On-Site Process Variability and Common Practices: a Case in Asphalt Compaction

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Abstract

Due to changing contracts, sometimes including design and maintenance, it becomes increasingly important for contractors to improve process and quality control during on-site construction. Improving on-site process control, however, requires understanding about current practices. This understanding is mainly lacking, because current practices lean heavily on the on-site experience and craftsmanship of operators and hardly any technologies are used during the on-site process for performance enhancement. Also, the guidelines for on-site operations are vague or even lacking. Therefore, it is near impossible for contractors to distinguish poor and good operational practices.

To develop a deeper insight into the on-site construction processes, the on-site operations need to be made explicit. This paper takes the asphalt construction industry as an example, where the on-site operations of 29 projects in the Netherlands are explicated using technologies, such as D-GPS, a laser linescanner and infrared cameras.

The results show there is substantial variability in key parameters and on-site operations, such as the roller types used for compaction, the number of roller passes undertaken and the time and temperature windows in which these passes are conducted, which are all key for the final asphalt quality. Also, a method is demonstrated to extract common compaction practices from this kind of data-set.

The results are a stepping stone for a structured and systematic design of the on-site process including improved guidelines for on-site operations rather than current experience-based ad-hoc working methods. This is a starting point to distinguish good and poor operational practice and reduce process variability. This will help contractors to improve their understanding about on-site construction processes in order to improve process and quality control.

Keywords: Common practices, innovative technologies, operational strategies, process control, process variability.

1 Introduction

Process and quality control during on-site construction is becoming increasingly important. This is caused by changing roles between contractors and clients. Agencies shift towards service level agreements with lengthy guarantee periods, sometimes including design and maintenance. Within these new roles and contracts, the contractors are directly confronted with shortcomings in quality during the guarantee period creating more pressure on process and quality control during on-site construction.

In the current technological age, one might expect contractors to embrace the new ICT-opportunities, which become increasingly available and affordable, for process improvement and performance enhancement. In reality however, the construction process still mainly is carried out without the use of (high-tech) instruments to monitor key process parameters and to map the on-site construction process (Miller, 2010). Additionally, in many domains of the construction industry traditional working practices lean heavily on the on-site experience and craftsmanship (tacit knowledge) of operators and teams. Operators may implicitly learn based on experience from previous construction projects, but this is based on limited observations and data, resulting in slow process improvement and individualised lengthy learning. It is therefore near impossible for contractors to understand what transpired during on-site construction, assess the quality of the on-site operations and thus trace back what poor and good operational practice is.

To develop a deeper insight into on-site processes, a first step is to make current process variability and the common practices explicit, which are based on years of experience and craftsmanship of operators. When process variability and common practices are explicit, it becomes possible to distinguish good and poor practices under more controlled circumstances in the laboratory. Also, a change can be instigated towards explicit method-based learning as previously described by Bijleveld and Dorée (2013). This paper takes the asphalt paving industry as an example and makes process variability and common practices explicit, especially regarding asphalt compaction. Asphalt compaction is the final stage of the asphalt road construction process and still is a muddy box regarding process and quality control. Although the asphalt technologist put substantial effort into creating a mix with intended characteristics, once delivered on-site the actual compaction sequence primarily depends on experience and gut feeling of the roller operators without clear guidelines. This unknown element in the process and in quality control is bothering the contractors more than ever before due to increasing pressure in service level agreements. The search is on for proper compaction guidelines. From 29 monitored projects on-site operations are explicated and this paper focuses on the process variability and common practices regarding compaction.

The paper is structured as follows: The next section of the paper hones in on the asphalt compaction process, followed by the aims and research methods of this study. Next, process variability within the monitored projects will be discussed, followed by the extraction of common operational compaction strategies. Finally, the main conclusions and directions for future research for the paving industry specifically and the construction industry in general will be discussed.

2 Asphalt construction domain and asphalt compaction

The focus in this paper is on the asphalt compaction phase, which is one of the most relevant operations for the asphalt quality. The Asphalt-Institute (2007) defines compaction as the process of compressing a given volume of asphalt into a smaller volume. The result is a certain density of the asphalt mixture. Achieving the target density will influence the desired mixture characteristics including strength, durability, and resistance against deformation, cracking and moisture (Decker, 2006). If the mixture is over-compacted, the mixture becomes overfilled and can lose its essential stability. If the mixture is under-compacted, deformation of the asphalt mixture during usage of the road can occur and rutting can be the result.

