Professionalising the asphalt construction process

Aligning information technologies, operators' knowledge and laboratory practices

Frank Bijleveld

Propositions accompanying the dissertation

Professionalising the asphalt construction process

Aligning information technologies, operators' knowledge and laboratory practices

By Frank Bijleveld

21st of January 2015

1. Progressively improving on-site operational strategies of asphalt teams requires research from (1) a technological perspective, (2) a human (operator) perspective, and (3) a laboratory perspective (Chapter 8).

2. To enable a transition to method-based construction practices, the on-site construction process must be explicit and improved reflection competencies should be included in the process (Chapter 4).

3. If the compaction process is conducted outside a certain time and temperature window, it might still be possible to achieve the target density, but the asphalt's mechanical properties will suffer (Chapters 5 and 6).

4. It is essential to further align laboratory procedures with the on-site construction process in order to design the on-site process and to evaluate the employed strategies (Chapter 9).

5. Current performance tests in the laboratory determine the potential quality of the asphalt mixture, but, in practice, both the asphalt mixture and the on-site construction process determine the quality of the constructed asphalt layer.

6. Having a collective research network and opportunities to experiment are vital to professionalise the asphalt construction industry.

7. Use-inspired basic research (Stokes 1997), undertaken as a quest for basic understanding while giving consideration to use, is underestimated in the construction industry.

8. By asking chess-players to reason out loud, knowledge and understanding about chess-thinking and the recognition of patterns was boosted (de Groot 1946). By asking asphalt operators to reason out loud, much becomes clear about the profession of asphalting.

9. Geniuses are made, not born (László Polgár).

10. Perfection is a road, not a destination. Every time I live, I get an education (Burk Hudson).

PROFESSIONALISING THE ASPHALT CONSTRUCTION PROCESS

ALIGNING INFORMATION TECHNOLOGIES, OPERATORS' KNOWLEDGE AND LABORATORY PRACTICES

Frank Bijleveld

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PROFESSIONALISING THE ASPHALT CONSTRUCTION PROCESS

ALIGNING INFORMATION TECHNOLOGIES, OPERATORS' KNOWLEDGE AND LABORATORY PRACTICES

DISSERTATION

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on account of the decision of the graduation committee,
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by

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born on the 6th of July 1986
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Preface

Ten to fifteen years ago I certainly did not expect to do and finish a doctoral program. Now, I feel it is a logical result of four years of hard work. I am inspired by László Polgár, a Hungarian psychologist and chess player, who said that geniuses are made, not born. In his book 'Bringing up a Genius', he explains the importance of teaching children from an early age as well as specialising in some direction. He demonstrated this view by home-schooling three daughters, primarily in chess, and all three went on to become strong players. To me this shows that many things in life are possible with a combination of healthy ambitions, proper guidance, hard work and endurance.

Approximately four years ago, André Dorée and Seirgei Miller triggered me to think about undertaking a PhD. I felt this was a great challenge and decided to take this path as a next step in my career and life. This dissertation is one of the results of approximately four years of work at the University of Twente. Besides compiling this book, I met wonderful people and have built an extensive network that showed me the beauty of the asphalt construction industry. Many people, companies and institutions contributed to this research with guidance, financial support, openness, encouragement and joy. I would like to thank all of them – this book is also partially their accomplishment and many people deserve my thanks.

During the research trajectory my supervisors were of great importance, all with their own style and qualities of supervising. Firstly, I would like to thank my promotor André Dorée for the opportunity to undertake my PhD research, which became a great way of further developing myself. Many thanks for your positive encouragement, your patience, your critical way of asking questions, and finally your open style of supervising where I could really choose my own style and direction of research. Also, you gave me the opportunity to present my work in Turkey, in New Zealand, in the United Kingdom, in Sri Lanka and in the Unites States of America. This not only boosted my PhD work but also enriched myself as a person. Secondly, I would like to thank Seirgei Miller. Seirgei, you are always so positive and encouraging and that also reflects to other people. I know my research consumed some of your evenings and weekends, but you always took time to read and comment on my work. You are a true example to attract and inspire people for the asphalt construction industry. Thirdly, I would like to thank Timo Hartmann. Timo, I know I was not the easiest person to work with and we did not always agree, but the differences really stimulated me to critically look at my own work and improve the quality of it. Also I want to thank the committee members, Kim Jenkins, Sandra Erkens, Arian de Bondt, Eric van Berkum and Joop

Halman, for their positive comments, detailed feedback and reflections in order to improve the final manuscript.

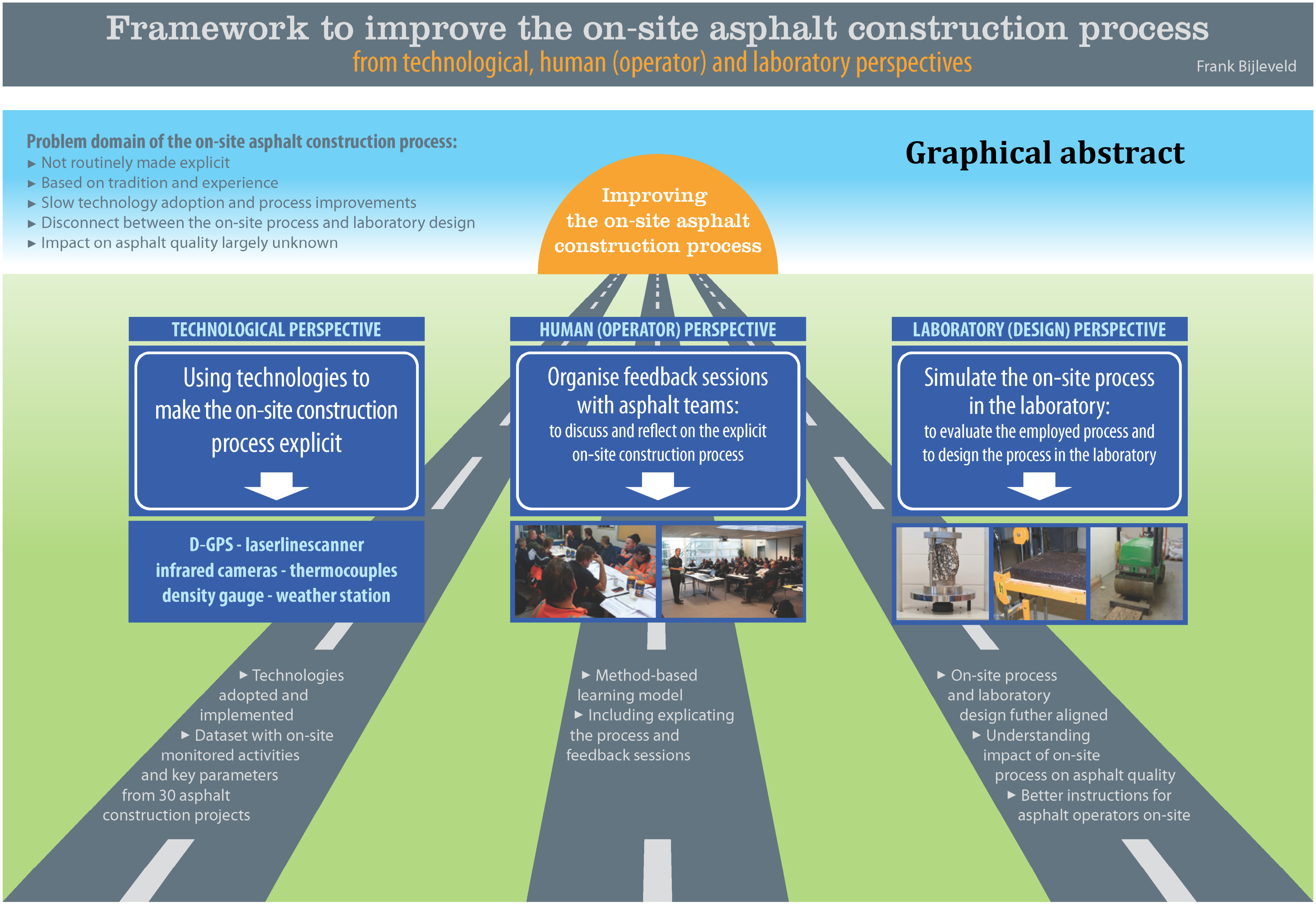
I am also grateful to those that initially motivated me for asphalt road construction and showed me its beauty. Two persons were specifically vital in the beginning of my career. First, Fedde Tolman, who already encouraged me at the age of seventeen, to critically look at my own work and the work of others. Fedde certainly taught me to think logically and write precisely. Later, Arian de Bondt encouraged me with his confidence, vision and constructive feedback. Arian, thank you for your enthusiasm and support for the research and your dry sense of humour.

This research would not have been possible without the cooperation provided within the ASPARi network. I would like to acknowledge the eleven contractors, their staff and their asphalt teams for the opportunity to conduct research at their companies. Ballast Nedam, BAM Wegen, Boskalis, Dura Vermeer, Heijmans, KWS, Mourik, Ooms, REEF, Van Gelder, TWW: Thank you for your confidence and financial support in this research. In particular, I want to thank the PQi working group: Mahesh Moenielal, Marco Oosterveld, Marcel Sprenger, Bas Laureijssen, Peter van Hinthem, Rudi Dekkers, Andre Bakker, Erik den Hollander, GertJan van Rijswijk, Evert Scholten, Erik van de Beek and Johnny Koster. Additionally, I would like to thank the Laboratory working group: Jan van de Water, Maarten Jacobs, Berwich Sluer, Laurens Smal, Henry Schaefer, Alex van de Wall, Jakob Toonstra, Radjan Khedoe, Gerard Oude Lansink. You all enriched my research and gave me more insight into asphalt construction.

I also wish to thank my colleagues and friends in the Construction Management and Engineering Department. Firstly, Jacqueline and Yolanda, thank you for all the non-academic support you provided as well as the informal talks in between. Secondly, I would like to thank the department for the nice and open atmosphere. I worked in this department with a lot of joy and pleasure. In particular, I want to thank Hendrik Cramer, Alexandr Vasenev, Frederick van Amstel and Léon olde Scholtenhuis. You became true friends and thanks to you I fully enjoyed these four years. Our trips to Madrid, Berlin and Hamburg were truly amazing and I will never forget them. Also, the wakeboarding both indoor and outdoor, mountain biking, snowboarding, the flying simulator, canoeing, karting, and all parties we had in Enschede, makes you unforgettable to me.

Finally, I will switch for the first and last time in this dissertation to Dutch to express some appropriate, truthful and understandable acknowledgements to my family who are always there for me. Pap en Mam, ik ben gezegend met jullie. Bedankt voor de onvoorwaardelijke liefde en steun evenals voor alle mogelijkheden die jullie me hebben geboden in mijn leven. Jullie hebben me geleerd om voor iedereen respect te hebben, met beide benen op de grond te blijven staan, hard te werken, maar ook om van het leven te genieten. Gerard en Martin, broeders, jullie zijn belangrijke pilaren in mijn leven. Vroeger heb ik, mede door jullie, een doorzettingsmentaliteit ontwikkeld die noodzakelijk is geweest om dit onderzoekstraject te kunnen doorlopen. Ook hebben de weekendjes Ardennen en Winterberg me erg veel ontspanning bezorgd. Jullie hebben altijd vertrouwen in me gehad, me aangemoedigd en laten zien dat niets onmogelijk is. Het voelt goed om jullie naast mij te hebben. Tot slot, Nadia, lieverd, je bent tijdens dit onderzoekstraject in mijn leven gekomen en hebt me enorm veel liefde, plezier en lol gegeven. Dank je wel, dat jij er voor me bent.

Frank Bijleveld
December 2014, Enschede


Framework to improve the on-site asphalt construction process
from technological, human (operator) and laboratory perspectives
Frank Bijleveld
Graphical abstract
Problem domain of the on-site asphalt construction process:
▸ Not routinely made explicit
▸ Based on tradition and experience
▸ Slow technology adoption and process improvements
▸ Disconnect between the on-site process and laboratory design
▸ Impact on asphalt quality largely unknown
Improving the on-site asphalt construction process
TECHNOLOGICAL PERSPECTIVE
Using technologies to make the on-site construction process explicit
D-GPS - laserlinescanner
infrared cameras - thermocouples
density gauge - weather station
▸ Technologies adopted and implemented
▸ Dataset with on-site monitored activities and key parameters from 30 asphalt construction projects
HUMAN (OPERATOR) PERSPECTIVE
Organise feedback sessions with asphalt teams:
to discuss and reflect on the explicit on-site construction process
▸ Method-based learning model
▸ Including explicating the process and feedback sessions
LABORATORY (DESIGN) PERSPECTIVE
Simulate the on-site process in the laboratory:
to evaluate the employed process and to design the process in the laboratory
▸ On-site process and laboratory design futher aligned
▸ Understanding impact of on-site process on asphalt quality
▸ Better instructions for asphalt operators on-site

Summary

This research addresses the need to improve the operational strategies of asphalt teams undertaken at the construction site. On-site operational strategies are defined as those covering the activities, the key process parameters and the underlying reasoning employed by asphalt teams, such as the selection of equipment and working methods, that affect important asphalt quality parameters, such as resistance to cracking.

The scientific community and roads industry aim for higher quality asphalt roads. To achieve this, the on-site operational strategies need to be improved. Current market conditions in the construction industry lead to a context that encourages contractors to seek improved operational strategies for their operators and teams. However, this is near impossible because operational strategies are generally not explicit, contractors do not routinely monitor and map their own operational strategies, decisions are mainly based on experience and craftsmanship, and operators receive little feedback about the quality of their work. In addition, the adoption of technologies available to monitor the on-site construction process, such as laser-linescanners, infrared cameras and GPS, has, in practice, been slow. Given that the construction process is not explicit and is mainly based on tacit knowledge, there is also a gap between the on-site construction process and the procedures followed in the laboratory. Therefore, the impact of the on-site construction process on the asphalt quality is largely unknown. Together, this results in individual, implicit and lengthy learning, and in slow process improvements. The literature emphasises that the on-site construction process is crucial to the final road quality, but that only limited understanding is available about the on-site construction process in rather fragmented areas. So, whilst there is a need for improving on-site operational strategies, there is limited understanding about the current experience-driven asphalt construction process. Therefore, the aim of this research is:

"To improve on-site operational strategies by developing deeper insights into the on-site activities and key parameters and their relationships with the asphalt quality"

The premise guiding this research is that improving current on-site operational strategies in the asphalt construction industry will require: (1) an explicit and controllable on-site construction process; (2) a reduction in process variability and thus a consistent on-site construction process; (3) method-based working practices in addition to current experience-based practices; (4) an understanding of the influence of on-site operational strategies on the resulting asphalt quality; and (5) a closer alignment of laboratory design procedures and on-site operational strategies.

This research is operationalised in terms of the following goals and realised using the research methods detailed:

1. Systematically monitor and map on-site construction processes and key parameters. This is realised by implementing various technologies in the construction process as used in the 'Process Quality improvement (PQi)' framework developed by Miller (2010);
2. Determine the process variability and the common operational strategies from the explicated on-site processes. This is realised through analysing the monitored on-site construction processes;
3. Enhance learning and reflection competencies in practice for on-site construction processes. This is realised through developing and applying a method-based learning model incorporating explicitly monitored data and organising feedback sessions with asphalt teams;
4. Determine and evaluate relationships between the monitored compaction strategies and the quality of the asphalt construction. This is realised through laboratory experiments that simulates the monitored on-site field compaction process;
5. Align laboratory compaction procedures with field processes. This is realised by adjusting laboratory compaction procedures based on the explicitly monitored on-site construction data.

An action research strategy for collecting data was designed that involved steps of: (1) introducing and implementing technologies in practice; (2) systematically monitoring and mapping field construction projects; and (3) experimenting with the effects of process variability on asphalt quality under controlled laboratory conditions. Applying this action research strategy resulted in the following key outcomes:

- The improved PQi framework and monitoring technologies have been widely implemented in Dutch construction practice resulting in a dataset of 30 systematically monitored and mapped asphalt construction projects;
- An overview of current process variability and common operational strategies giving impetus to reduce process variability towards a consistent asphalt construction process;
- A model to enhance method-based learning practices based on explicitly monitored data is developed and applied to an asphalt construction project;
- Empirically tested relationships of operational strategies, including compaction temperature, asphalt cooling and rolling regimes, on the resulting asphalt quality, including resistance to rutting and cracking;
- Procedures to better align laboratory design with the on-site operational strategies in terms of compaction temperature, asphalt cooling and rolling regimes.

Altogether, on-site operational strategies can be progressively improved by using a cyclical iterative strategy that includes: (1) making technology enhancements to the on-site construction processes; (2) using more consistent and method-based on-site operational strategies, including feedback sessions with operators; and (3) aligning laboratory procedures such that laboratory designs better relate to on-site operational strategies. This distinctive strategy helps to better connect technology development, on-site construction processes, and laboratory design. A vital component of this strategy is its cyclic and iterative character that results in progressively improving on-site operational strategies. It is essential to move forward gradually in all three components rather than addressing them individually. The three directions support and strengthen each other in advancing towards a more professional asphalting practice.

