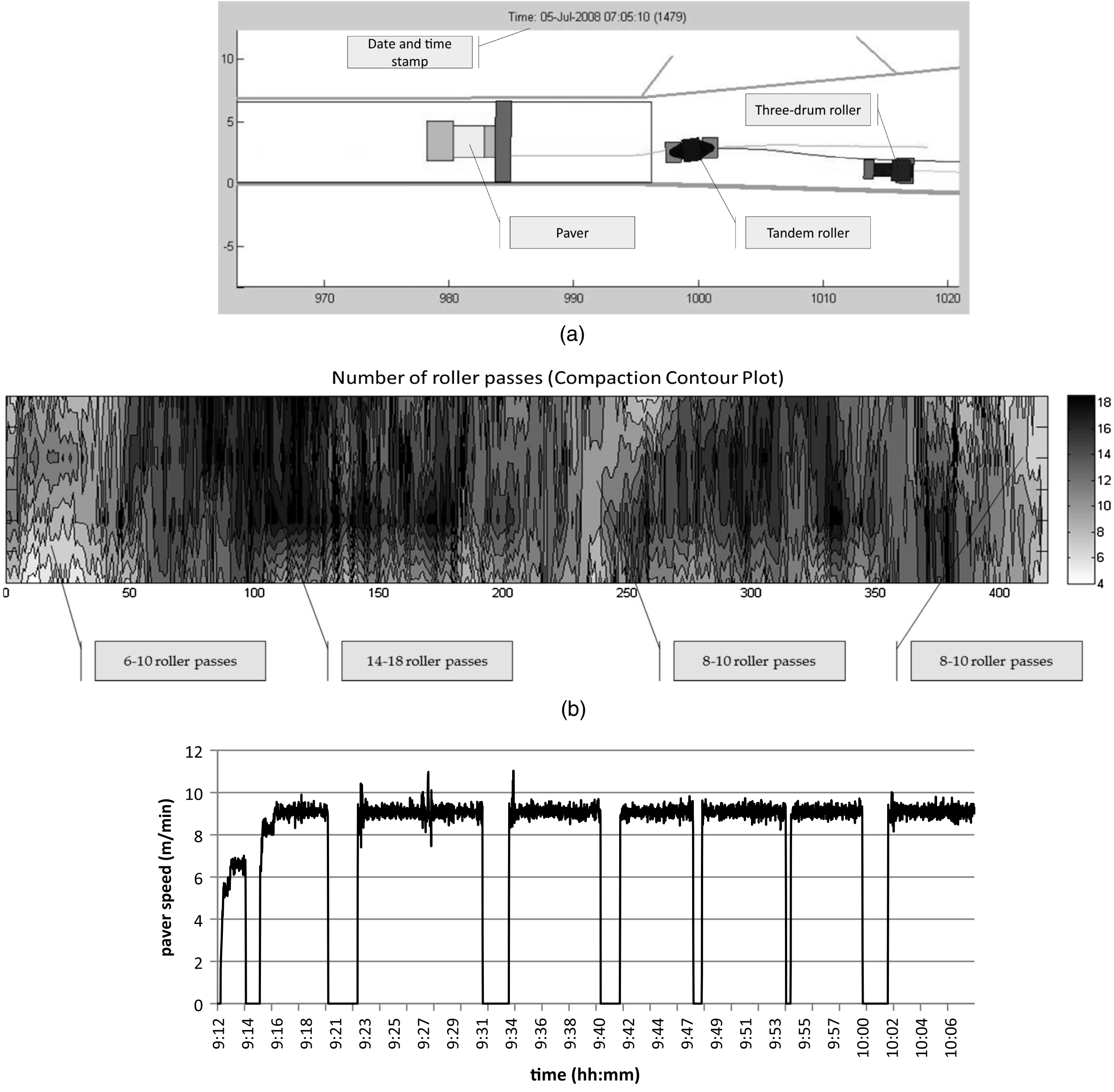
Following the authors' pragmatic perspective, the framework had to be evaluated according to its efficacy in practice. Three contractors evaluated the framework after 1.5 years (ter Huerne et al. 2012). They first applied the PQi framework after 2007 on five projects. The second contractor started conducting PQis in 2011 and has completed three PQi cycles. The third contractor has conducted four PQi cycles since 2009. The evaluation came from the organizational, operational, and managerial insights from the monitoring and feedback sessions.