The asphalt compaction process takes place through loading the mixture, in practice executed by rollers. The total compaction process by rollers generally can be divided into three phases from both material as operational perspective (Ter Huerne, 2004; Asphalt-Institute, 2007; Miller, 2010): (1) breakdown rolling, where particles will be be arranged and air need to be expelled, (2) intermediate rolling, where the asphalt mixture behaves differently due to increasing stiffness and elastic behaviour of the mixture, and (3) finish rolling, where the mixture need to be compressed further until its target density. From an operational perspective, these phases can be characterized by the type of roller and the time and asphalt temperature windows for compaction. Usually the machinery for compaction consists of several types of rollers, each with individual roles during the process, for example, squeezing, kneading or smoothing the surface. The challenge of the on-site compaction process is to decide when and how to compact in order to reduce the void content to a certain level and to reach an even surface (Ter Huerne, 2004).

Both researchers and practitioners acknowledge that the temperature of the asphalt mixture during compaction is important for the final quality of the pavement (Timm et al. 2001; Willoughby, 2003; Cho et al. 2012). If the material temperature is too low during compaction, the bitumen can no longer lubricate the mixture, resulting in an open surface and higher risks for ravelling. The same prevails for the maximum temperature: if the binder is too fluid and the resulting aggregate structure is weak (at high placement temperatures), the roller loads will simply displace or shove the material rather than compact it and cracks may originate behind the roll. So, the theory points to an optimal compaction temperature frame to compact the asphalt mixture, logically resulting in an optimal compaction time frame because of cooling of the asphalt mixture. If the asphalt mixture is compacted within these frames, from experience it is known that the intended design properties of the asphalt mixture will be achieved. If the mixture is compacted outside this temperature window there are high risks to negatively influence the final quality of the asphalt construction.

Significant research effort is put into intelligent compaction and automated monitoring of road construction operations to give roller operators more information during the process (Navon and Shpatnitsky, 2005; Beainy et al. 2012). Such systems includes GPS receivers, an integrated computer system to analyse roller information, accelerometers, and temperature information (Gallivan et al. 2011). Typical outputs of such systems are color-coded displays with the number of roller passes and the asphalt temperature. A workflow for clear visual data representation for operators on-site integrating various technologies is outlined by Vasenev et al. (2011). It is envisioned that research in intelligent compaction will capture many of the relevant variables in real-time (Bahia et al. 2006).

To effectively use these innovative technologies on-site in real-time, clear instructions for roller operators are needed regarding the number of roller passes and the asphalt temperatures for compaction. In current practices, roller operators mainly estimate the number of roller passes and temperature of the asphalt mixture throughout the process based on previously gained experience and craftsmanship. It is, however, generally unknown if the previously gained experience can also be applied to a new practical setting. In addition, the guidelines given in various textbooks (Shell, 1990; NAPA, 1996; Asphalt-Institute, 2007) provide general instructions especially about what not to do and about rolling patterns. However, clear instructions about the number of roller passes and temperatures in these textbooks are vague or even lacking. Examples are: "*Start rolling as soon as possible without causing undue displacement of the material, and to continue until all the roller marks had been removed*", "*Intermediate rolling should closely follow breakdown rolling, while the mix is still plastic and at a temperature that will result in maximum density*", "*Finish rolling should be accomplished while the material is warm enough for the removal of roller marks*". Methods or procedures to determine the number of roller passes and temperature windows for compaction are also lacking. This is normally determined by various test-sections and trial-and-error on-site which is very ineffective and uncertain.

So, the on-site compaction process of asphalt is a versatile task. The set of information for roller operators to make decisions include: the cooling rate of the mixture, the previously executed roller passes and patterns, and the roller passes conducted by colleagues. Many vital changing variables, such as the ambient temperature, the temperature of the underlying surface, the layer thickness, wind speed and rain, make on-site asphalt compaction even more difficult. Based on these parameters, operational choices for the roller operator, mainly based on experience, include choosing the type of rollers, the number of roller passes, when to start and finish rolling, and within which temperature windows these roller passes should be executed.