This research project makes four main scientific contributions:

- The monitoring framework and the explicitly gathered data from 30 asphalt construction projects provide deeper insights into the asphalt construction process for improving the operational strategies of asphalt construction teams. A structured and systematic data-collection is vital to improve the on-site construction process. The extensive dataset provides deeper insights regarding the extent of variability in lay-down temperatures, asphalt cooling, number of roller passes, density progression, compaction windows and paver speeds. The broad adoption of the improved PQi framework shows that the organisation and execution of monitoring construction projects can be carried out by contractors themselves, which is an important step to systematically collect data about the construction process. This is relevant and practical for researchers in further analysing and promoting research into the asphalt construction process.
- By implementing and using technologies in the asphalt construction process, an enhanced understanding is created of the technology adoption and implementation process in the traditional experience-driven construction industry. This research provides evidence of the value of using new technologies and sensors, thereby breaking down barriers to technology adoption. This is essential to break out of the vicious circle of ‘no technology adoption - no evidence of the value of using new technology - no technology adoption’. Also, a research network that provides opportunities to test prototypes, synthesise them with practitioners’ needs, and improve the solutions and researchers adopting a mediating role, are both relevant for enhancing technology adoption and implementation in the experience-driven construction industry.

- The developed method-based learning model enhances the transition from current lengthy, experience-based learning towards method-based learning practices based on explicit data from the monitoring of on-site operational strategies. It leads to improved process and quality awareness and to improved communications with and within the asphalt team. The method-based learning model might also be useful in other experience-driven domains in the construction industry, such as the sub-surface domain, to change from experience-driven practices to method-based practices.
- This research provides an enhanced understanding of the relevance of connecting laboratory procedures with the on-site construction process. Procedures were developed to better simulate field compaction in the laboratory based on on-site monitored data, in terms of compaction temperature, asphalt cooling and rolling regimes. The results of the laboratory experiments demonstrate that the on-site process parameters and activities substantially influence asphalt quality characteristics, by up to 30%. The procedures and data can be used to evaluate the impact of employed on-site compaction strategies on asphalt quality, and to design improved on-site compaction strategies in the laboratory to provide better guidelines to operators on-site.

Given the research findings and implications, the researcher is confident that the aim of this research has been achieved, and that it contributes to a deeper understanding of the asphalt road construction process. This research also provides recommendations for contractors to improve their on-site operational strategies, for agencies to reduce their risks and for machine manufacturers to enhance technology adoption and implementation in practice. Altogether, this research is an important step that provides methods for researchers and practitioners to implement technologies, analyse operational strategies of asphalt teams and their effects on asphalt quality, design the asphalt construction process and enhance reflective and method-based construction practices. It leads to construction process improvements, more consistent asphalt quality, and more professional operators and asphalt construction companies.

This research should be seen as a step towards professionalising the asphalt construction process. It was not the first step and it will not be the last. Miller (2010) conducted ground-breaking work by implementing various technologies in the asphalt construction process and developing a framework for making several key parameters and operations explicit.

This research has built and advanced on this initial work. The developed monitoring framework was further advanced and implemented in construction practice and, through this, created an extensive dataset that made operational strategies and process variability explicit. This research validated the work of Miller (2010) relevant for making the on-site process explicit and demonstrating process variability for a broad spectrum of asphalt projects. Further, this research has made advances towards more consistent and method-based working practices and has brought laboratory design procedures closer to the measured on-site construction process.

In the near future, further attention must be given, both in science and in practice, to the on-site construction process rather than focussing mainly on advanced construction materials and production techniques. Professionalisation in the next few years should focus on: providing real-time information support to operators on-site; further aligning laboratory and on-site procedures including a thorough evaluation and redesign of the on-site construction process based on realistic laboratory tests; and on developing a broad educational programme in the Netherlands to support the asphalt construction industry. Together, these actions should lead to a more professional asphalt construction process and to better constructed asphalt roads.

Nederlandse samenvatting

Dit onderzoek gaat over de noodzaak om operationele strategieën van asfaltploegen op de bouwplaats te verbeteren. Operationele strategieën zijn gedefinieerd als de activiteiten, de essentiële procesparameters en de onderliggende redeneringen van asfaltploegen, zoals de selectie van materieel en werkmethoden, die de asfaltkwaliteit, zoals de weerstand tegen scheurvorming, beïnvloeden.

De wetenschappelijke gemeenschap en de wegenbouwindustrie beogen een hogere kwaliteit asfaltwegen. Om dit te bereiken moeten de operationele strategieën van asfaltploegen worden verbeterd. De huidige marktomstandigheden in de asfaltwegenbouw stimuleren opdrachtnemers (aannemers) te zoeken naar verbeterde operationele strategieën van hun asfaltploegen. Echter, dit is vrijwel onmogelijk omdat hedentendage de operationele strategieën van asfaltploegen nauwelijks expliciet zijn, opdrachtnemers hun eigen operationele strategieën niet routinematig monitoren en registreren, beslissingen veelal worden genomen op basis van vakmanschap en ervaring en asfaltploegen nauwelijks feedback ontvangen over de kwaliteit van hun werk. Daarnaast is de adoptie van beschikbare technologieën om het uitvoeringsproces op de bouwplaats te monitoren, zoals laserlijnscanners, infrarood camera's en GPS, in de praktijk, langzaam. En omdat het uitvoeringsproces niet expliciet is en grotendeels gebaseerd is op impliciete ervaringskennis, is het ook moeilijk om het uitvoeringsproces aan ontwerpprocedures in het laboratorium te verbinden. De impact van het asfaltuitvoeringsproces op de asfaltkwaliteit blijft daarom grotendeels onbekend. Dit resulteert in individuele, impliciete en lange leercycli en tot een langzaam proces om procesverbeteringen te realiseren. De literatuur onderstreept het belang van het asfaltuitvoeringsproces op de bouwplaats, echter slechts beperkte kennis is beschikbaar over het uitvoeringsproces in gefragmenteerde delen. Er is dus behoefte en noodzaak om de operationele strategieën op de bouwplaats te verbeteren, maar de noodzakelijke kennis over het ervaring gedreven asfaltuitvoeringsproces ontbreekt grotendeels. Daarom is het doel van dit onderzoek:

"Het verbeteren van de operationele strategieën van asfaltploegen door het ontwikkelen van inzichten in de operationele activiteiten en belangrijke procesparameters en hun relaties met de asfaltkwaliteit"

De sturende veronderstelling in dit onderzoek is dat het verbeteren van de huidige operationele strategieën in de asfaltwegenbouw het volgende vereist: (1) een expliciet en controleerbaar asfaltuitvoeringsproces; (2) een vermindering van de variabiliteit in het uitvoeringsproces en dus een consistent uitvoeringsproces; (3) werkmethoden gebaseerd op basis van methoden en procedures aanvullend aan de huidige ervaring gebaseerde werkmethoden; (4) kennis over de invloed van het uitvoeringsproces op de asfaltkwaliteit; en (5) het verbinden van ontwerpprocedures in het laboratorium met het uitvoeringsproces op de bouwplaats.

Dit onderzoek is geoperationaliseerd in de volgende doelen gerealiseerd door de bijbehorende onderzoeksmethoden:

1. Systematisch monitoren en vastleggen van de operationele activiteiten en belangrijke procesparameters. Dit is gerealiseerd door het implementeren van verschillende technologieën in het asfaltuitvoeringsproces met behulp van het eerder ontwikkelde 'Process Quality improvement (PQi)' framework door Miller (2010);
2. Bepalen van de variabiliteit in het uitvoeringsproces en de eventuele gemeenschappelijke werkpraktijken van asfaltploegen. Dit is gerealiseerd door het analyseren van 30 gemonitorde projecten;
3. Verbeteren van de leer- en reflectie competenties van asfaltploegen. Dit is gerealiseerd door het ontwikkelen en toepassen van een leermodel gebaseerd op expliciet gemonitorde data en het organiseren van feedbacksessies met asfaltploegen;
4. Bepalen en evalueren van de relaties tussen gemonitorde verdichtingsprocessen en de resulterende asfaltkwaliteit. Dit is gerealiseerd door het uitvoeren van laboratoriumexperimenten die de gemonitorde verdichtingsprocessen op de bouwplaats simuleren;
5. Verbinden van ontwerpprocedures in het laboratorium met het asfaltuitvoeringsproces. Dit is gerealiseerd door de huidige verdichtingsprocedures in het laboratorium aan te passen gebaseerd op de gemonitorde verdichtingsprocessen op de bouwplaats.

Een participatieve strategie voor de dataverzameling is ontworpen met de volgende stappen: (1) introduceren en implementeren van technologieën in het huidige asfaltuitvoeringsproces; (2) systematisch monitoren en vastleggen van uitvoeringsprocessen op de bouwplaats; en (3) experimenteren met de effecten van procesvariabiliteit op de asfaltkwaliteit onder gecontroleerde omstandigheden in het laboratorium. Het uitvoeren van deze participatieve onderzoeksstrategie heeft geresulteerd in de volgende voornaamste uitkomsten:

- Het verbeterde PQi-framework en de technologieën om het asfaltuitvoeringsproces te monitoren zijn breed geïmplementeerd in de Nederlandse asfaltwegenbouwpraktijk en heeft geleid tot een dataset met 30 systematisch gemonitorde en vastgelegde projecten;
- Een overzicht van de huidige variabiliteit in het uitvoeringsproces en de operationele strategieën van asfaltploegen dat een impuls geeft

om de variabiliteit in het proces te verminderen tot een consistenter asfaltuitvoeringsproces;
- Een leermodel is ontwikkeld en toegepast om een transitie te bewerkstelligen van het huidige werken op basis van ervaring naar werken op basis van methoden en procedures die gebaseerd zijn op expliciete data;
- Empirisch geteste relaties tussen operationele strategieën, namelijk de verdichtingstemperatuur, de afkoeling van het asfalt en het walsregime, op de asfaltkwaliteit, namelijk de weerstand tegen spoorvorming en scheurvorming;
- Procedures om verdichting in het laboratorium beter te verbinden met asfaltverdichting op de bouwplaats met betrekking tot de verdichtingstemperatuur, de afkoeling van het asfalt en het walsregime.

Alle uitkomsten samengenomen kunnen de operationele strategieën van asfaltploegen stapsgewijs worden verbeterd door een cyclisch iteratieve strategie van: (1) technologie uitbreiding en implementatie in het asfaltuitvoeringsproces; (2) het toepassen van consistente en methoden gebaseerde operationele strategieën inclusief feedbacksessies met asfaltploegen; en (3) het relateren van ontwerpprocedures in het laboratorium aan het uitvoeringsproces op de bouwplaats. Deze strategie helpt om technologieontwikkeling, asfaltuitvoeringsprocessen en laboratoriumontwerp beter met elkaar te verbinden. Essentieel in deze strategie is het cyclische en iteratieve karakter dat resulteert in het stapsgewijs verbeteren van de operationele strategieën. Het is noodzakelijk om geleidelijk in al deze richtingen vooruitgang te boeken in plaats van in één richting individueel. De drie richtingen ondersteunen en versterken elkaar tot een professioneler asfaltwegenbouwproces.

Dit onderzoek heeft vier bijdragen aan de wetenschap opgeleverd:
- Het PQi-framework en de verzamelde expliciete data van 30 asfaltprojecten leveren een breder en dieper inzicht in het uitvoeringsproces en de operationele strategieën van asfaltploegen. Een gestructureerde en systematische dataverzameling is essentieel om het uitvoeringsproces te verbeteren. De dataset levert een dieper inzicht op in de variabiliteit van aanlegtemperaturen, afkoeling van het asfalt, aantal walsovergangen, dichtheidsprogressie, verdichtingsvensters en snelheden van afwerkmachines. De brede implementatie van het verbeterde PQi-framework demonstreert dat aannemers zelf in staat zijn om de monitoring van hun uitvoeringsprocessen uit te voeren en te organiseren. Dit is een

belangrijke stap om systematisch data te verzamelen over het asfaltuitvoeringsproces. Dit is relevant en praktisch voor onderzoekers om het asfaltuitvoeringsproces verder te analyseren en vervolgonderzoek naar het uitvoeringsproces te stimuleren.

- Door het implementeren en gebruiken van technologieën in het uitvoeringsproces is een beter begrip verkregen van technologie-adoptie en –implementatie in de traditionele ervaring gedreven asfaltwegenbouw. Dit onderzoek levert bewijs over de toegevoegde waarde van het gebruik van nieuwe technologieën en demonstreert daarmee de mogelijkheden om barrières voor technologie adoptie af te breken en het gebruik ervan aan te moedigen. Dit is essentieel om de vicieuze cirkel te doorbreken van geen technologie adoptie door onvoldoende data over de toegevoegde waarde; en geen data over de toegevoegde omdat de technologieën niet geadopteerd zijn. Ook zijn zowel een onderzoeksnetwerk om prototypen te testen, te synthetiseren met de wensen van de gebruikers en het verbeteren van de technologieën, als onderzoekers die een bemiddelende rol bekleden, beide relevant om technologieadoptie en implementatie in de bouw te versterken.
- Het ontwikkelde leermodel stimuleert een transitie van het huidige werken op basis van ervaring naar werken op basis van methoden en procedures gebaseerd op expliciete data. Het leidt tot een beter proces- en kwaliteitsbesef en tot betere communicatie met en binnen de asfaltploeg. Dit leermodel kan ook bruikbaar zijn in andere ervaring gebaseerde domeinen in de bouw, zoals in het ondergronds bouwen, om een transitie van ervaring gedreven werkpraktijken naar methoden gebaseerde werkpraktijken te bewerkstelligen.
- Dit onderzoek levert een beter inzicht in de relevantie om ontwerpprocedures in het laboratorium te verbinden met het uitvoeringsproces op de bouwplaats. Er zijn procedures ontwikkeld om het uitvoeringsproces op de bouwplaats beter te simuleren in het laboratorium gebaseerd op expliciet gemonitorde data, met betrekking tot de verdichtingstemperatuur, de afkoeling van het asfalt en het walsregime. De resultaten van de laboratoriumexperimenten demonstreren dat het uitvoeringsproces de asfaltkwaliteit substantieel beïnvloedt, tot wel 30%. De procedures en data maken het mogelijk om de effecten van verschillende verdichtingsstrategieën op de asfaltkwaliteit te kunnen evalueren en om uitvoeringsprocessen in het laboratorium te ontwerpen om zo asfaltploegen beter te kunnen informeren en instrueren.

Gegeven de belangrijkste onderzoeksuitkomsten en -bijdragen is de onderzoeker ervan overtuigd dat het doel van het onderzoek is behaald en dat aan een dieper inzicht in het asfaltuitvoeringsproces is bijgedragen. De resultaten van dit onderzoek leiden ook tot aanbevelingen aan opdrachtnemers om de operationele strategieën van asfaltploegen te verbeteren, aan opdrachtgevers om hun risico's te verminderen en aan materieel- en technologieleveranciers om technologieadoptie en implementatie in de praktijk te stimuleren. Gezamenlijk is dit onderzoek een belangrijke stap die methoden verschaft aan onderzoekers en de praktijk om technologieën te implementeren, asfaltuitvoeringsprocessen en hun effect op de asfaltkwaliteit te analyseren, het asfaltuitvoeringsproces te ontwerpen en een methoden gebaseerde uitvoeringspraktijk te realiseren. Dit leidt tot procesverbeteringen, een meer consistente asfaltkwaliteit en meer professionele vakmensen en asfaltwegenbouwbedrijven.

Dit onderzoek moet beschouwd worden als een stap richting de professionalisering van het asfaltwegenbouwproces. Het was niet de eerste stap en het zal ook niet de laatste zijn. Miller (2010) heeft baanbrekend werk verricht door nieuwe technologieën te testen in het asfaltuitvoeringsproces en door een framework te ontwikkelen om essentiële procesparameters en activiteiten expliciet te maken.

Dit onderzoek heeft voortgebouwd op Miller's werk en is verder gevorderd. Het PQi-framework inclusief de technologieën is verder ontwikkeld en breed geïmplementeerd in de praktijk om een dataset te verzamelen die de variabiliteit in het uitvoeringsproces en de operationele strategieën van asfaltploegen explicit maakt. Dit onderzoek heeft het werk van Miller gevalideerd, waarvan is gebleken dat het bruikbaar en relevant is om het uitvoeringsproces expliciet te maken, en dit onderzoek demonstreert de procesvariabiliteit voor een breed scala aan asfaltprojecten. Ook heeft dit onderzoek gepusht richting consistente en methoden gebaseerde werkpraktijken en zijn laboratoriumprocedures beter verbonden aan het uitvoeringsproces op de bouwplaats.