Organization within the Company

All the contractors involved were able to conduct the PQi framework unaided. The organization of the monitoring differed from team to team and from machine to machine. For example, the power supply from the laptops connected to the laser linescanners varied between the pavers. This sometimes made the organization difficult, and greater standardization would help. Similarly, measurements must be well prepared, and the people involved need to be well informed, such as when attaching equipment to the machines, which requires good preparation and assistance from the asphalt team.

Operational Insights

The data collected showed the contractors and asphalt teams the variability in the process. The animation of the process and the



(a)

(b)

(c)

Fig. 5. (a) Screenshot of the animation of the process; (b) number of roller passes (compaction contour plot); and (c) paver speed during the process

plots with the number of roller passes showed the consistency of the paving and compaction process. Further, it is relevant for the contractors that temperature differentials are influenced significantly by truck changes and the temperature of the underlying layer. All contractors concurred how important it is to organize the transport logistics from the plant to the construction site.

PaveCool and *MultiCool* were broadly adopted by the companies to forecast the cooling of the asphalt mixture, predict compaction times, and estimate the time required for road closures.

The contractors emphasized that thin surfaces cool down fast under good and poor weather conditions. This means that the breakdown roller has limited time to put the planned compaction energy into the mixture, especially under less-than-ideal circumstances. For thin surfaces, the contractors suggested the use of an MTV to reduce the temperature differentials and to allow a continuous process.

Managerial Insights

The process monitoring and provision of explicit data to the asphalt team enabled a healthy discussion by the companies about working methods and the use of additional technologies, improved process quality, and how quality is influenced during the on-site process. These discussions made the operators more aware and increased their insight into the construction process. This complemented their experience and practical knowledge. They concluded that when more data are collected systematically, improved strategies can be determined and better guidelines can be given to operators.

The monitoring results were incorporated in the winter training programs and discussed with more asphalt construction teams. One contractor concluded that the differences between teams were relatively small and that they all learned the same lessons from the training and use of explicit data that enhanced knowledge transfer within the company.

The contractors emphasized the need to develop tools and equipment to support roller operators during the compaction process. In the near future, the contractors want to progress toward providing real-time information on site to assist the operators during construction. It was also suggested that machines, such as MTVs, can be evaluated on their merits using the additional technologies in the process.

All contractors concluded that continuity is vital for the final quality of the pavement, given that the data still show many discontinuities in the process and variability in key parameters. From a managerial perspective, more attention is needed to organize a continuous process from the plant during logistics and during the on-site process.

Reflection and Discussion

The pragmatic driver behind this research was to respond to road contractors' needs to reduce process variability and improve process and quality control. In this research, a framework was developed and then implemented in construction practice to explicitly monitor, visualize, and map on-site construction processes and key parameters using various technologies. The results add elements to asphalt construction research and provide practical pointers for improving asphalt construction practice.

Implications for Asphalt Construction Research

The main conclusion drawn from the monitored projects in this research is that there is substantial variability in key parameters and operations. This is in line with previous research findings. The authors' findings confirm the existence of temperature differentials, as observed by Lavoie (2007) and Cho et al. (2012), and emphasize the large scale of the projects where these differentials occur. The monitored variability in compaction operations also corresponds with previous research findings (Leech and Powell 1974; El-Halim et al. 1993; Zambrano et al. 2006). Further, the authors' findings highlight the large variability in on-site density measurements using both nuclear and nonnuclear gauges. Cho et al. (2013) have proposed a method to improve nonnuclear density measurements but still found relatively low correlation rates and recommended taking cores from the road. This suggests a need to reevaluate on-site density measurements and possibly search for alternatives. Commuri et al. (2011) and Beainy et al. (2012) propose the *Intelligent Asphalt Compaction Analyzer* and show higher correlation rates between estimated density and core density. The debate continues as to whether the estimations made by these systems are sufficiently accurate for on-site process control.

Through monitoring the process and discussing operational choices with asphalt teams, this research shows that the tacit knowledge represented in the everyday practice of operators becomes explicit. The tacit knowledge uncovered can be shared within the company among asphalt teams and, according to Zhang et al. (2013), this will increase the flexibility of integrated project teams and increase the overall collaboration and synergy of the team.