3 Aims and research methods

Little research effort is put onto systematic mapping and analysing on-site construction processes. It is therefore near impossible to know what operations transpired on-site and how these were carried out, making it difficult to distinguish good and poor practices. The textbooks are also unclear about guidelines for on-site processes. In the quest towards improved process and quality control, on-site operations need to be explicated and analysed.

The aim of this paper is firstly to make operational practices in asphalt construction explicit and to demonstrate the degree of variability in key parameters and compaction operations, such as the number of roller passes and the time and temperature windows for compaction, based on actual monitored projects. Secondly, this paper aims to determine common practices regarding asphalt compaction. When more insight is gained into the variability and common practices in on-site construction operations, it becomes possible to analyse the effects of different observed compaction strategies on the final quality of the road under more controlled circumstances in the laboratory.

To systematically monitor and map on-site construction operations, a previously developed framework is adopted. This framework, initially developed by Miller (2010), explicitly and systematically works towards more insight and process improvements and is called Process Quality improvement (PQi). The aim of the PQi-framework is the improvement of the process quality by closely monitoring asphalt construction works, and making operational behaviour explicit by introducing new technologies in the current process. Then, the explicit monitored process is made available to the asphalt team so that they can reflect on their work, discuss and analyse the results and propose improvements to their working methods and operational strategies for future projects. This should lead to a cycle of continuous process improvement.

The technologies that are introduced in the PQi-framework are three-fold: (1) D-GPS to monitor the movements of machinery, (2) a laser linescanner, infrared cameras and thermocouples to monitor the initial lay-down asphalt temperature and asphalt temperature throughout the process, and (3) a density gauge to monitor the density progression during the compaction process. These are important parameters in determining asphalt quality. In order to better understand and contextualise this data, weather data is collected and analysed and a logbook records all the (important) events during the process. More information about the technologies that were used in working with this framework and the systematic way in which data were collected, analysed and mapped are described in Miller (2010).

After a testing period of four years, this framework was broadly implemented in the Dutch industry and 11 contractors committed themselves to monitor two projects per year for a period of four years. Researchers at the university formalised the process using manuals and procedures to use the equipment and analyse the data. Two-day courses were held to educate the contractors to use the equipment and analyse the data themselves. To date, 29 projects were monitored by the contractors using this framework and systematically stored in a structured database. This data is used as a basis to analyse process variability and common compaction practices.

4 Monitored process variability in compaction operations

During the cooling process of the asphalt mixture roller passes are conducted on site by several types of rollers having a different effect on the density and mechanical properties. Data is gathered regarding the roller type, number of roller passes during certain temperatures and the density progression of the asphalt after every roller pass. This is visualized in a graph combining the cooling curve and the density progression – an example is shown in Figure 1. The impact of the different rollers are clearly visible: Firstly breakdown rolling using a tired roller until approximately 98% degree of compaction, then a tandem roller until 100-101% compaction and finally a 3-drum roller to erase unevenness’s, but hardly influencing the density. Also, the time and temperature windows for the different roller types become visible in these graphs. In this example, the tired roller conducts 3 roller passes within 145 and 135 °C in 4 minutes, next the tandem roller conducts 4 roller passes within 135 and 107 °C in 7 minutes and finally a 3-drum roller than conducts 4 roller passes within 102 and 83 °C in 7 minutes.