Ook in de nabije toekomst moet er meer aandacht aan het asfaltuitvoeringsproces worden gegeven, in zowel de wetenschap als de praktijk, in plaats van grotendeels te focussen op het verbeteren van de asfaltsamenstelling en de productietechnieken. Professionalisering in de komende jaren zal zich moeten focussen op real-time informatievoorziening naar asfaltploegen; op het verder verbinden van laboratoriumprocedures met het uitvoeringsproces inclusief een grondige evaluatie en herontwerp van het uitvoeringsproces op basis van realistische laboratoriumproeven; en op de ontwikkeling van een breed onderwijsprogramma (MBO-HBO-WO) over het asfaltuitvoeringsproces. Gezamenlijk zal dit leiden tot een professionelere wegenbouwpraktijk en tot beter aangelegde asfaltwegen.

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Publication record

List of papers in this dissertation (double peer reviewed)

Chapter 2: Bijleveld, F.R., Miller, S.R., Dorée, A.G. Making operational strategies of asphalt teams explicit to reduce process variability. Accepted for publication in the *Journal of Construction Engineering and Management (ASCE).*

Chapter 3: Bijleveld, F.R., Miller, S.R., Dorée, A.G. (2014). On-site process variability and common practices: A case in asphalt compaction. Published in the proceedings of the *CIB International Conference on Construction in a changing world*, 4-7 May 2014, Kandalama, Sri Lanka.

Chapter 4: Bijleveld, F.R. and Dorée, A.G. (2014). Method-based learning: A case in the asphalt construction industry. Published in *Construction Management and Economics*, 2014, Vol. 32, No. 7-8, p. 665-681.

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Chapter 1

Introduction

1.1 A changing industry – a changing context

Significant changes are occurring in the construction industry that encourage construction companies to adopt improved on-site operational strategies. A parliamentary inquiry into collusion in the Dutch construction industry sparked new procurement strategies and altered the business environment for construction companies (Dorée 2003, 2004). Agencies are changing their procurement strategies to 'performance contracting' including longer guarantee periods that contain incentives for better quality of work (Sijpersma and Buur 2005). Contractors are experiencing the pressures of new types of competition, but at the same time acknowledge the opportunity to distinguish themselves from their competitors. Within these new roles and contracts, contractors are directly confronted with any quality shortcomings during the guarantee period. As such, it is increasingly important for contractors to control the quality of the construction throughout this guarantee period. Overall, performance contracting and increased guarantee periods drive companies to advance in product and process improvement and towards improved on-site process and quality control.

The changed procurement strategies and business environment have resulted in new roles for clients, agencies and contractors. Clients currently seem to concentrate on their core tasks: governing and exploitation. Contractors nowadays also undertake the design, maintenance and financing of a project, instead of only its construction. Within these roles, contractors are often free to choose the materials, the construction and the on-site construction process to develop and improve their own products in order to distinguish themselves (Dorée *et al.* 2008). As part of these changing roles, the responsibility for significant risks shifts from agencies to contractors. Improved control over their on-site processes reduce the risk of construction failure during the guarantee period.

In this technocratic age of the Internet, pervasive networks and rapid progress in technologies, one might expect contractors to embrace the new ICT opportunities to enhance performance. However, in reality, the construction process is still largely carried out without high-tech instruments to monitor key parameters during the process. As such, contractors have little information on what operations transpired during construction, how these were carried out and, therefore, find it difficult to determine what constitutes poor and good operational practices.

Further, if the construction process is not explicit, causes of possibly failing to meet the required specifications cannot be traced back to on-site operational strategies. With off-the-shelf technologies becoming increasingly available in the market to monitor, visualise and map construction processes, it should be increasingly possible to make operational strategies explicit and to learn what good and poor operational strategies are. However, while these technologies are available, their adoption in practice is slow because of a lack of evidence that they add value in terms of the final quality of the construction. So, although explicating operational strategies requires the adoption of technologies, these technologies are seldom adopted because of insufficient evidence on how they improve construction quality. This amounts to a vicious circle of non-adoption, no evidence and non-adoption. To break through this vicious circle, technologies must be introduced into current practices to provide evidence of the value of these technologies for the on-site construction process.

Implementing the available monitoring technologies requires an understanding of current on-site operational practices. However, current operational strategies in the construction industry lean heavily on the implicit skills and experience of operators on the construction site. Operators still work largely based on their feelings and experience of previous projects (Dorée and ter Huerne 2005, Miller 2010). Operators may well learn implicitly from previous construction projects, but this will inevitably be based on limited observations and data. Also, given their expanded roles, contractors are free to develop new innovative products and construction techniques, and so operations are nowadays often outside the experience-domain of the construction team. This makes improving the experience-driven practices and implementing the available technologies more difficult. On-site operators also receive little feedback on their work, or on the work and results of others, resulting in implicit learning being a slow and individual process based on tacit knowledge. Although there is discussion on how tacit knowledge should be defined (Styhre, 2009), in this dissertation tacit knowledge is understood to the kind of knowledge that is difficult to transfer to another person by means of writing it down or verbalizing it, and is used in line with Nonaka and Tekeuchi (1995), where a transition from tacit knowledge to explicit knowledge is essential in the cycle of knowledge creation. To improve current on-site operational strategies, it is necessary to move away from the current implicit and lengthy individual learning towards a more method-based learning and process-improving approach. To improve consistency and move towards more method-based operational strategies, the relevant operational parameters need to be identified and the relationships between them thoroughly understood.

While contractors lean heavily on the tacit knowledge of operators which is difficult to transfer verbally, both experience and craftsmanship are slowly diminishing in the construction industry. More richly experienced operators are retiring than joining the industry. At the same time, the pressure on operators and teams is increasing: little time and space are available to conduct on-site operational activities and high penalties are imposed for exceeding specified limits.

Résumé: Various changes in the construction industry are leading to a changing context that encourages contractors to seek deeper insights into the processes undertaken at the construction site in order to improve the operational strategies of their operators and teams. However, generally these operational construction strategies are not explicit. Contractors do not routinely monitor and map their own operational activities, operators receive little feedback about the quality of their work, resulting in learning being individual and implicit, lengthy learning cycles and slow process improvements. In addition, technology adoption is slow in practice because there is no explicit evidence of these technologies adding value to the quality of the implicit process. Given that the construction process is not explicit and mainly relies on the tacit knowledge of operators and asphalt teams, there is also a gap between the on-site process and the other parts of the construction chain, such as the laboratory design and work preparation phase.

Thus, contractors seeking to develop deeper insights into the on-site construction processes, in order to improve operational strategies, while understanding, procedures and guidelines for on-site operational strategies of construction teams are lacking. To improve current operational strategies, it is vital to: first make the on-site construction processes and key parameters explicit using available off-the-shelf technologies; then develop methods and collect data to analyse the on-site construction process; and finally to relate these variable strategies to the final quality of the construction.

Given the need for improved operational strategies and to gain greater understanding of the on-site construction process, this research focuses on the operational strategies of construction teams. The next paragraph discusses the field of study, the asphalt road construction industry, and describes the focus of this research within this domain.

1.2 Field of study: Asphalt road construction

Asphalt plays a vital role in the global transportation infrastructure and drives economic growth and social wellbeing in both developed and developing countries (Magnum 2006, EAPA 2011). In 2007, an estimated 1.6 trillion metric tonnes of asphalt was produced worldwide, and Europe produces about 435 million metric tonnes per year. In Europe, public investment in highways, roads and bridge construction totals about €80 billion annually, and in the USA the public investment is around €55 billion per year (with private investment on top of this). In the USA and Europe, the asphalt paving industry collectively employs about 400,000 workers (EAPA 2011).

The focus in this research is on the on-site asphalt road construction process. Whereas the quality of the asphalt layer is generally well defined through various functional and mechanical properties (such as stiffness, resistance to fatigue, rutting, stripping), the quality of the on-site construction process is largely unknown. This is mainly because the key characteristics of the construction process are not monitored and systematically mapped and their variability is unidentified. This was illustrated by an extensive literature review by Miller (2010) that concluded that the majority of the related research deals with the characteristics of asphalt from the perspective of a construction material and that only about 5% of asphalt-related papers deal with asphalt paving operations. The next sections briefly describe the asphalt construction process, including the research boundaries, and the focus of this research.

The asphalt construction process

The asphalt construction process is according to Roberts *et al.* (1996), VBW-asfalt (2000), Asphalt-Institute (2007) and Miller (2010) in general divided into a production phase, where the asphalt mixture is produced at a plant, and a transportation phase in which the mixture is brought from the plant to the construction site. At the construction site, the laydown phase involves a paver spreading the asphalt mixture to a specified width and thickness while compacting the asphalt mixture to a certain extent. Shortly thereafter, while the mixture is still warm, rollers undertake the final compaction phase to achieve the target density and mechanical properties.

Production

In broad terms, asphalt is a mixture of aggregate, sand, filler and bitumen. The asphalt mixture is produced at an asphalt mixing facility using a range of mechanical and electronic equipment to merge the various components of the mixture. This involves blending, heating, drying and mixing to produce an asphalt mixture that meets specified requirements. In general, a facility can be categorised as either (1) a batch facility, where asphalt mixes are produced in certain specified amounts, or (2) a drum-mix facility, where a continuous stream of asphalt is produced. Particular attention should be given at the facility to maintaining control over the flow of (raw) materials. Particularly important aspects in this production process are the drying of the raw materials, the mixing temperature and the duration of the mixing.

Transportation

The transportation phase involves all the actions and equipment required to convey the asphalt mixture from the production facility to the construction site. This includes truck loading, weighing and ticketing, hauling to the site, transferring the mixture to the paver or a material transfer vehicle hopper (i.e. shuttle-buggy) and the return of the empty truck to the production facility (Roberts *et al.* 1996). The goal of transport phase should be to preserve the characteristics of the asphalt mixture between the production facility and the construction site. Transport practices can have a significant effect on the temperature of the asphalt mixture, mixture segregation and, with this, the final asphalt quality. Uniformity in operations is essential to ensure that a continuous stream of asphalt can be laid by the paver since uniform, continuous operations by the paver produce the highest asphalt quality (Asphalt-Institute 2007). So, using too many asphalt trucks leads to mixture and temperature variability, whereas not enough trucks results in the paver having to pause operations, potentially resulting in weak points in the construction. So, clearly, it is essential that plant production and on-site paving operations are well coordinated. Ideally, the paver should be continuously supplied with the mix but, at the same time, full trucks should not be waiting around to discharge their loads into the paver hopper (Asphalt-Institute 2007). From a contractor's perspective, the essential criterion is the productivity of the asphalt paving operation. The number of trucks used in the asphalt paving cycle is therefore critical to ensure that the paver is supplied with sufficient asphalt mix (Miller and Dorée 2008). A smooth operation can result in a higher quality pavement and prevent potential problems related to stop-go operations such as unnecessary construction joints, inconsistent material density and unsmooth surfaces (De Freitas *et al.* 2005).

Laydown (paving)

The role of the asphalt paver is to spread a uniform layer of the asphalt mixture to the desired thickness and shape, or to bring the surface layer to the desired elevation and cross-section, ready for compaction. The paver receives the asphalt mixture from the asphalt trucks, temporarily stores it in a hopper and uses a conveyor system that takes the material from the hopper to the rear of the machine and deposits it onto the prepared surface in front of the augers. These lateral augers then distribute the asphalt mixture transversely across the width of the screed of the paver. While the asphalt in front of the screed is initially loose, the material discharged behind the paver is significantly compacted. Both the weight of the screed itself and a combination of vibrating and tamping produce an increase in density usually referred to as the pre-compaction density. The speed of the paver is critical in creating a continuous stream of asphalting. There is no advantage in the paver travelling at a speed that uses the mixture faster than the asphalt plant can produce it - trying to pave too quickly can result in the paver having to frequently stop and wait for trucks to deliver more asphalt mixture. Another constraint is that the paver speed should not exceed the capacity of the rolling equipment available for the final compaction stage. Conversely, if the paver speed is too low, this will negatively influence the contractor's productivity.

Compaction

After the paving operation, the mixture must be compacted to achieve stability and avoid subsequent deformation under traffic loads. Compacting the newly paved asphalt mixture is critical, and generally forms the final stage of the construction process. It is probably the most important given that it is the last activity where operational discontinuities can negatively affect the quality of the laid surface. Several authors have acknowledged that proper compaction is important in achieving a satisfactory pavement service life (Alexander and Hughes 1989, Elhalim *et al.* 1993, Fitts 2001). The Asphalt-Institute (2007) defines compaction as the process of compressing a given volume of asphalt into a smaller volume. Compaction aims to produce an asphalt mixture with a specific density, to provide a smooth surface and to increase the load-bearing capacity of the material. This is achieved by pressing together the bitumen-coated aggregate particles, thereby eliminating most of the air voids in the mix and increasing the density of the mixture. Compaction is considered complete when the finished material achieves the optimum void content and density. The concept of an optimum void content and density is perhaps best understood by considering the effect of air, water and traffic on an under-compacted pavement. The voids in an under-compacted mix tend to be interconnected and this permits air and water to spread throughout the pavement. Both air and water carry oxygen that oxidises the bitumen in the mix causing it to become brittle. The pavement will then fail because it can no longer withstand the repeated traffic loading. A pavement that has not been adequately compacted will rut as a result of traffic loading. However, if there are too few voids in the compacted mix, the pavement will become unstable due to the thermal expansion and contraction of the asphalt layer. A too high air void content will lead to ravelling and disintegration, while insufficient air voids create a danger of the pavement becoming unstable.

Focus of this research

Although it is clear that the different phases of the asphalt road construction process should not be studied in isolation, this research focuses on the processes undertaken at the construction site, i.e. the laydown (paving) and compaction phases. The reasons for this decision are two-fold: first, because the literature argues (ter Huerne 2004, Delgadillo and Bahia 2008, Schmitt *et al.* 2009, Miller 2010) and practice demonstrates (Dorée and ter Huerne 2005, Miller 2010) that there is much to gain in the on-site construction process; and, second, because of an ongoing line of research about the asphalting process and technology development in road construction also focussed on the on-site construction process (ter Huerne 2004, Caerteling 2008, Miller 2010). The next section describes the research background related to the on-site asphalt construction process.

1.3 Research background

Technologies to monitor on-site construction processes

Given the need to make the operational strategies of asphalt teams explicit, recent technological developments have resulted in a plethora of equipment suitable for monitoring construction processes. However, little research effort has been put into systematically mapping and analysing construction processes. Although the impact and importance of the on-site construction process to the final quality of the asphalt layer is recognised in the scientific community, knowledge of the on-site process and its effects on the final quality of the construction is still in its academic infancy. Whilst important research deals with the characteristics of asphalt materials (de Bondt 1999, Erkens 2002, Molenaar 2004, Muraya 2007), only a limited focus is given to systematically mapping and analysing the effects of construction processes on the final quality of the constructed layer (Dorée and ter Huerne 2005, Miller 2010).

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 using GPS for checking crane paths for heavy lifting in industrial projects. Akhavian and Behzadan

(2013) developed a knowledge-based simulation model 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 analysers for estimating compaction quality. Ulmgren (2000), Lavoie (2007) and Cho *et al.* (2012) have assessed the effects of temperature segregation on pavement distress in the early stages of the lifecycle. These studies show that technologies are now available that can help contractors to make their processes explicit, learn explicitly what they do and, hence, gain greater understanding of their own processes.

However, although some experimental trials were developed into industrial applications, their adoption in practice is slow and very few have become widely accepted by the industry (Pries and Janszen 1995, Mitropoulos and Tatum 2000, Bossink 2004, Hartmann 2006, Miller 2010, Gallivan *et al.* 2011, Beainy *et al.* 2012). Many technologies fail to be adopted commercially due to being built on an insufficient understanding of the current operational strategies, which are again not explicit. As a result, the technologies lack evidence of added value for the asphalt quality. These barriers to the technology adoption of an asphalt compaction innovation were demonstrated by El-Halim and Haas (2004). A vicious circle prevails in which technologies are hardly adopted because of the lack of evidence of added value, whilst evidence of added value is lacking because the technologies are rarely adopted, which is shown in Figure 1.1.

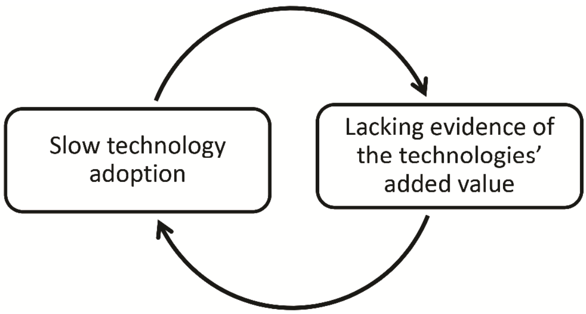

Figure 1.1: Vicious circle technology adoption

Technology adoption may also be hindered by the scepticism and reluctance of operators. They can feel that their workmanship is being devalued or that management could use the technology punitively (Miller 2010).