The monitored projects have provided data that demonstrate the importance of using new technologies and their added value for current on-site operational strategies. The authors' research approach, which gradually introduced and evaluated technologies so as to align them with the operators' needs, helped to gain the support from contractors both technically and financially, as indicated by El-Halim and Haas (2004) and Pellicer et al. (2014), as a way to successfully adopt and implement technologies.

With the opportunity to make on-site activities and parameters explicit and to monitor process variability, it also becomes possible to overlay on-site construction data with later inspection data during service life. Initial steps have been taken to overlay these data sets, but it is too early to observe significant damage. In further research, it may be possible to trace damages back to construction operations and then draw conclusions on the impacts of on-site construction on the durability and serviceability of the road.

The monitored process variability is also vital in attempting to relate on-site parameters to the asphalt quality and provides opportunities to investigate sensitivity to quality parameters. Initial steps were taken by conducting experiments in the laboratory. These aimed to simulate the monitored process variability with respect to temperature and compaction strategies, determine their effects on the mechanical properties of the asphalt layer, and thus better align laboratory tests with on-site field operations (Bijleveld and Dorée 2012).

Practical Pointers for the Construction Industry

The results of this study provide practical pointers for contractors, agencies, and machine manufacturers. The developed framework provides contractors with a deeper understanding of on-site asphalt construction. Using the developed framework, it is possible for contractors to create transparency in their own processes and operational choices, and this will help asphalt teams in sensemaking regarding the processes and their interdependencies, as discussed by Weick and Sutcliffe (2007). The gathered data set from on-site monitoring makes the process variability explicit and serves as a basis for contractors to improve process quality by reducing variability.

Reducing process variability can first be realized by better specifying and improving forecasting of the key process parameters; second, by monitoring (direct observation) the key process variables; and, third, by real-time information during construction.

Designing the key process parameters, such as compaction operations, is relevant in providing clear instructions to operators and to creating awareness of the relevant parameters. Two programs that predict asphalt cooling—*PaveCool* (Chadbourn et al. 1998) and *CalCool* (Timm et al. 2001)—are both suitable for Dutch asphalt mixtures, with the exception of open-graded mixtures. These programs could help develop an overall estimate of the cooling process prior to the start of a project.

In order to monitor key process parameters, asphalt paving companies should adopt and implement technologies, such as D-GPS, laser linescanners, and infrared cameras in their daily practice. The use of an MTV is suggested to reduce the temperature differentials and to enable a continuous process. The authors' research demonstrates the value of technologies in making the on-site construction process explicit, enhancing learning competencies, and improving understanding of the process.

Tools and equipment to support roller operators with real-time information on site, such as asphalt temperatures and the number of roller passes, would allow operators to adjust the process when deviations occur. The contractors emphasized the need to develop such tools and equipment in further research.

The authors' findings are also relevant for agencies responsible for asphalt roads. Agencies can support the use of technologies for improved process and quality control by making process monitoring a contractual requirement or by rewarding additional process control measures in their performance contracting.

Finally, machine manufacturers should align their machines with operators' needs to ensure adoption in construction practice. Manufacturers should be urged not only to design their machines from a mechanical perspective but also to accommodate the practical on-site asphalting needs.

Conclusions

On-site operational strategies of asphalt teams have a critical impact on pavement quality. Remarkably, most current asphalting strategies are not systematically monitored and mapped. The main challenge for the authors' research was to make the operational strategies of asphalt teams explicit and to establish a framework to monitor process variability.

A framework was developed to make on-site operations and key parameters explicit using D-GPS, laser linescanners, infrared cameras, thermocouples, and a weather station. This framework was used in 29 projects, creating an extensive data set allowing analysis of various important relationships between on-site processes and key parameters and the extent of process variability. Considerable variability was found in the delivered asphalt temperatures, the cooling of the asphalt mixture, the compaction process and density progression, and the on-site movements of the machinery.

The framework developed to explicate on-site processes and monitor process variability was implemented and shown to be relevant, applicable, and useful in asphalt construction. The framework and the explicit data generated enable asphalt operators to synthesize and verbalize their tacit knowledge and promote learning processes. The research identified and offered opportunities to improve process quality by reducing process variability and, as such, facilitate more professional practices in the asphalt construction industry.

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