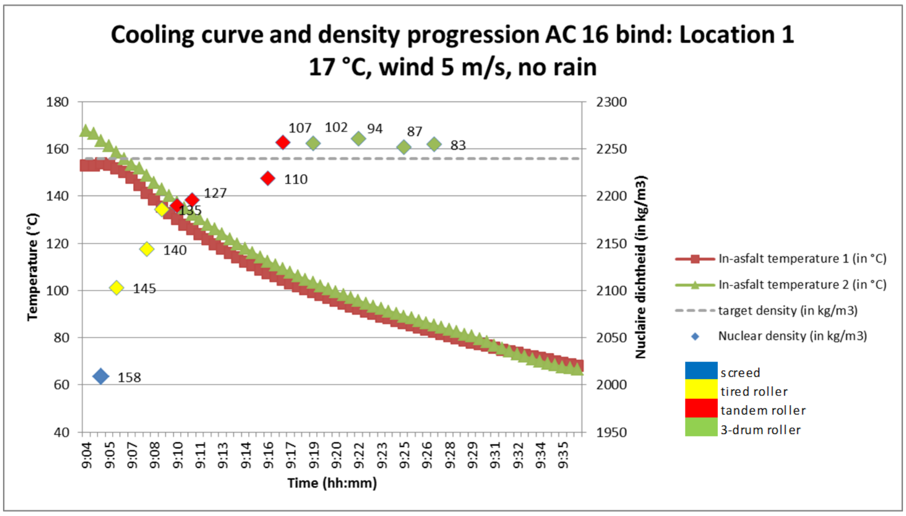


Figure 1: Visualization of the cooling curve and the density progression for 1 location

It is however difficult to determine a reliable relationship between the impact of certain roller passes at a certain temperature under various conditions, because of the many changing variables. The monitored projects demonstrated the extend of the many changing variables and the different operational strategies for asphalt construction. An example of the many changing variables in operational rolling strategies is shown in Table 1. For the construction of three provincial roads an AC 22 base (80 mm thick) mixture was constructed and monitored, where the following variability is highlighted:

- In three different projects, three different sets of rollers are used: (1) tandem roller + 3-drum roller, (2) combi-roller (pneumatic tires at the front and steel wheel at the rear) + small tandem roller for the joints and (3) tired roller + tandem roller. Also in the first project, the sequence of the rollers has changed twice. At locations 1-4, the roller sequence was first the tandem roller and then the 3-drum roller, where at location 5 first the 3-drum roller started and then the tandem roller. At location 6 they only used the 3-drum roller.

- The total number of roller passes in all projects ranges from 8 to 28 roller passes at one location (using different sets of rollers). Also within the same project using the same set of rollers, the total number of roller passes varies significantly. For instance, in project 1 this varies from 10 to 17 passes for the 3-drum roller and 7 to 11 passes for the tandem roller.
- The time and temperature windows in which the roller passes were conducted varies considerably. For example, the total compaction time of the 3-drum roller in project 1 ranges from 53 until 90 minutes. Also, the temperature window in which the roller passes of the tandem roller were conducted varies from 145-100 °C to 120-65 °C.
- The first roller pass behind the paver (and with that the temperature of the mixture at the first roller pass) varies substantially. For instance in the first project, the tandem roller starts rolling between 2-9 minutes after the paver placed the mix and the 3-drum roller starts between 10-19 minutes after the paver placed the mix. Relating this difference in time to the cooling curve, the difference of compacting after 2 minutes or after 9 minutes behind the paver can make a difference of approximately 25 °C for only the first roller pass.
- At almost all the projects roller passes were conducted after the target density was reached to make the surface even. This varies from 1 roller pass after the target density was reached up to 9 roller passes conducted after the target density was reached. This difference will not significantly influence the density, but its significance for mechanical properties is unclear.

Table 1: Variability in compaction operations for the same asphalt mixture

Mixture and weather condition	*Loca-tion*	*Roller type and sequence*	*Number of passes*	*Compaction time*	*Compaction temperatures*	*Time between paver and 1st pass*
Mix: HMA - AC 22 base (80 mm) *Weather: 15-17 °C, solar 100-200 W/m^2, wind 8-13 km/hr*	*1*	*tandem*	*10*	*38*	*130-85*	*5*
		3-drum	*15*	*53*	*115-60*	*14*
	2	*tandem*	*11*	*30*	*145-100*	*2*
		3-drum	*17*	*62*	*120-65*	*19*
	3	*tandem*	*7*	*43*	*120-75*	*7*
		3-drum	*17*	*90*	*110-70*	*10*
	4	*tandem*	*7*	*43*	*120-65*	*9*
		3-drum	*15*	*54*	*110-65*	*17*
	5	*3-drum*	*10*	*65*	*140-70*	*10*
		tandem	*11*	*30*	*125-60*	*32*
	6	*3-drum*	*14*	*65*	*140-65*	*5*
Mix: HMA - AC 22 base (80 mm) *Weather: 5-10 °C, wind 5-8 km/hr, rain*	*1*	*combi*	*8*	*30*	*130-90*	*8*
		small tandem	*joints*			
	2	*combi*	*12*	*35*	*110-60*	*15*
		small tandem	*joints*			
Mix: HMA - AC 22 base (80 mm) *Weather: 15-25 °C, solar 200-700 W/m^2, wind 0-1 km/hr, clear & dry*	*1*	*tired*	*6*	*11*	*150-125*	*2*
		tandem	*11*	*35*	*125-80*	*16*
	2	*tired*	*6*	*6*	*155-140*	*1*
		tandem	*9*	*27*	*140-90*	*7*
	3	*tired*	*6*	*11*	*155-120*	*2*
		tandem	*11*	*35*	*120-80*	*17*
	4	*tired*	*5*	*4*	*130-100*	*1*
		tandem	*8*	*29*	*100-75*	*8*