So, although many technological solutions are available to meet the need for improved on-site operations by asphalt teams, many fail to be successfully adopted in practice. Progress in adopting and fully integrating new technologies into operational strategies will only come about 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.

When the available technologies will be adopted and implemented in practice, it becomes possible to make the construction process explicit and when the on-site process is explicit, it is becoming possible to experiment with the effects of different operational strategies on the asphalt quality under controlled circumstances in the laboratory. This requires an understanding of testing asphalt quality characteristics in the laboratory and how the on-site construction process can be closely simulated in the laboratory.

Testing asphalt quality characteristics in the laboratory

Since 2008, the Dutch asphalt construction industry has worked with functional and mechanical properties of asphalt (CE-marking). As such, characteristics are now tested in the laboratory that are relevant in practice, such as resistance to cracking and rutting, rather than specifying a recipe to construct the asphalt mixture, such as the percentage of air voids. An essential element in this transition is understanding the relationship between characteristics tested in the laboratory and the performance in the field (Erkens and van Vliet 2014, Erkens *et al.* 2014, Sluer and Stigter 2014).

A considerable research effort has been put into determining potential asphalt quality characteristics, in terms of functional and mechanical properties, and corresponding laboratory tests. Various laboratory tests have been developed and accepted for determining certain asphalt characteristics, such as the Indirect Tensile Strength test, the triaxial test and the four-point-bending test (EN 12697). However, there is limited agreement throughout the industry with regard to the test procedures required to predict asphalt mixture performance and how this relates to field performance (NAPA 1996, ter Huerne 2004, de Visscher 2006, Schmitt *et al.* 2009, Erkens *et al.* 2014, Plati *et al.* 2014). Little research effort has gone into aligning laboratory procedures with the actual on-site construction process or into the sensitivity of asphalt quality characteristics determined in the laboratory to changes in on-site construction processes. Clearly, this has traditionally been near impossible given the essentially implicit on-site processes. Only when an on-site process is systematically monitored and mapped does it become possible to align laboratory design procedures with realistic on-site operational strategies and through that to provide better guidelines for operators on-site.

This research focuses on the compaction process. European standard EN 12697 describes four methods for simulating field compaction in the laboratory: impact compaction (Marshall), kneading compaction (gyratory), vibration compaction and rolling compaction. Various studies have shown that rolling compactors simulates field compaction the closest (Renken 2002, de Visscher *et al.* 2006, Muniandy *et al.* 2007, Mollenhauer and Wistuba 2013, Airey and Collop 2014, Plati *et al.* 2014, Wistuba 2014). In this method, field compaction is simulated in the laboratory using a segmented steel drum roller that moves back and forth across the asphalt mixture in a heated mould. The result is a relatively large asphalt slab, typically 500 mm by 500 mm or 700 mm by 500 mm. An advantage of this test setup is that the equipment can be pre-heated and that the slabs are large enough to produce several test samples from a single slab. This reduces the variability in the results from subsequent tests.

Muniandy *et al.* (2007) conducted experiments with Stone Mastic Asphalt (SMA) slabs using a roller compactor. A compaction procedure was developed that involved 75 passes with 8 kg/cm^2 of pressure to achieve the targeted 4% air voids. This pressure is not dissimilar to that applied by rollers in road construction. However, the number of passes is far higher than in field operations, and was determined by the aim of achieving a target density rather than of simulating field compaction.

Mollenhauer (2009) developed a two-step standardised compaction procedure using a rolling compactor. First, applying a position-controlled compaction procedure designed to achieve a certain thickness and density, thereby simulating the paver and, second, a force-controlled compaction procedure to simulate compaction using rollers. Based on these procedures, research into more accurately simulating field compaction and pre-compaction in the laboratory is currently being undertaken by Paffrath *et al.* (2012). However, the laboratory procedures do not explicitly take on-site construction parameters into account to better reflect field compaction.

Using the procedures developed by Mollenhauer (2009), Mollenhauer and Wistuba (2013) studied the effect of various laboratory compaction procedures on the resistance to permanent deformation using triaxial cyclic compression tests. They concluded that the deformation behaviour of laboratory specimens produced by a rolling laboratory compactor best represented field-compacted mixtures. However, the mould used in producing this form of compacted specimen led to higher resistance to deformation and higher stiffness than that found in field specimens.

Airey and Collop (2014) also investigated the mechanical performance of laboratory and field compacted asphalt mixtures. They studied the internal structures of asphalt specimens produced using various forms of laboratory and field compaction as well as their impact on stiffness and permanent deformation. 2D images were used to determine the aggregate sizes and orientations. Their research concluded that gyratory and vibratory laboratory compaction tended to mimic field compaction in terms of aggregate orientation, but that the mechanical properties of rolling compacted specimens tended to be closer to field compacted specimens.

Plati *et al.* (2014) conducted similar research and concluded that rolling compacted laboratory specimens were less stiff than field compacted specimens. This contradicts the findings of Mollenhauer and Wistuba (2013). They have also developed a compaction procedure for open-graded asphalt mixtures that delivers similar stiffness properties to field compaction.

However, none of these procedures explicitly take process parameters and activities into account to reflect field compaction. More importantly, the different approaches to asphalt compaction make the relationship between mechanical properties determined in the laboratory and the properties that can be achieved in the field uncertain. Therefore, there is a need to further connect laboratory procedures and the on-site activities and relevant parameters during the construction process.

Further, a basic assumption in the literature is that the compaction temperature is a key determinant of asphalt quality (NAPA 1996, Asphalt-Institute 2007). The traditional approach used to determine the compaction temperature in the laboratory is based on the binder viscosity, and this provides a single compaction temperature. However, a roller operator on-site operates within a temperature window as the asphalt cools during construction. It is therefore hard to give operators appropriate guidelines about the temperature window in which they should compact. Decker (2006) and Bahia *et al.* (2006) argue that determining the compaction temperature through viscosity-temperature plots is no longer appropriate. Practical experience using modified bitumen over the last twenty years in the Netherlands confirms this (Sullivan and de Bondt 2009). The different approaches used to determine compaction temperatures have consequences for the target density and mechanical properties, the significance of which remains unclear. This emphasises the need to align laboratory procedures and the on-site construction process.

In conclusion, there is a need (1) to increase understanding of how key on-site parameters and activities influence asphalt quality and (2) to develop improved compaction procedures in the laboratory that more closely simulate field compaction as a step towards better informing and guiding roller operators. In response, this thesis specifically focuses on the influence of variability in on-site key parameters, such as the asphalt temperature and cooling rate, and activities, such as the number of roller passes, on the density and mechanical properties of the asphalt layer. It also explores methods for better aligning laboratory and field compaction from an on-site asphalting perspective such that the results of laboratory experiments can be used to evaluate employed operational strategies and design the on-site construction process in the laboratory.

Closely related research efforts in this field

This research builds upon the work of Miller (2010), who conducted exploratory research into key parameters of the asphalt construction process by making operational behaviour explicit using a combination of new technologies, models and visualisations. The aim was to enrich understanding of the asphalt construction process and to work towards consistently reducing the variability in quality inherent in the process.

The initially developed Process Quality improvement (PQi) framework (Miller 2010) provides an approach for improving process quality and can be used for monitoring and exposing variability in the asphalt construction process. This enables asphalt teams to systematically work towards professionalising their primary processes. Two features are particularly noteworthy: (a) the proposed framework combines a data measurement process using new technologies (such as GPS and thermal imaging) and visualisations (graphics and animations) to make on-site operational behaviour explicit, and (b) the visualisations are used to assist asphalt teams in improving process quality. The data and visualisations invoke dialogue among the operators that contributes to their understanding of the construction process and their own operational strategies.

An important feature of the PQi framework is data visualisation. Three visualisation tools were developed by Miller (2010) to make operational behaviour explicit: (a) 2D animations developed using Matlab showing all the equipment movements during construction; (b) AsphaltOpen, a 3D tool that combines asphalt temperature and compaction visualisations in an automated, database-driven environment; and (c) ProPave, a tool that visualises all the paving and compaction operations in a realistic, 4D environment. The Asphalt Logistics Simulation Model (ALSIM), developed my Miller (2010), can be used for planning, scheduling and making resource decisions related to asphalt logistics in coordinating asphalt supply and the on-site processes to ensure uniformity in operations.

Overall, Miller (2010) concludes that, for the asphalt construction process, a reduction in quality variability is possible if: (1) operational behaviour is made explicit; (2) work processes are simplified through meaningful and easy-to-understand visualisations to support and empower the asphalt construction teams; and (3) the construction teams are at the heart of process improvements since they are ultimately responsible for the quality of the final product. Miller's findings indicate that the developed PQi framework and supporting software tools are valuable in making operational behaviour explicit and for tapping into the wealth of the implicit knowledge of asphalt teams.

This research project set out to build on Miller's initial work: (1) by implementing the PQi framework, including the monitoring technologies, in construction practice and creating an extensive dataset to make the process variability and operational strategies explicit for a broad spectrum of asphalt projects; and (2) by bringing existing laboratory design procedures closer to the measured on-site operational strategies in terms of compaction temperature, asphalt cooling and rolling regimes, to better understand the relationship between operational strategies and asphalt quality and to better inform and guide operators on-site.

Further, this research is also related to the work of Vasenev (2011, 2012, 2013, 2014). Vasenev conducted important work in combining various 'hard' sensor data with 'soft' operator data and translating this into understandable visualisations. Also, important work was done related to on-site data processing and providing real-time information to operators, such as the initial lay-down temperature, asphalt cooling rates and the number of roller passes.

The research efforts of Vasenev aimed to develop a virtual construction site, where operators could be trained and educated and gain a deeper understanding of the on-site asphalt construction process. The virtual construction site visualises actual construction activities, such as the paver speed, the roller type and the number of roller passes, and then offers support in demonstrating and evaluating alternative operational strategies. As such, it provides practitioners with an opportunity to experiment with alternative working strategies. Indicators were developed, such as the number of roller passes and the length of the roller paths, to assess the continuity and consistency of both the actually conducted and the suggested alternative construction processes. The virtual construction site aims to support communication and reflection among construction professionals who possess different sets of knowledge and experience. The virtual construction site enables asphalt teams to evaluate the process, individually and as a team. It also provides opportunities to reconstruct a conducted process and discuss how it could be improved. In so doing, it helps operators verbalise their tacit knowledge and make that knowledge explicit.

The work of Vasenev and this research are complementary. Vasenev's developed visualisations, as well as the systems developed to provide real-time information support to operators on-site were used in the current research. The construction projects monitored in this research can be used in the virtual construction site, and the virtual construction site can be used during feedback sessions to enhance the learning and reflection competencies of the asphalt teams.

Finally, this research is related to the research work of Caerteling (2008) and Caerteling *et al.* (2013). Caerteling has studied the academic and policy debates on the roles of government in technology development for the road construction industry. The aim of Caerteling's research project was to enrich understanding of technology development processes within road infrastructure and the relevance of government behaviour for the development and adoption of new technology. To achieve this goal, Caerteling carried out (1) a literature study to examine the relevant roles and dimensions of government (road agencies) and firms (contractors) regarding technology development, (2) a qualitative research consisting of three case studies that spanned eight technology developments to confront the findings from the literature study with empirical findings and develop conceptual and analytic models for assessing the government roles, and (3) a large-scale survey in the US to quantitatively examine and test the conceptual models.

A framework has been developed to analyse strategy implementation in project-based firms showing that there are insufficient incentives and capabilities at the cross-level to apply solutions from technology development projects into business projects. The lack of program management in technology development projects seems to limit the opportunities for new lines of business. Also, the extensive use of external sources of technology impedes the accumulation of knowledge and the development of routines for efficient execution of similar projects, thereby, restricting the opportunities for repetition.

Caearteling's findings show that government championing behaviour is key in the success of technology development projects, and exceeds both public procurement and government assistance. The defensiveness dimension in a firm's strategic orientation is most important for enhancing the benefits of the new technology to customers. Previous studies showed that the defensiveness dimension supports business profitability, whereas the proactiveness dimension is positively related to exploiting market opportunities. Caerteling shows that these dimensions should not be seen as opposites but complementary in achieving high performance. Overall, the research showed that government roles extend beyond regulations and funding. Government as a buyer and champion is a significant factor in the success of technology development projects and thus that championing behaviour is an important instrument in technology development and commercialisation.

Although the current research has no intention to contribute directly to the academic or the policy debate on the roles of government in technology development, it is however, useful to understand the context of technology development in road construction and the roles of agencies and contractors. In this research, not the technology development process will be studied, but how technologies could be useful for improving operational strategies of asphalt teams. Nevertheless, one of the goals of this research is to implement various technologies in practice to make the on-site process explicit, and some roles of government and contractors in technology development can be observed.

1.4 Problem statement

The scientific community and roads industry aim for higher quality asphalt roads. To achieve this, current developments in the road construction industry urge contractors to professionalise their own processes and improve the on-site operational strategies of their asphalt teams.

Operational strategies need to be explicit if they are to be improved, and a deeper understanding of how these strategies impact on asphalt quality is also required. However, current on-site processes are not routinely systematically monitored or mapped, resulting in little understanding about the on-site construction process. In addition, current operational strategies are largely based on tradition, experience and craftsmanship, and this makes it challenging to unravel the logic and reasoning of operators and teams. This results in individuals learning implicitly and in lengthy learning cycles. Together, this makes it difficult to create deeper insights into the asphalt construction process and to improve on-site operational strategies.

Making the asphalt construction process explicit requires the adoption of technologies. While appropriate technologies are available, and becoming increasingly affordable, the rate of adoption remains slow and very few have become widely accepted by the industry. A vicious circle prevails in which technologies are seldom adopted because of the lack of evidence of added value, whilst evidence of added value is lacking because the technologies are rarely adopted. Thus, the adoption and implementation process of technologies in the traditional experience-driven construction industry is slow and complex.

If on-site construction operations and key parameters are not explicit, they also cannot be incorporated in laboratory design procedures and cannot be evaluated for their impact on the quality of the asphalt construction. This results in a disconnect between laboratory procedures and the on-site construction process. The influence of on-site operational strategies on asphalt quality will therefore remain unknown. This makes it nearly impossible to evaluate employed operational strategies and to design the on-site construction process.

To sum up the current situation: on-site operational strategies are not systematically monitored, captured and made explicit; current practices are mainly based on tradition and experience resulting in lengthy learning cycles; technology adoption and process improvements are slow and complex; and the impact of on-site operational strategies on asphalt quality is unknown. This makes it hard to improve current operational strategies in order to achieve higher asphalting quality. So, there is a need to increase our understanding of the asphalt construction process and the impact on asphalt quality in order to improve the operational strategies of asphalt construction teams.

1.5 Research design

This research focusses on the practical need to improve the operational strategies of asphalt teams and on the search for an improved fundamental understanding of the on-site asphalt road construction process. In addressing some of the challenges in the road construction industry, the aim of this PhD research is:

"To improve on-site operational strategies by developing deeper insights into the on-site activities and key parameters and their relationships with the asphalt quality"

On-site operational strategies are defined as those covering the activities, the key parameters during the process and the underlying reasoning employed by asphalt teams that affect important quality parameters.

Asphalt quality is defined as its mechanical and functional properties, immediately after construction, such as stiffness, resistance to cracking and rutting.

This research aim led to the following main research question.

"What is a comprehensive strategy for progressively improving on-site operational strategies?"

The premise guiding this research was:

Improving current on-site operational strategies in the asphalt road construction industry will require: an explicit and controllable on-site construction process; a consistent on-site construction process; method-based working practices; an understanding of the influence of on-site operational strategies on the resulting asphalt quality; and an alignment of laboratory design procedures with on-site operational strategies.

This guiding premise led to the following research questions:

1. How can available technologies be implemented and used in current practice in order to develop an extensive dataset with explicitly monitored on-site operational strategies?
2. What is the extent of on-site process variability and what are the common on-site operational strategies in the gathered dataset?
3. How can the current experience-based operational construction practices be changed to more method-based practices?
4. What is the influence of variability in on-site operational strategies on the asphalt quality?
5. How can laboratory design procedures be better aligned with on-site operational strategies?

To answer these research questions and achieve the overall aim, the research is operationalised in terms of the following goals to be realised using the research activities detailed:

1. Systematically monitor and map on-site construction processes and key parameters. This will be realised by implementing various technologies in the construction process as used in the 'Process Quality improvement (PQi)' framework by Miller (2010);
2. Determine the process variability and the common operational strategies of asphalt teams from the explicated on-site processes. This will be realised through analysing the monitored on-site construction activities and key parameters;
3. Enhance learning and reflection competencies in practice for on-site construction processes. This will be realised through developing and applying a method-based learning model incorporating explicitly monitored data and organising feedback sessions with asphalt teams;
4. Determine and evaluate relationships between the monitored compaction strategies and the quality of the asphalt construction. This will be realised through laboratory experiments that will build on the on-site field measurements;

5. Align laboratory compaction procedures with field compaction processes. This will be realised by adjusting laboratory compaction procedures based on the explicitly monitored on-site construction data.