At the locations where the cooling and density progression was monitored, also cores were extracted determining the lab-density to compare this with the on-site measured density. However, at for example thin surfacings this is not desirable. The differences between the on-site measured density and the density determined in the lab is shown in Table 2 based on 130 cores from 23 projects.

The relationship between the measured density on-site and the core density determined in the laboratory is very weak. This relationship differs from project to project, but also within one project. The differences vary from +137 to -213 kg/m^3. During the WMA-projects only a negative relation was observed, which means that the nuclear density was always higher than the core density, but still varies from -7 to -213 kg/m^3. The measurements on-site are highly influenced by the underlying layer (asphalt or foundation), the circumstances (especially rain), the measurement device (the same device provides different results) and the operator who measures (how does the operator place the device at the asphalt mixture). The on-site measurement devices seem useful to determine whether density progression is achieved or not. However, in determining the absolute density the current devices are imprecise and show a lot of variability in results and are therefore difficult to use. This is one of the reasons to re-evaluate the density measurements on-site and possibly search for alternatives.

Table 2: Relationship between on-site density and lab-density based on 130 cores (in kg/m^3)

Difference nuclear and lab-density (in kg/m^3)	*base/bind 80 mm*	*base/bind 50-60mm*	*WMA 60-80 mm*	*Surf 40-50 mm*	*Surf 30-35 mm*
average difference	*-27*	*-1*	*-61*	*-24*	*13*
minimum difference	*-81*	*-76*	*-213*	*-120*	*-102*
maximum difference	*55*	*93*	*-7*	*41*	*137*
standard deviation	*38*	*53*	*39*	*46*	*59*

* A negative number means that the on-site density is higher than the core density determined in the lab

The conclusion drawn is that there is significant variability in key parameters and construction operations. Although at all locations generally the target density was reached, the compaction operations to achieve this target density are significantly different. However, how this variability in compaction operations influences the final mechanical properties is still unclear. The second goal was then to extract common practices regarding asphalt compaction in order to distinguish good and poor operational practice and to give improved instructions to roller operators. The common compaction practices are described in the next section.

5 Common operational practices for asphalt compaction

From the monitored projects the operational strategies of the rollers per project were extracted. The combinations of roller types per asphalt mixture were firstly determined and these are shown in Table 3.

Table 3: Variability in chosen roller types for asphalt compaction

base/bind 80 mm (3 projects)	*base/bind 50-60mm (12 projects)*	*WMA 60-80 mm (4 projects)*	*Surf 40-50 mm (3 projects)*	*Surf 30-35 mm (7 projects)*
• *tandem, 3drum* • *combi, small tandem* • *tired, tandem*	• *tired, tandem, 3drum (3x)* • *tandem, 3drum (3x)* • *3drum, tandem,* • *tandem* • *tired, tandem* • *combi, tandem* • *tandem, tandem* • *small-tandem, tandem*	• *tandem, 3drum (2x)* • *3drum, tandem* • *small tandem, tandem*	• *small tandem, tandem (2x)* • *3drum, tandem*	• *3drum, tandem (6x)* • *tandem, 3drum*