The complexities in the asphalt road construction process can only be captured by describing what really happens when asphalt teams are doing their job, incorporating the context in which they operate, as well as their frame of reference. Therefore, an action research strategy is chosen because these have proven their value within the complex and continuously changing construction domain (Hartmann *et al.* 2009, Miller 2010).

An action research strategy for collecting data was designed that involved steps of: (1) introducing and implementing technologies in practice; (2) systematically monitoring and mapping field construction projects; and (3) experimenting with the effects of process variability on asphalt quality under controlled laboratory conditions. Variability, in this dissertation, is used as how spread out or closely clustered a set of data is.

This data-collection strategy is not a sequential process but rather a cyclic iterative process. The intention is to progressively implement technologies, improve on-site operational strategies and create deeper understandings of the on-site asphalt construction process. This cyclic iterative strategy enables improvements to practice and, at the same time, realises increasingly stable theories that will emerge over time. The action research approach involved the researcher, innovative technology and asphalt operators, technicians and engineers moving the research process forward. The researcher participated within the problem domain, in both asphalt paving projects and in asphalt testing laboratories, and was positioned inside the research in order to be able to understand the complex problems.

This strategy involves quantitatively and qualitatively exploring the asphalt construction process, and identifies opportunities for learning and process improvements for contractors, agencies and machine manufacturers. Explicit, quantitative data facilitate practitioners in synthesising and verbalising their tacit knowledge and promote learning processes. By utilising a qualitative approach, i.e. feedback sessions with operators, this research aims to gain an understanding of the asphalting process from the perspective of the operators involved.

To conduct this action research strategy and become engaged with the asphalt industry, this research was embedded within the ASPARi network (short for ASphalt PAving, Research and innovation): a network of 11 Dutch contractors and the University of Twente sharing the ambition to gain a greater understanding of the asphalt road construction process. These contractors agreed to conduct on-site measurements on asphalt paving projects on their own and to make their laboratories and staff available to provide data for the laboratory research. The strategy followed for data collection was that the contractors within the ASPARi network would conduct the field studies and laboratory experiments themselves but under guidance and according to manuals and procedures written by the researcher. As part of this research, two platforms were built in the ASPARi network to exchange and discuss the findings of the collected data: one platform for the laboratory experiments and one to discuss the results of the monitored and mapped on-site construction projects. In March 2011, two two-day courses were organised for the contractors to educate and train them on how to undertake the measurements on their own projects. Feedback-days for both platforms were planned to discuss the findings and the possibilities for improving data-collection. For the laboratory research, a brainstorming session was organised in April 2011 to determine the possibilities for aligning laboratory design procedures with field processes and how this could be organised practically. In total, 30 asphalt construction projects were monitored and 4 experiments were conducted in the contractors' laboratories.

Applying this action research strategy achieved several key outcomes. The key outcomes and their relationships with the research questions are shown in Table 1.1.

Table 1.1: Key outcomes related to the research questions

Key outcomes	**Research questions**
Paper 1: The improved PQi framework and accompanying technologies are implemented in Dutch construction practice resulting in an extensive dataset from 30 projects with on-site process data	1, 2
Paper 2: An overview of key compaction parameters and activities from 30 projects to demonstrate process variability and common operational compaction strategies	1, 2
Paper 3: A model to enhance method-based learning practices based on explicitly monitored data applied to an asphalt construction project	3
Paper 4: Empirically tested relationships between compaction temperature and mechanical properties, and pointers to aligning laboratory and field compaction processes in terms of compaction temperature	4, 5
Paper 5: Empirically tested relationships between asphalt cooling and rolling regimes, and the resulting mechanical properties; and pointers to aligning laboratory and field compaction processes in terms of asphalt cooling and rolling regimes	4, 5

Using these outcomes, on-site operational strategies can progressively be improved using an iterative cyclic strategy that includes (1) technology enhancements in the on-site operational construction process; (2) consistent, method-based on-site operational strategies; and (3) laboratory procedures that relate asphalt quality to on-site operational strategies. Overall, this should lead to a deeper understanding of the on-site asphalt road construction process. Figure 1.2 provides an overview of the entire research design.

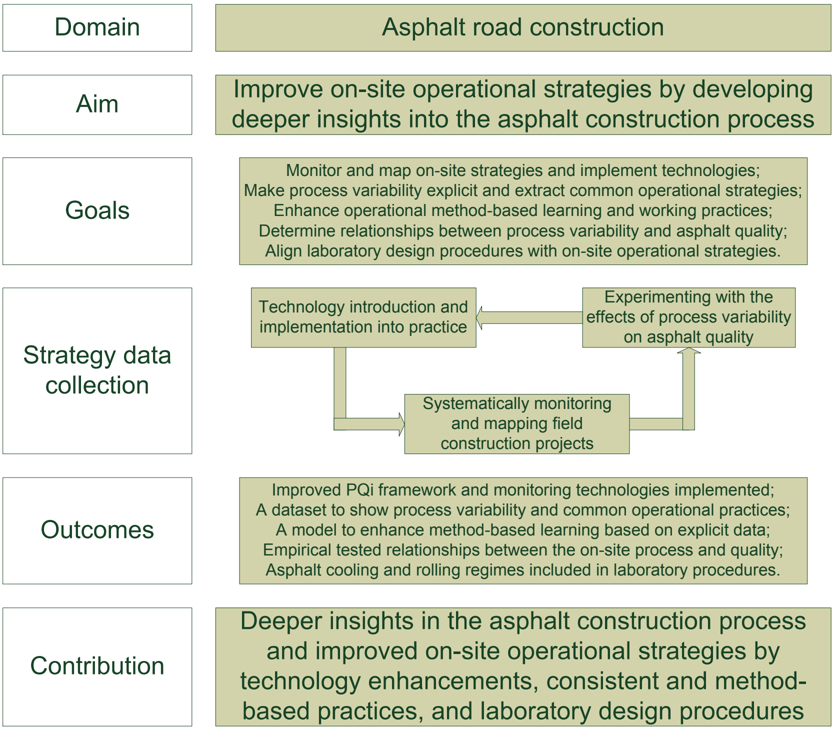

Figure 1.2: Overview of the research design

The outcomes of this research contribute to three ongoing scientific debates: (1) the need to create deeper insights into the asphalt construction process for improving operational strategies of asphalt construction teams, (2) the complexity of technology adoption and implementation in the traditional experience-driven construction practice, and (3) the relevance to connect laboratory design procedures and the on-site asphalt construction process. Also, the relevance of the participative action research strategy for the asphalt road construction domain is validated and further explored. The outcomes also have practical contributions: for contractors to improve the on-site operational strategies of their asphalt teams and to reduce process variability; for agencies to reduce their risks for accepting a poorly constructed road and to improve contractual requirements; and for machine and technology manufacturers to enhance technology adoption and implementation in practice.

1.6 Science and research perspective

As a researcher, or on the path to becoming a responsible researcher, it is important to think about and to take a position on which perspective you will use to look at constructs such as reality, knowledge and science, and on how you want to conduct research. There are different philosophies and principles in conducting scientific research. The main philosophies are positivism, relativism, pragmatism and realism, with a range of sub-divisions and crossovers. Although there is no intention to contribute directly to these research philosophies, it is useful to discuss some of these constructs in more detail to help the reader better understand the thoughts and decisions taken in this research. Researchers that helped the author in clarifying thoughts included Latour (1987), Stokes (1997) and Van de Ven (2007).

The philosophical stance used in this research is essentially pragmatism (referring back to Peirce 1995). Various important concepts of this pragmatic philosophy influenced this research. First, it is supposed that meaningful new theories are built upon the existing experimental knowledge of practitioners. So, if practice needs to be improved, then experimental, tacit knowledge provides a rich foundation on which to build and needs to be explicated. Also, the motives of practitioners, their experiences, senses and emotions, are vital and have to be considered. All this knowledge is intrinsically embedded in practice and, therefore, theory and practice are inseparably related (Hartmann *et al.* 2009). So, in our research, experience and practical knowledge will be extracted by looking at everyday practice. Further, determining whether a theory that is built on practitioners' concepts is a good theory is only possible by testing it in a practical setting. This goes to the heart of pragmatic inquiry: pragmatic researchers believe that a system is only good if it works in practice (Rescher 2000). New theory will be evaluated and legitimised based on its success, or its efficacy of application and implementation, in practice. The starting point in such research is to describe the experiential knowledge of practitioners within a specific setting to avoid developing over-generalised theory that will be too abstract for a given local context. Knowledge is developed based on reasonable and plausible beliefs through testing and experimentation in practice, while accepting that each of these beliefs may turn out to be false at any time. This is not a quest for perfect knowledge but for a steady improvement in knowledge, to be achieved by implementing cyclic loops of constantly replacing existing with new knowledge and looking at how well the new works in a practical setting. This allows persistent improvements to practice and evaluates how well the improvements work in practice and, at the same time, realises increasingly stable theories that will emerge over time. The type of reasoning employed will mainly be abduction – understood as the 'inference of the best explanation' – which fits with the pragmatic research philosophy (Peirce 1995).

The gap between scientific discovery and practical application is often very real. Various studies show that practitioners often struggle or fail to adopt research findings (Denis and Langley 2002, Dopson *et al.* 2002, Anderson *et al.* 2001, Rynes *et al.* 2002, Van de Ven 2007). Stokes (1997) suggests that a classic distinction between 'basic' research, intended to develop general knowledge and understanding and performed without practical ends, and 'applied' research, performed in the service of some immediate end, is both inaccurate and counter-productive. Stokes, therefore, proposed a 'user-inspired' research domain undertaken as a quest for basic understanding (rigour) while giving consideration to use (relevance). This PhD research is conducted in this spirit: theory on the on-site asphalt construction process is developed and further tested alongside considering the implementation of theories in practical settings.

Today, Van de Ven's 'engaged scholarship' seems the most relevant concept to apply in this research domain. Engaged scholarship is a participative form of research for obtaining the advice and perspectives of key stakeholders, in this case practitioners and researchers. It is argued that an engaged research approach produces knowledge that is more penetrating and insightful than when practitioners and researchers work alone on a problem (Van de Ven 2007). Within the engaged scholarship approach, combining the adopted action research strategy with the pragmatic philosophical stance seems appropriate for creating deeper understanding of on-site construction processes and closing the gap between theory and practice (Van de Ven 2007, Sexton 2009).

1.7 Outline of this thesis

This thesis is structured according to the key outcomes of this research (Table 1.1) that resulted in five papers – listed in Figure 1.3. Chapter 2 describes the framework used to explicate on-site construction processes and to systematically map and analyse these processes, and describes the gathered dataset with monitored on-site construction data of 30 asphalt road construction projects. The dataset is used to analyse various important relationships between on-site processes and key parameters, and the extent of process variability. Chapter 3 also uses the dataset and demonstrates the degree of process variability, specifically for the compaction process, and proposes a method to extract common operational compaction strategies from this dataset. Chapters 2 and 3 contribute to deeper insights into the operational strategies of asphalt teams and provides pointers to reducing process variability. Next, Chapter 4 describes a method-based learning approach based on the explicated on-site construction processes. This contributes to move away from current experience-based practices to explicit method-based practices. Chapter 5 describes how the variability in asphalt temperatures in the monitored on-site processes influences the asphalt quality in terms of cracking resistance. Chapter 6 discusses how asphalt laboratory procedures can be aligned with the on-site process. It also describes how asphalt cooling and rolling regimes influence the asphalt quality. Chapters 5 and 6 contribute to further aligning laboratory procedures and the on-site construction process and to a deeper understanding on how on-site key activities and parameters influence asphalt quality. Chapter 7 summarises some complementary research efforts that were relevant during the research trajectory but were not directly considered prior to commencing the research project. Finally, Chapter 8 describes the main outcomes and findings of this research and Chapter 9 outlines the main implications for practice and for science, and reflects on the results and the methodology.

Chapters 2 to 6 consist of journal papers that are accepted, under a re-review or are published in conference proceedings. The author has chosen to directly include these papers in the thesis as chapters. This approach is seen as having several advantages. Firstly, in aspiring to become an academic professional, writing and publishing papers is an important skill that has to be developed. Also, the process of peer review improves the quality of the research, and dealing with the comments is valuable in boosting the quality of written material. Also, a collection of papers can provide a concise summary of the research conducted. However, this approach has some drawbacks. Firstly, the journal review process can be lengthy, making it difficult to have 3 or 4 journal papers published within the time constraints of the PhD trajectory (in this case four years). Also, the thesis becomes a collection of storylines rather than one unified story. Some storylines inevitably overlap, contain redundancies and have different levels of description. The styles and focus of the various journals can also introduce inconsistencies into a multi-paper thesis. Nevertheless, on balance, for this research, the researcher believes that the advantages of the chosen approach outweigh the limitations. Therefore, this thesis is based on a collection of papers.

To summarise, following this introduction, the next five chapters (Chapters 2-6) are five academic papers each with their own storyline. Chapter 7 is an intermezzo chapter with complementary work that was necessary for the research. However, these activities were not directly considered before the research started, and are not explicitly described in any of the papers. Chapter 8 starts with an overview of the key outcomes of the five papers. Following this, the key outcomes are aggregated to summarise the main findings and conclusions of the entire research, and the research questions are then answered. Finally, Chapter 9 positions the key findings of this research in the on-going scientific and societal debates. It describes the scientific and practical relevance and gives meaning to the outcomes of this research.

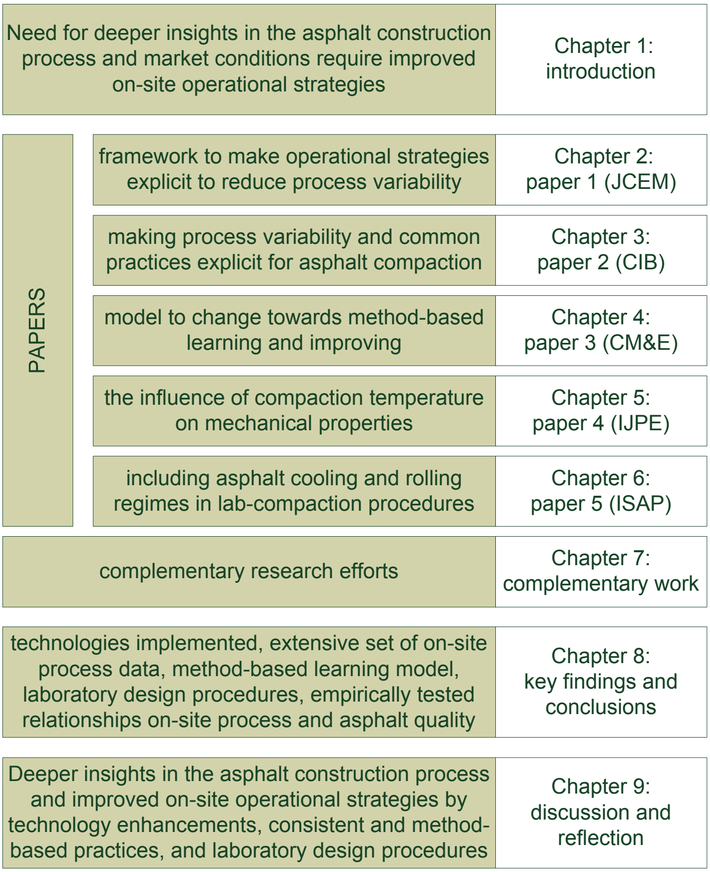

Figure 1.3: Outline of this thesis

Chapter 2

Making operational strategies of asphalt teams explicit to reduce process variability[1]

The on-site construction process undertaken by asphalt teams has a critical impact on pavement quality. Process improvement and learning requires 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 GPS (Global Positioning System), laser and infrared, 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 in 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 to 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.

Keywords: Action research; Asphalt pavements; Process variability; Process quality; Technology adoption.

[1] This chapter has been accepted for publication as: Bijleveld, F.R., Miller, S.R., Dorée, A.G. (forthcoming). Making operational strategies of asphalt teams explicit to reduce process variability. *Journal of Construction Engineering and Management (ASCE)*.

2.1 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 the main, contractors do not systematically monitor and map their own operational strategies (Miller 2010; Gallivan *et al.* 2011). Here, on-site operational strategies are defined as the activities, the key parameters during the process, and the underlying reasoning employed by asphalt teams that affects key quality parameters. If on-site operational strategies are not explicitly mapped it is nigh on 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 from the perspective of a construction material, whilst only some five percent of the asphalt related journal papers dealt with asphalt construction operations. Several important studies have been undertaken which 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 was found and suggested this was caused mainly 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. In order to manage and improve the process adequately, it is necessary to move away from implicit towards 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 to make their processes explicit and, hence, gain more understanding about their own processes. Although some experiments were developed 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, encouraging the introduction of technologies into the process. By an operational framework it is meant that the framework is validated in practice and ready for use.