** The number in brackets corresponds to the frequency of monitored roller combinations*

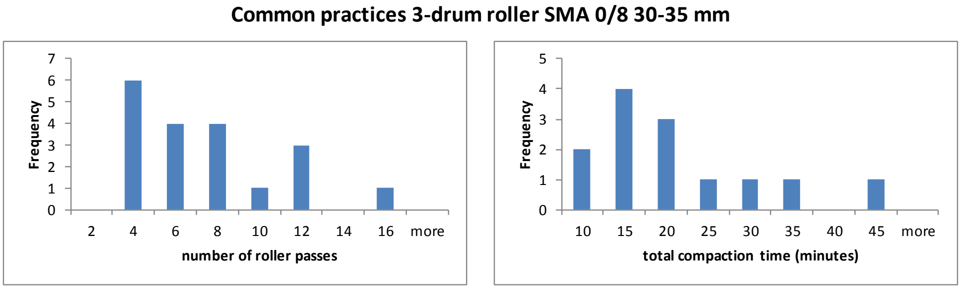
This data demonstrates that the same asphalt mixtures are compacted using different sets of rollers. Most extreme are the AC base/bind (80 mm) mixture, where 3 projects were monitored and 3 different strategies were used and the AC base/bind (50-60 mm) mixture, where 12 projects were monitored and 8 different compaction strategies were used. The most visible and explicit commonly used roller strategy is for the Surf (30-35 mm) mixture, where on 6 of the 7 monitored projects, first a 3-drumm roller and then a tandem roller was used. Therefore, this roller strategy is appointed as common practice and analysed more in detail.

Based on the temperature and density measurements, and the machine movements, (1) the total number of roller passes, (2) the total compaction time, (3) the starting temperature for compaction and (4) the finishing temperature for compaction were determined per roller and used for analyses. For these parameters, the frequencies were determined and visualized in histograms. These histograms are shown in Figure 2 for the 3-drum roller and Figure 3 for the tandem roller for the compaction of an Surf (30-35 mm) mixture.

From the histograms, common roller strategies for an Surf (30-35 mm) were extracted, based on the frequency of occurrence in the monitored projects. Common practices of compacting an Surf (30-35 mm) based on the monitored projects are:

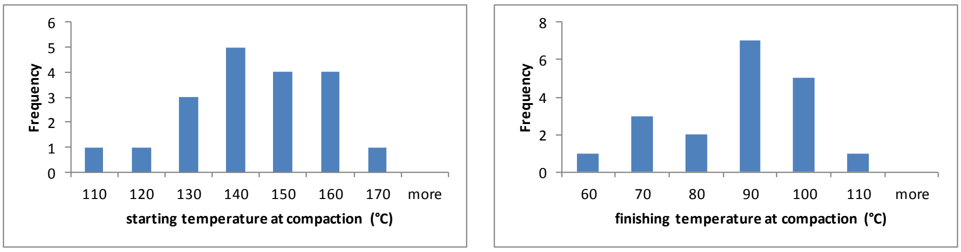
- The 3-drum roller conducts between 4 and 8 roller passes (sometimes 12) in 10-20 minutes, starting the compaction process at approximately 160-130 °C en finishes around 100-90 °C.
- The tandem roller conducts between 6 and 8 roller passes, starting the compaction process between 110-80 °C and finishes around 60-50 °C. The compaction time mainly depends on the cooling curve and thus on the weather conditions.

Applying this common roller strategy at this specific asphalt mixture does not necessarily mean that the target density will be achieved. However, at all the monitored projects target density was achieved and it is assumed that the roller strategy is based on years of experience of operators. Of course, the rolling strategy will also vary based on the weather and project conditions, but this strategy is based on limited data of 7 different projects with 19 measurement points regarding roller passes and asphalt mix temperature. If more projects are monitored and more data collected, rolling strategies can be determined for different weather and project conditions using the same method.