2.2 Method

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 dataset with on-site monitored data for enhancing learning, for reducing process variability, and for boosting 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. Since 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 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, we 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 is best extracted by observing day-to-day practice. Secondly, 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, our 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 engaged scholarship (2007) and Van Aken's design science (2004) seemed the most relevant concepts to apply. Engaged research involves participative forms of research that obtain the perspectives of key stakeholders. This claim is that this produces 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 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, and (3) analyzing the on-site process and variability, and evaluating the implemented technologies. Our 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 to professionalize the on-site construction process. This network is called 'ASPARi' (short for ASphalt PAving, Research and innovation).

2.3 Background

Technologies to monitor on-site processes and key parameters

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 lift in industrial projects using GPS (Global Positioning System). 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 the pavement distress in the early stages of the life cycle. These studies show that technologies can help contractors to make their processes explicit and 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 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 due to an insufficient understanding of the non-explicit operational strategies, as a result of which 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 where technologies are hardly adopted because of the lack of evidence of added value; whilst evidence of added value is lacking because technologies are hardly adopted. The adoption of technology may also be hindered by the skepticism and reluctance of the operators. They can 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.

2.4 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 the process quality by closely monitoring on-site asphalt operations and making key parameters explicit. The PQi-framework has 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 eleven contractors in the Netherlands.

Technology introduction

The technologies introduced in the PQi-framework are shown in Table 2.1. In general, the focus is three-fold: Monitoring 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 were introduced and aligned with operator's needs and 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.

Table 2.1: Instruments introduced in the PQi-framework

Instrument	Task	Method	Variables
Weather station (vintage pro)	Monitor weather conditions	Set up a weather station at the construction site	Temperature, wind speed, humidity, sun radiation (every minute)
Laserlinescanner (Raytek)	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	Thermo-graphic picture (every minute)
Thermocouples	Measure cooling in-asphalt temperature at fixed positions	Insert thermocouples in the middle and in the bottom of the asphalt layer	In-asphalt temperatures (every minute)

Instrument	Task	Method	Variables
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 etc.)

Framework development

The same parameters were monitored in a structured and systematic way in order to compare the same parameters of different projects. A framework (cycle) was developed to work gradually towards 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 with asphalt teams confronting them the explicit data and triggering them to reflect on their work, to discuss and analyze the results, and to propose improvements to their future operational strategies.

The typical PQi-framework consists of the following phases:

- Phase 1: *Preparation* – check site design, undertake site calibration, record site conditions and hold a preparatory meeting with the asphalt team;
- Phase 2: *Data collection* – asphalt temperature profiling, monitoring all machine movements, monitor weather conditions, measuring density progression and recording noteworthy events;
- Phase 3: *Data analysis* – analyze all data and prepare visualizations and animations;
- Phase 4: *Feedback* – discuss the measurements, visualizations and animations with the asphalt team, laboratory technicians and others involved in the project;
- Phase 5: *Improve* – make 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 up-scale the number of the experiments to make the process variability explicit. The ASPARi research network assisted with the contractors committing themselves for four 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 eleven contractors to form a team to implement the framework. Two-day courses were held to educate the contractors to use the equipment and to analyze the data. Using the technologies and the manuals, the contractors aimed to monitor two projects per year and to 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. Figure 2.1 provides an 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 asphalting 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.

Thus, a framework was developed to make on-site processes and key parameters explicit using a specific set of technologies. This framework was broadly implemented in Dutch construction practice leading to insights into process variability. The next section describes the insights and highlights the monitored process variability.

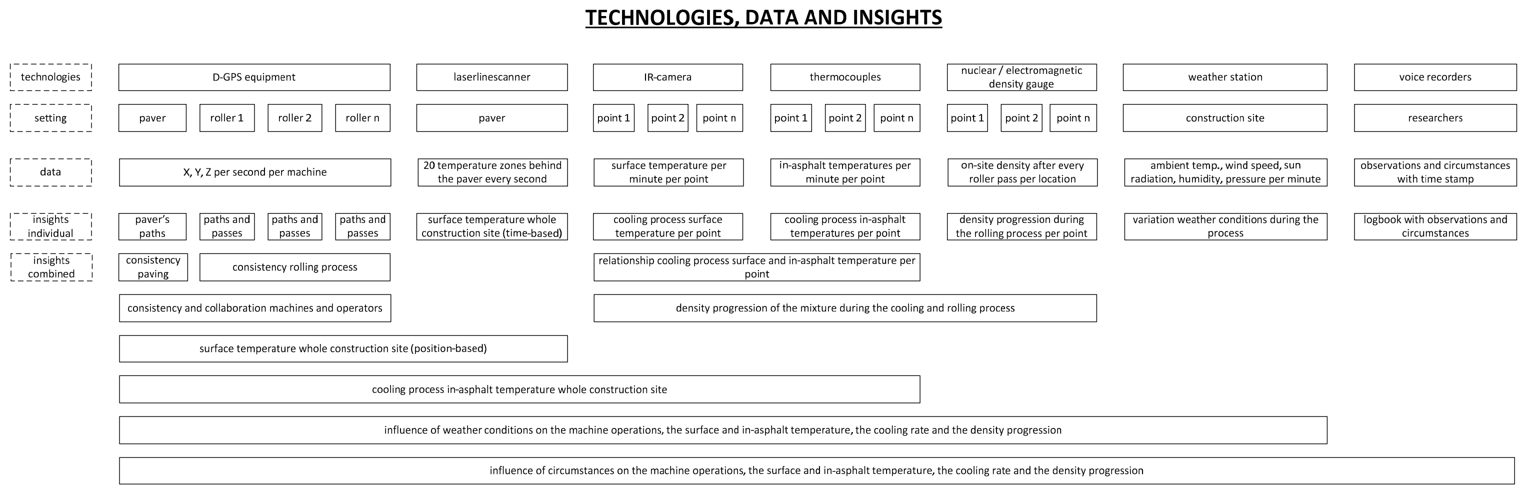

Figure 2.1: The technologies included in the PQi-cycle and the resulting data and insights

2.5 Demonstration of the insights from the monitored projects

In the period 2007-2013 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 also at 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, short and longer stopping places of the paver on the surface temperature became explicit. Depending on the asphalt mixture, corresponding layer thickness and the 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). Figure 2.2 shows an TCP with examples of paver stops and the resulting temperature differentials.

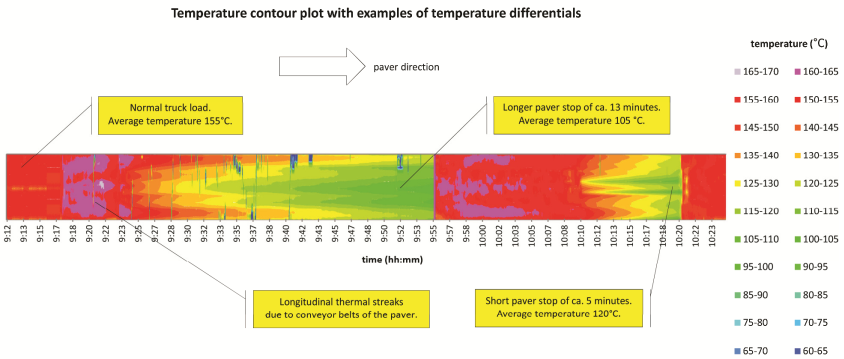

Figure 2.2: Temperature Contour plot (TCP) with examples of temperature differentials

Table 2.2 shows 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 minutes are considered as truck changes, 4-9 minutes as short paver stops, and 10 minutes and longer as hiccups with the plant or the logistical process. From the data, the authors drew the following conclusions:

- 140 paver stops were observed from the 29 projects constructing 35 asphalt layers. Of these stops, 50 were between 0-3 minutes with an average temperature drop of 24 °C, 61 stops were between 4-9 minutes with an average temperature drop of 32 °C, 11 stops were between 10-15 minutes with an average temperature drop of 45 °C, and 18 stops were longer than 15 minutes with a temperature drop between 40-100 °C.
- During truck changes the temperature drop is in the range of 5-40 °C. During the short stops (3-9 minutes) and longer stops (> 10 minutes), 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.
- 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 minutes.
- 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 minutes.
- At Warm Mix Asphalt (WMA), short paver stops (0-3 minutes) 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.

Table 2.2: Summary of paver stops and temperature drops

Paver stops	surface-layer (30-50 mm)		base/bind (50-80 mm)		WMA (60-80 mm)	
	12 layers		20 layers		3 layers	
	nr. of stops	average temp. drop (°C)	nr. of stops	average temp. drop (°C)	nr. of stops	average temp. drop (°C)
0-3 minutes	21	25	28	22	1	hardly noticable
4-9 minutes	17	40	34	33	10	18
10-15 minutes	3	55	7	46	1	30
15-50 minutes	5	63	12	62	1	50

The existence of temperature differentials was acknowledged already 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-linescanner made it possible to systematically monitor and map the temperature variability.

MTVs were used during three monitored projects where some short stops (0-3 minutes) and mainly stops longer than 15 minutes (i.e. huge logistical hiccups) were measured. The surface temperature of the asphalt mixture cooled ultimately down to 120 °C during the short stops. This was mainly caused by geographical conditions or communication between paver and MTV. Figure 2.3 shows that the MTV successfully reduces the temperature differentials behind the screed of the paver, but the average temperature slightly drops (about 5-20 °C). In this example, the average temperature drops from 150 °C to 145 °C, and the standard deviation falls from 15 °C to less than 5 °C.

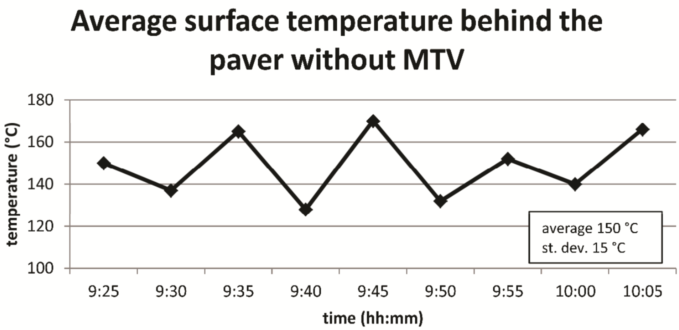

Figure 2.3a: Surface-temperature behind the paver without using a MTV

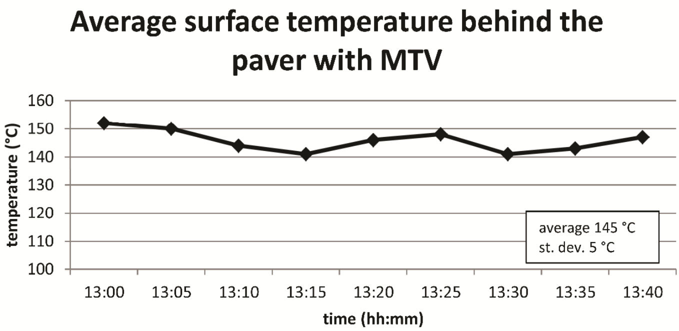

Figure 2.3b: Surface-temperature behind the paver when using a MTV

The existence of temperature differentials was acknowledged already in the literature (Stroup-Gardiner *et al.* 2000; Cho *et al.* 2012) and had been confirmed in practice (ter Huerne 2004; Miller 2010). The use of the linescanner made it possible to systematically monitor and map the temperature variability.

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- and in-asphalt temperatures. 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. Vasenev *et al.* (2014) reports more about this data fusion.

The asphalt cooling process measured over time generates cooling curves. Their analysis divides the data into three assumed phases of compaction: breakdown, intermediate and finish rolling represented by the following temperature windows: (1) starting temperature down to 120 °C, (2) 120 to 90 °C, and (3) 90 to 60 °C (Shell 1990; NAPA 1996; Asphalt-Institute 2007). The measured cooling curves also are compared with the predicted cooling curves of PaveCool (Chadbourn *et al.* 1998) and CalCool (Timm *et al.* 2001). Table 2.3 shows the monitored information about the various asphalt layers and layer thicknesses, combined with cooling information for all the projects.

Table 2.3: Asphalt mixtures and monitored cooling times (in minutes)

project and cooling data	ba/bi 80mm	ba/bi 50-60mm	surf 40-50mm	surf 30-35mm	WMA 80mm	WMA 60mm
nr. of projects measured	6	14	4	8	1	2
nr. of curves measured	14	45	8	24	2	13
cooling time start-60 °C	84	72	54	46	72	49
cooling time start-120 °C	15	11	6	7	-	-
cooling time 120-90 °C	21	20	11	9	15	17
cooling time 90-60 °C	48	41	37	31	57	33

** ba/bi corresponds to base/bind asphalt mixtures*

From the data, the authors drew the following conclusions:

- The asphalt cooling takes longer for thicker mixtures. The base/bind mixtures and WMA cooling takes approximately 15-30% longer. For the surface layers this is about 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.
- 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.
- 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 minutes until the mixture cooled down to 40 °C, while the cooling of the Hot Mix Asphalt (HMA) laydown-temperature until the WMA laydown-temperature takes much shorter. 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 °C and 90 °C for both HMA as for WMA, there is less time available. So, adjustment of the rolling procedures is required.
- The prediction of the cooling curves derived from PaveCool and CalCool correspond well with the measured cooling curves on site. However, this is during post-processing 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 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 due to insufficient information. Tables 2.4 and 2.5 show 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:

- 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.

- Especially for the thinner asphalt layers (30-35 mm) the higher cooling rate makes a major difference; namely a decrease of 40-50% in the time available for compaction. Cooling to 60 °C takes only 31 minutes; and 120 °C is reached after only 5 minutes. Thus, the construction of thin surfaces seems really critical if there is a wind speed of more than 5 m/s.
- 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 and in-asphalt temperature.

Table 2.4: Cooling times (minutes) for a wind speed higher than 5 m/s

cooling times wind < 5 m/s	**base/bind 80 mm**	**base/bind 50-60mm**	**surf 40-50 mm**	**surf 30-35 mm**
start – 60 °C (minutes)	95	80	63	57
start-120 °C (minutes)	16	13	7	8
120-90 °C (minutes)	25	21	12	10
90-60 °C (minutes)	55	46	44	39
difference surface and in-asphalt temperature (°C)	6	8	7	5

Table 2.5: Cooling times (minutes) for a wind speed lower than 5 m/s

cooling times wind > 5 m/s	**base/bind 80 mm**	**base/bind 50-60mm**	**surf 40-50 mm**	**surf 30-35 mm**
start – 60 °C (minutes)	80	40	40	31
start-120 °C (minutes)	15	6	6	5
120-90 °C (minutes)	20	15	10	7
90-60 °C (minutes)	45	19	26	19
difference surface and in-asphalt temperature (°C)	15	16	13	8

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 2.6 and 2.7 show the effect of solar radiation on cooling times for various mixtures. From the data, the authors drew the following conclusions:

- At high solar radiation (more than 100 W/m^2) the asphalt mixture cools very slowly in the 80 to 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.

- 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.

Table 2.6: Cooling times (minutes) for a solar radiation higher than 100 W/m²

cooling times solar radiation > 100 W/m²	**base/bind 80 mm**	**base/bind 50-60mm**	**surf 40-50 mm**	**surf 30-35 mm**
start – 60 °C (minutes)	91	81	67	59
start-120 °C (minutes)	16	14	7	7
120-90 °C (minutes)	23	21	14	12
90-60 °C (minutes)	51	45	47	39

Table 2.7: Cooling times (minutes) for a solar radiation lower than 100 W/m²

cooling times without solar radiation	**base/bind 80 mm**	**base/bind 50-60mm**	**surf 40-50 mm**	**surf 30-35 mm**
start – 60 °C (minutes)	76	61	50	39
start-120 °C (minutes)	14	8	6	5
120-90 °C (minutes)	18	18	11	7
90-60 °C (minutes)	43	35	34	26

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: the number of passes; the temperature and the time windows in which each roller compacts; and the impact of the roller passes at certain temperatures on the density.

The monitored projects demonstrated well the extent of the many changing variables and the different operational strategies for asphalt compaction. An example is shown in Table 2.8, where the following variability's were apparent:

- The number of passes of the tandem roller ranged from 7 to 11, and between 10 to 17 passes for the three-drum roller, with a standard deviation of between 2 and 3 passes. The total number of roller passes per location varied from 14 to 28 roller passes.
- 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 minutes and the temperature compaction window of the tandem roller varied from 145-100 °C to

120-65 °C. Interestingly, the standard deviations in compaction time and in asphalt temperature at the start of compaction was higher for the three-drum roller, whereas the standard deviation in asphalt temperature when compaction was finished was higher for the 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.

- 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. Only the three-drum roller was used at location 6.
- 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 2-9 minutes after the paver had laid the mixture. Relating this time difference to the cooling curve, the temperature difference for the first roller pass can be 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, also considerable variability was 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. The correlation between the on-site measured density and the density determined in the laboratory for 130 cores from 23 projects is shown in Figure 2.4. 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 kg/m^3. The on-site measurement devices seem useful to determine whether density progression is achieved or not. However, the current devices are imprecise in determining the absolute density. The results show much variability and, therefore, are difficult to use.

Table 2.8: 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 (minutes)	temperature start compaction (°C)	temperature finish compaction (°C)	time between paver and 1st roller pass (minutes)
HMA - AC 22 base (80 mm) 15-17 °C, solar 100-200 W/m², wind 8-13 m/s	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
Summary of variability in operational strategies rollers	avg.	tandem	9	37	128	77	11
		3-drum	15	65	123	66	13
	st.dev.	tandem	2	7	10	16	12
		3-drum	3	18	14	4	5

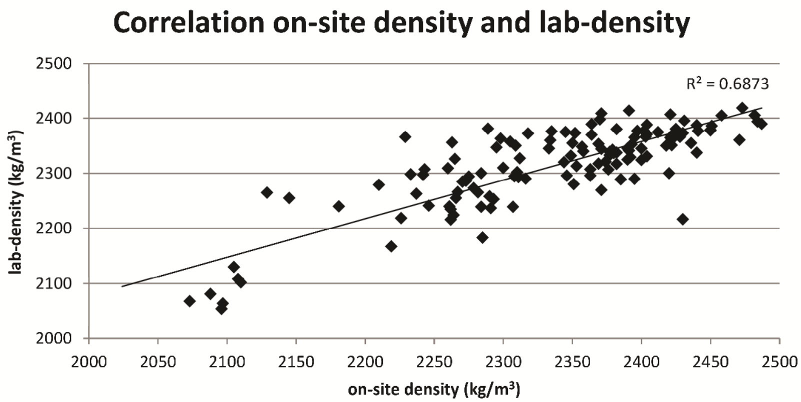

Figure 2.4: Correlation on-site density and lab-density

Movements of the machinery on the construction site

The movements of the machinery on-site were analyzed using high-accuracy D-GPS (Differential Global Positioning System) equipment attached to the machinery. This data were used to produce: (a) animations of the construction process; (b) visualizations of how often a roller passed a certain point on the construction site; and, (c) graphs of the speed of the paver, as shown in Figure 2.5.

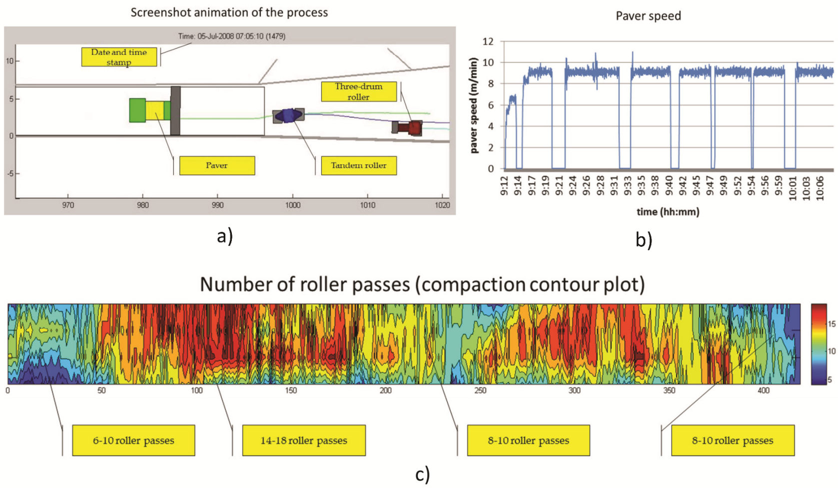

Figure 2.5: Visualization drawn from the GPS-data

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, as well as 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 re-fill the water tank.

How often a roller passes a certain location was analyzed using the GPS-data of rollers and was made visual in Compaction Contour Plots. Analysis shows much 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. 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 target density is reached. This practice of starting too late or too early with compaction highlights the operator behavioral problem of not knowing when to start and finish compaction.

The analysis of various paver speeds for the different asphalt mixtures show that the paver speed during the construction of base/bind layers is higher and more variable than at 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, for example: delays in the asphalt supply; manual work around the paver; or changes in the speed of the paver.

2.6 Validation of the framework in practice: Contractors perspectives

Following our pragmatic perspective, the framework had to be evaluated according to its efficacy in practice. Three contractors evaluated the framework after one and a half years (ter Huerne *et al.* 2012). The first applied the PQi-framework after 2007 on five projects. The second contractor started conducting PQi's 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 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 are broadly adopted by the companies to forecast the cooling of the asphalt mixture and to predict compaction times and to estimate the time required for road closures.

The contractors emphasize 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 suggest 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, then 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 are relatively small and that they all learnt 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 towards providing real-time information on-site to assist the operators during construction. It was also suggested that machines, such as an MTV, 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.

2.7 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. Our 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, our findings highlight the large variability in on-site density measurements using both nuclear and non-nuclear gauges. Cho *et al.* (2013) have proposed a method to improve non-nuclear density measurements, but still found relatively low correlation rates and recommended taking cores from the road. This suggests a need to re-evaluate 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. Our research approach, which gradually introduced and evaluated technologies so as to align them with the operator's 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 datasets but it is too early to observe significant damage. In further research, it may be possible to trace damage back to construction operations and then draw conclusions on the impacts of on-site construction on 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 and to 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 helps contractors to develop 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 in terms of Weick and Sutcliffe (2007). The gathered dataset 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 firstly be realized by better specifying and improving forecasting of the key process parameters; secondly by monitoring (direct observation) the key process variables; and thirdly 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. Our 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.

Our findings are relevant also 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.

2.8 Conclusion

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 our 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 dataset 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 enables 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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Chapter 3

On-site process variability and common practices: A case in asphalt compaction[2]

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.

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3.1 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.

3.2 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 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.

3.3 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.

3.4 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 3.1. 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.

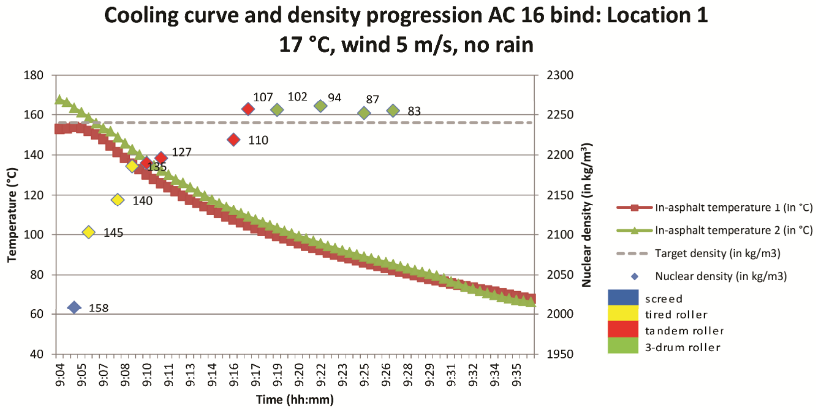

Figure 3.1: Visualization of the cooling curve and the density progression for 1 location

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 3.1. 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 3.1: Variability in compaction operations for the same asphalt mixture

Mixture and weather condition	Location	Roller type and sequence	Number of roller passes	Compaction time (minutes)	Compaction temperatures (°C)	Time between paver and 1st roller pass (minutes)
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 3.2 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 3.2: 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)	**ba/bi 80mm**	**ba/bi 50-60mm**	**WMA 60-80mm**	**Surf 40-50mm**	**Surf 30-35mm**
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.

3.5 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 3.3.

Table 3.3: 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 3.2 for the 3-drum roller and Figure 3.3 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.

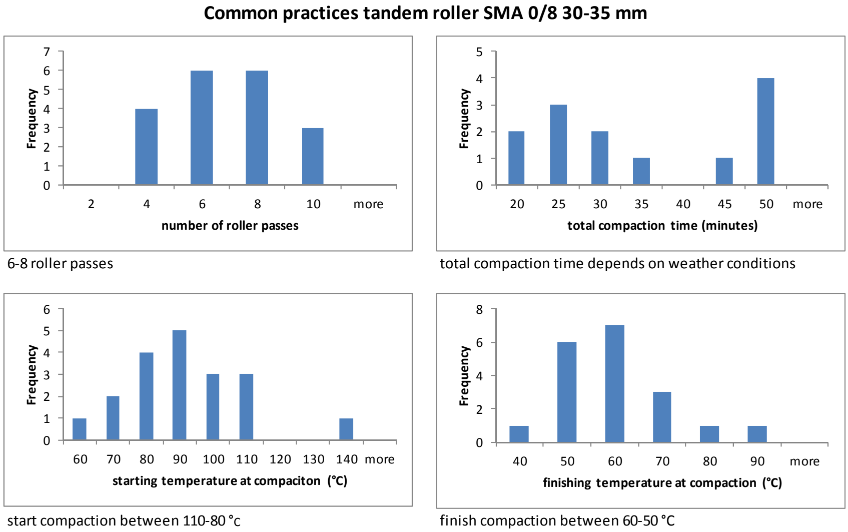

Figure 3.2: Common practices compaction 3-drum roller for a Surf 30-35 mm

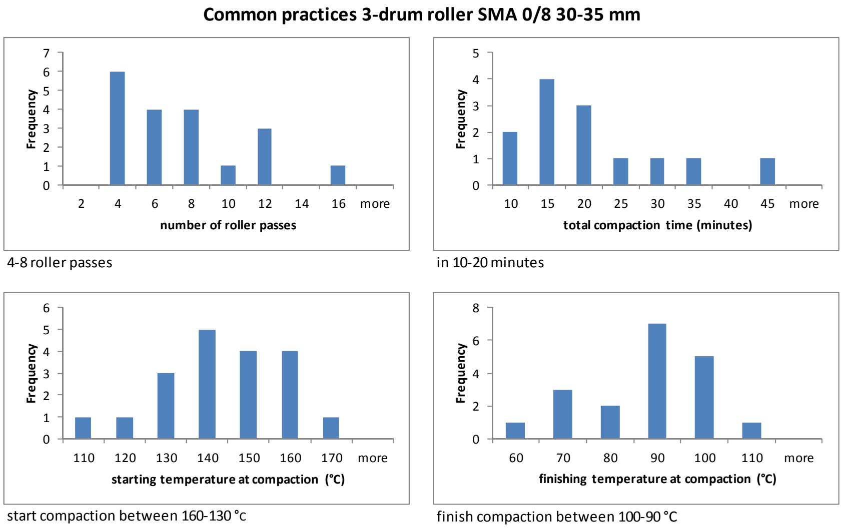

Figure 3.3: Common practices compaction tandem roller for a Surf 30-35 mm

3.6 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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Chapter 4

Method-based learning: A case in the asphalt construction industry[3]

Traditional working practices in the construction industry rely heavily on the on-site experience and craftsmanship (the tacit knowledge) of operators and teams. This results in implicit learning and lengthy learning cycles. The aims of the research are to develop a deeper insight into construction processes and to instigate a change from current implicit learning to explicit method-based learning. To change to explicit method-based learning, the experiential learning model of Kolb (1984) was introduced into current practices and 'explicating the process' was added to this learning cycle. Further 'reflective observation' and 'abstract conceptualisation' were incorporated explicitly during an actual road construction project using feedback sessions with an asphalting team. The adopted learning framework was found to be applicable and useful in the quest for enhanced learning capabilities and improved process control. Fusing Kolb's learning model with on-site collected data was vital in explicating tacit knowledge and implicit processes. The approach made it possible to have a meaningful discussion with operators to unravel their intentions and reasoning behind the chosen strategies. Explicit method-based learning, as here, leads to improved quality awareness, better understanding of the processes and their interdependencies, and improved communication with and within the asphalting team.

Keywords: action research; experiential learning; information technology; roads; tacit knowledge.

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4.1 Introduction

Significant changes are currently occurring which are changing the roles of agencies (clients) and contractors in the construction industry. Agencies are shifting towards service-level agreements with lengthy guarantee periods (Minchin *et al.* 2008). Within these new roles and contracts, contractors are directly confronted with any quality shortcomings that emerge during the guarantee period. These changes urge contractors to develop a deeper insight into on-site processes (Sijpersma and Buur, 2005; Ang *et al.* 2005; Dorée, 2004). Also, it is becoming increasingly important for contractors to improve process and quality control during on-site construction operations.

With the emergence of the internet, pervasive networks and the rapid progress in technologies, one might expect contractors to embrace new information and communications technology (ICT) opportunities for performance enhancement. However, in reality, the construction process is carried out still mainly without the use of high-tech instruments to monitor key process parameters. Also, in spite of the significance of the on-site process, the major part of the literature deals with the characteristics of a construction from a material perspective, while limited focus has been put into the systematic mapping and analysis of on-site construction processes. In general, contractors know what activities are undertaken on site at a certain time, but the actual on-site operational activities performed and decisions taken are not systematically mapped. This makes it difficult for contractors to relate the on-site operational activities to the final quality of the construction. As such, it is nearly impossible to identify or distinguish between good and poor operational practices and to improve process control.

If the construction process is not explicit, the causes of any failure to meet the required specifications cannot be traced back to actual operational strategies on the construction site. Also, as in many domains in the construction industry, the current operational strategies rely heavily on the skills and experience of operators, engineers and managers on the construction site. This results in implicit learning based on tacit knowledge and lengthy learning cycles.

To enhance learning and to improve the construction process, as well as to achieve improved process and quality control, it is essential to move away from the current implicit individual lengthy learning towards explicit and method-based learning. Given that current practices largely depend upon the on-site experience of operators, it seemed appropriate to adopt and introduce the experiential learning lens of Kolb (1984) to current practices. Consequently, a method to instil change towards explicit method-based learning was proposed and its merits were demonstrated during the construction of an asphalt highway in the Netherlands.

The asphalt industry plays a vital role in the global transportation infrastructure. It helps drive economic growth and social well-being in both developed, as well as developing, countries. World production of asphalt in 2007 was estimated at around 1.6 trillion metric tonnes, with Europe producing about 435 million metric tonnes per year. Europe's annual public investment in highway, street and bridge construction totals some €80 billion compared to €55 billion per year in the USA. Collectively, the asphalt industries of the USA and Europe employ approximately 400,000 workers (EAPA, 2011).

In spite of its obvious importance, the asphalt industry is still relatively under-developed and a low-tech domain. Most of the scientific and other literature for the industry deals with material characteristics whilst there is little systematic mapping and analysis of on-site processes and their effects on the quality of the asphalt layer (Leech and Selves, 1976; Elhalim *et al.* 1993; ter Huerne, 2004; Miller, 2010). This makes it inherently difficult to improve process control and enhance learning competencies. Therefore, testing and improving learning methods in construction, as well as improving the learning competency of operators on-site, is relevant for both scientific community and the industry as a whole.

This research discusses the conceptual background relating to learning in the construction industry and the transition from tacit to explicit knowledge. The various phases of the adopted learning model are described for the highway project selected for this research, drawing up conclusions and suggestions for future research for road construction and for the construction industry in general.

4.2 Conceptual background

Learning in the construction industry

Nowadays, much attention is given to how organisations learn (Chan *et al.* 2005) or how learning takes place between projects (Bakker *et al.* 2011). These investigations are driven by the intention to improve operations in the industry which has often been blamed for its poor performance and learning culture (Hartmann and Dorée, 2013).

Various learning approaches are described in the literature, such as a sender/receiver approach, action learning and social learning. Many of these studies assume that there is a knowledgeable sender that is willing and, maybe even more importantly, able to share that knowledge with a receiver who can absorb that knowledge through an effective communication channel between the sender and the receiver. However, because the operational processes in construction generally are not explicit, it is difficult for the sender (operator) to share such knowledge. Also, the implicit knowledge embedded in the experience and craftsmanship of operators is very often not easy to verbalise.

In our research, we take the view that learning takes place through interaction between people, rather than in the human mind only as social learning theory claims (Easterby-Smith *et al.* 2000).

Kolb (1984) described experiential learning as a perspective on learning in which experience plays a central role. This differs from the cognitive view that emphasises acquisition, manipulation and recall of abstract symbols, from the behavioural view that denies any role for consciousness and subjective experience, and from the constructionism view of psychology that views learning as a reconstruction rather than as a transmission of knowledge.