4-8 roller passes

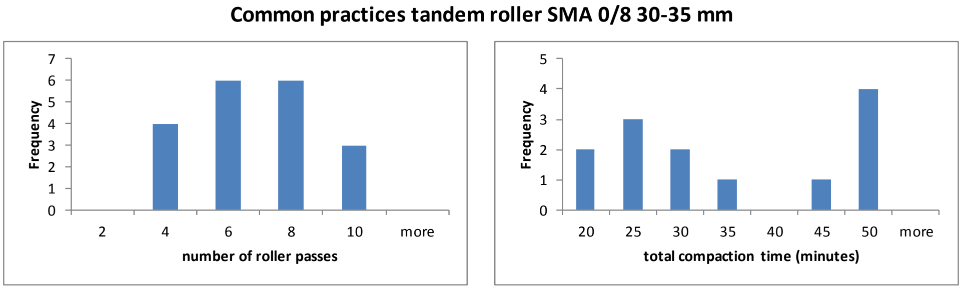
in 10-20 minutes



start compaction between 160-130 °c

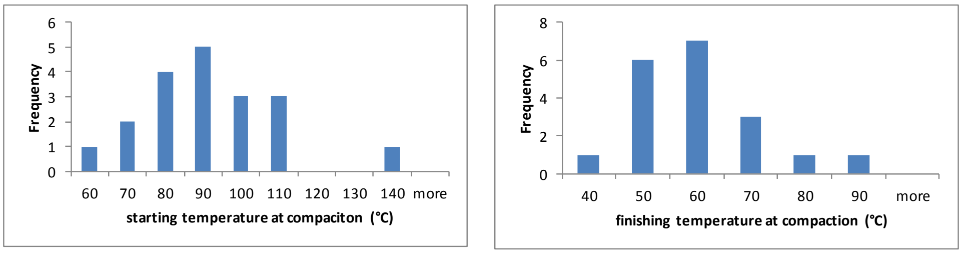
finish compaction between 100-90 °C

Figure 2: Common practices compaction 3-drum roller for a Surf 30-35 mm



6-8 roller passes

total compaction time depends on weather conditions



start compaction between 110-80 °c

finish compaction between 60-50 °C

Figure 3: Common practices compaction tandem roller for a Surf 30-35 mm

6 Discussion and conclusion

In current contracts and agreements it is becoming increasingly important for contractors to improve process and quality control during on-site construction. In the current technological age one might expect contractors to embrace the technology-opportunities for performance enhancement. However the actual construction process still is mainly carried out without (high-tech) instruments and little research effort is put onto the systematic mapping and analysing of on-site construction operations. Therefore, it is hard for contractors to trace back what poor and good operational practice is and to improve process and quality control.

This paper adopted a previously developed framework for process quality improvement (Miller, 2010) to make on-site construction processes in the asphalt paving industry explicit. Twenty-nine asphalt construction projects were monitored using this framework and process variability was demonstrated and common practices for compaction were extracted. This framework is applicable for broad implementation in the industry and relevant for making current practices explicit in order to improve process control. Also, the technologies used in this framework are helpful to explicate on-site construction processes, process variability and common practices.

A substantial degree of process variability became clear from the monitored and analysed projects. First, the compaction process very often is executed using different sets of rollers. Also, the number of roller passes and the time and temperature windows in which these roller passes are conducted vary considerably. For one asphalt mixture (Surf 30-35 mm), a common compaction practice could be extracted from the monitored projects. When more projects will be monitored and more data will be gathered, this method can also be used to extract more common operational strategies for other asphalt mixtures under varying conditions. The process variability and common practices lead to an improved understanding about the construction process from an operational perspective and the underlying corresponding difficulties.

The results provide information and methods to move towards method-based learning and improving as described by Bijleveld and Dorée (2013) rather than current variable experience-based and ad-hoc working practices. The results also help to start a discussion with the operators of the asphalt team about the on-site construction process and to extract common practices that can be used in training and education of (new) operators. This can be the input for a virtual construction site for training and education, as described by Vasenev et al. (2013). After demonstrating this substantial process variability, it must also be acknowledged that the relationships between process variability and the resulting quality variability is under-researched and mainly unclear. Further research is being conducted to imitate the various strategies observed on construction sites under controlled circumstances in the laboratory and to determine its influence on quality characteristics (Bijleveld et al. 2012). Moreover, the structured way of monitoring actual construction projects and mapping the information in a database will be continued, creating increasingly more information about on-site process variability and common practices.

Similarly as in the asphalt industry, many domains in the construction industry lean on the on-site experience of operators. The approaches to make process variability and common practices explicit may also be applicable to other traditional experience-driven practices in the construction industry. Lessons learned are the importance of simultaneously introducing new technologies in the process and at the same time explicating current practices. This helps to demonstrate the value of using available technologies and hence of breaking down barriers to technology adoption. Also, having data gathered in a structured and systematic way and synthesised with the needs of the practitioners, proved helpful to adopt the technologies. Altogether this will help to create more understanding about on-site processes and bring the on-site process closer to the other processes in the chain, such as the design, planning and preparation phases. It will also help to fill the gap between current individualised lengthy learning and slow process improvement, and the quest for improved process and quality control on-site.

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