Kolb (1984, p.38) examined experiential learning from an educational perspective and defined learning as 'the process whereby knowledge is created through the transformation of experience'. This definition firstly emphasizes that learning is best conceived of as a process and not in terms of outcomes, so ideas and thoughts are formed and reformed through experience. Secondly, that learning is grounded in experience whereby knowledge is continuously derived from and tested out in the experience of the learner. Kolb (1984) showed statistically that there are various learning styles through which people learn. For example, some people grasp new information through experiencing the qualities of the world: they rely on their senses and immerse themselves in concrete reality. Others tend to perceive, grasp or take hold of new information through symbolic representations or by abstract conceptualisation: thinking about, analysing or systematically planning, rather than using sensation as a guide. Similarly, in transforming or processing experience, some people tend to carefully watch others who are involved in the experience and reflect on what happens. Meanwhile, others choose to jump right in and actively start doing things (Kolb *et al.* 2001). Kolb identified four statistically prevalent learning styles: diverging, assimilating, converging and accommodating.

Opportunities for operational-level reflection provided by a known communication channel are rare in the construction industry, because the focus is on production, rather than on learning and reflection. As a result, learning as a team is nigh on impossible. Also, operators receive little feedback on their work, or on the work and results of others. Although reflective practice models might be seen as necessary in the construction industry, in practice they are often lacking (Orange *et al.* 2005). For example, most roller operators report that they are not informed about the final density of the completed layer, before, during or after site operations, despite its importance for the final quality of the asphalt layer. This illustrates a significant shortcoming in terms of quality control and shows the absence of closing the feedback loop (Montgomery, 2005). As such, the outcome negatively affects any learning that might have occurred otherwise.

Several researchers have confirmed the importance of reflection and they stress that reflection is important in facilitating and contributing to learning (Schon, 1983; Boud and Walker, 1998; Harrison *et al.* 2003). In terms of reflective practice models, the concepts of single and double loop learning are also relevant (Argyris and Schon, 1978). Single loop learning occurs when a practitioner continues to rely on current strategies, techniques or policies, even after an error has occurred and a correction has been made. Double loop learning involves the modification of objectives and strategies, so that when a similar situation arises a new context is considered. Again, if the operational strategies and key parameters are not explicit, it becomes harder to adopt double loop learning and to adjust strategies to a new practical setting.

The key to the effectiveness of various learning practices, such as project-to-project and organisational learning, in construction is the component that occurs at the operational and team level. However, current operational-level learning practices are based mostly on the hands-on experiences and craftsmanship of operators. Ideally, operational parameters, such as the number of roller passes, should be determined by asphalt technologists and mix designers so that field engineers can give clear guidance to the operators. However, standardised procedures to determine the number of roller passes and temperature windows for compaction are lacking, and instructions in textbooks are vague or even lacking. Sometimes the number of roller passes is determined from various test-sections and on-site trial-and-error, but this is both ineffective and uncertain as it is unknown if the previously gained experience is relevant to a different practical setting. Therefore, decisions regarding on-site operational activities are still mainly taken by the operators rather than field engineers offering clear guidance based on information from management or technologists. So, in practice, to improve process quality, operators have to draw on their inherent skills and craftsmanship and use their experiences to actively and informally experiment with how various new strategies might influence quality parameters (Figure 4.1). Using this approach, operators may, based on their experience from previous construction projects, individually and implicitly learn and improve quality. However, this process is based on limited observations and data, and with many changing variables, thus results in lengthy learning cycles.

These informal and implicit characteristics of the construction industry make learning and improving difficult. To improve process and quality control, a change is needed from individual implicit learning towards an explicit and method-based learning approach. By method-based learning, we mean structured and systematic learning based on explicit data.

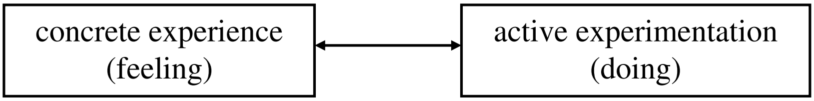

Figure 4.1: Current individual implicit learning in the construction industry

The experiential learning cycle of Kolb (1984) was adopted in an attempt to move from individual implicit learning towards explicit method-based learning. According to Kolb (1984), experiential learning centres on the transformation of information into knowledge, an event that takes place after a situation has occurred. It entails a practitioner reflecting on that experience, then gaining a general understanding of the concepts encountered during that experience and, afterwards, testing these general understandings in a new situation. Several other authors have also argued that learning takes place in this sequence (Brock and Cameron, 1999; Daft, 2000).

The experiential learning model is well-known and has been applied frequently in management education (Vince, 1998). However, it has not very often been applied explicitly in construction. A notable exception is Lowe and Skitmore (1994), who did apply it to cost estimating in construction in order to understand what types of experience are vital for cost estimating and how this can be utilised. They found that the utilization of concrete experiences in cost estimating increased while the use of reflective observation decreased. Based on experiential learning theory, they proposed the introduction of feedback and self-monitoring systems as a mechanism to improve the accuracy of pre-tender estimates.

In terms of Kolb's learning model, current learning processes in the asphalt industry mainly concentrate on the 'concrete experience' and 'active experimentation' parts of the experiential learning cycle. The 'reflective observation' and 'abstract conceptualization' aspects are neglected mostly because the operational strategies and key parameters are not explicit and are not systematically monitored and mapped. Therefore, in our research, we have added 'monitoring the process (explicating)' to Kolb's experiential learning cycle (Figure 4.2). Further, a comparison can be made between the concrete experience (feeling) of the operators and the monitored process (data). In addition, 'reflective observation' and 'abstract conceptualisation' should be added to the enacted learning cycle in order to improve quality and process control and to develop additional learning and reflective competencies within construction teams. Feedback sessions were conducted with operators in order to introduce these competencies and to open up a communication channel between the operators and the field engineers. In this way, learning can take place with the field engineer learning to give improved guidance to operators and with the operators learning how to improve the actual operations, together improving road quality. We enabled various learning styles during the feedback sessions with operators, who mainly learn through experience, becoming involved with university graduates trained to critically reflect and who are able to transform the operator's experiences into abstract concepts and make plans for experimentation.

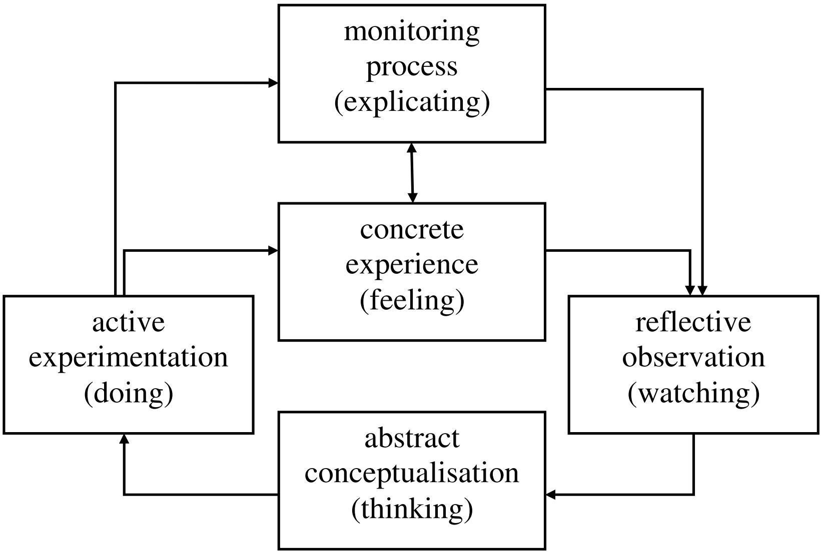

Figure 4.2: Monitoring the process (explicating) added in the experiential learning cycle after Kolb (1984)

From tacit to explicit knowledge

Given that current operational strategies rely heavily on the on-site skills and experiences of operators, who have implicitly learnt from their experiences in previous projects, it is important that, in the quest towards method-based learning, the operators' implicit and tacit knowledge is made explicit.

The concept of tacit knowledge is used widely in the construction management domain (Gherardi and Nicolini, 2000; Bresnen *et al.* 2005; Ewenstein and Whyte, 2007; Styhre, 2009). Although there is discussion on how the concept should be defined (Styhre, 2009), there is consensus on the importance of this type of knowledge. Some researchers claim that tacit knowledge is, by definition, what cannot be turned into explicit knowledge (Gourlay, 2006). However, in line with Nonaka and Tekeuchi (1995), we believe that a transition from tacit knowledge to explicit knowledge is essential in the cycle of knowledge creation. Nonaka and Takeuchi (1995) developed a knowledge management model that focuses on knowledge spirals in the transformation of tacit knowledge into explicit knowledge, and used this to explain why Japanese companies became world leaders in the automotive and electronics industries. In this model, knowledge follows a cycle in which implicit knowledge is 'extracted' to become explicit knowledge, and this explicit knowledge is 're-internalized' into implicit knowledge as the basis for innovation and learning.

The focus in our research is on the challenge to discover an operators' tacit knowledge and convert this into information and visualisations that can be communicated within the asphalt team and within contracting organisations.

New technologies may encourage a more explicit and method-based approach. However, many technologies fail to be commercially adopted due to an insufficient understanding of the current operational strategies and as a result, lacking evidence of added value (Elhalim and Haas, 2004). This evidence is often lacking because the operational strategies are not explicit. The various causalities involved result in a vicious circle of both 'no adoption of technologies' and 'no understanding of current operational strategies'.

Various studies using new technologies have been initiated to map the asphalt construction process. Several experiments to map parts of the process have been conducted in recent years: Krishnamurthy *et al.* (1998) developed an automated paving system for asphalt compaction operations, Gowda *et al.* (1998) described and modelled an holistic enhancement of the production analysis of paving operations, Peyret *et al.* (2000) used a high-precision real-time field application of GPS in positioning asphalt machinery, Navon and Shpatnitsky (2005) developed a model for automated monitoring of road construction, Commuri *et al.* (2011) developed a neural network-based intelligent compaction analyser for estimating compaction quality, and Beainy *et al.* (2012) developed a quality assurance tool using an intelligent asphalt compaction analyser. Although some experiments were developed into industrial applications, few have become accepted widely by the industry for application on asphalt construction sites. For example, some equipment manufacturers now provide GPS as an option for clients but, as yet, GPS does not play a part in operational strategies and working practice in asphalt processes. While new features and functions have been added to the equipment, such as temperature and density measurements, most operators acknowledge that still they hardly make use of this available technology (Miller, 2010).

Previous interviews indicated that operators are uncomfortable with new technologies (ter Huerne *et al.* 2007). The adoption of technology may also be hindered by the scepticism and reluctance of the operators who feel that their workmanship is being devalued or that management could use the technology to track their movements and possibly use it punitively. The conclusion to draw is that, in asphalt construction, new technologies must be harmonised and better aligned with the actual needs of the operators if they are to be adopted and fully integrated into operational strategies and methods.

To change implicit knowledge about on-site operational activities and key parameters into explicit knowledge and also to break down barriers to technology adoption, we introduced various technologies into the construction process.

4.3 Method

Aims

Two issues are addressed in this research. Firstly, that on-site asphalt construction processes are low-tech with an apparent reluctance to adopt new technologies. These processes, in the main, are not explicit and the on-site knowledge of operators is mostly implicit. Secondly, that market conditions are currently encouraging contractors to enhance process improvement and learning. This is difficult given the current experience-based learning practices based on limited data and projects.

The aims of our research are: (1) to adopt the method-based learning approach of Kolb (1984) and to include 'reflective practice' and 'abstract conceptualization' in current learning practices by conducting feedback sessions with operators where they can reflect on their work and their collaboration with others, and (2) to enable operators to learn explicitly, using a monitored and explicated process (based on data), rather than the current implicit experience and craftsmanship-based approach.

The goal of this paper is to demonstrate the adopted method-based learning framework in actual use in a road construction project. During the construction of a Dutch highway, the learning phases were incorporated into current practices and the full experiential learning cycle was observed. Two nights of asphalting were monitored and observed, separated by a one-week gap during which a feedback session was held.

Methodology

Various studies show that practitioners often struggle or fail to adopt research findings (Dopson *et al.* 2002; Rynes *et al.* 2001; Van de Ven, 2007). The gap between scientific findings and practical application is often very real. Stokes (1997) suggests that the classic distinction between 'basic' research, intended to develop general knowledge and understanding performed without practical ends, and 'applied' research, performed in the service of some immediate end, is both inaccurate and counter-productive. Stokes, therefore, proposed a 'user-inspired' research domain undertaken as a quest for basic understanding (rigour) but with considerations given to use (relevance). This study is conducted within this research domain, where method-based learning theory is developed and further tested, alongside considering the implementation of enhanced practical learning competencies. Today, Van de Ven's engaged scholarship seems the most relevant concept to apply in this research domain. Engaged scholarship is a participative form of research for obtaining the advice and perspectives of key stakeholders, in this case practitioners and researchers. It is argued that an engaged research approach produces knowledge that is more penetrating and insightful than when practitioners and researchers work on the problems alone (Van de Ven, 2007).

The philosophical lens used for the research presented in this paper is pragmatism (going back to Peirce), with various important concepts of this philosophy influencing our research. First, we believe that meaningful new theories are built upon the existing experimental knowledge of practitioners. So, if we want to improve practice, experimental and tacit knowledge provides a rich foundation to on which to build but this needs to be explicated first. Further, the motives of practitioners along with their experiences, sensations and emotions are vital and have to be considered. All this knowledge is intrinsically embedded in practice and, therefore, theory and practice are inseparably inter-related (Hartmann *et al.* 2009). Thus, experience and practical knowledge will be extracted by observing day-to-day practice.

To validate whether a theory that is 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). New theory should be evaluated and legitimatised according to its success or efficacy when applied and implemented in practice.

The focus in this study is on describing the experiential knowledge of practitioners within a specific setting and avoiding the development of over-generalised theory that will be too abstract for any given local context. Knowledge is developed based on reasonable and plausible beliefs through testing and experimentation in practice. Each of these beliefs may turn out to be false at any time. This is not a quest for perfect knowledge, but rather to constantly improve knowledge by implementing cyclic feedback loops which repeatedly replace previous knowledge with new knowledge and then assess how well the new systems work in practice. This allows persistent improvement to practice and evaluates how well the improvements work in practice and, at the same time, enables increasingly stable theories to emerge.

An action research strategy, combined with this pragmatic philosophical stance, seems appropriate in aiming to diminish the gap between theory and practice (Van de Ven, 2007; Sexton and Lu, 2007). Also, it will further develop method-based learning theory and implement emerging theory to enhance learning competencies, both at the individual and team levels.

Our action research approach involved the researcher, innovative technologies and asphalt operators in the research process. The designed action research approach alternated progressive steps of (1) asking asphalt operators about the planned process through questionnaire surveys, (2) explicating the actual construction processes using off-the-shelf technologies, and (3) feedback with the operators about the explicated processes.

This approach quantitatively and qualitatively explores the asphalt construction process and identifies opportunities for learning and process improvement. Explicit, quantitative data facilitate practitioners in synthesizing and verbalizing their tacit knowledge and promote learning processes. By utilising a qualitative approach (i.e. feedback sessions with operators) we aim to understand the asphalt construction process from the subjective perspective of the operators and the team involved.

The complexities in the construction process can only be captured by describing what really happens when operators are doing their job and incorporating the context in which they operate, as well as their frame of reference. The asphalt operators were challenged to make sense (as in Weick, 1995) of their process choices and the results. Weick (1995) used the term sensemaking to refer to how the unknown can be structured to be able to act in it. Sensemaking involves coming up with a plausible understanding - a map - of a shifting world; testing this map with others through data collection, action and conversation; and then refining, or abandoning, the map depending on its credibility. The level of analysis in our study is the operational and team level of the on-site construction processes, i.e. asphalt temperatures during the process and on-site compaction operations. The next paragraphs discuss the methods used for data-collection in more detail.

4.4 Methods for data-collection

The methods used for data-collection in this research were questionnaire surveys, monitoring and observing the construction process, and feedback sessions with operators.

Questionnaire surveys were used to explicate the planned process of operators and certain technologies (GPS, laser, infrared) were used to explicate the actual construction process (concrete experience). Next, a feedback session was organised with the asphalt team. In this session, the intentions and reasoning of the operators regarding the process 'as constructed' were made explicit (reflective observation). Based on the 'as constructed' process and the feedback, a list of possible learning aspects and improvements were addressed (abstract conceptualization). During the second asphalting night, any changes in strategies, quality and process awareness and learning effects were experimented with and monitored (active experimentation). These data-collection methods and their outputs are summarised in Table 4.1.

Table 4.1: Data-collection phases, methods and output

Data-collection phase	Data collection method	Output
Explicating the planned process (1)	Questionnaires operators	Planned and predicted process (1)
Monitoring the process 'as constructed' (1)	D-GPS, laser linescanner, infrared cameras, thermocouples, density gauge, weather station	Process 'as constructed' (1)
Reflective observation	Feedback session recordings	Reflection operators on the planned process and process 'as constructed'
Abstract conceptualization	Feedback session recordings	List with changes and improvements for future projects
Explicating the planned process (2)	Questionnaires operators	Planned and predicted process (2)
Monitoring the process 'as constructed' (2)	D-GPS, laser linescanner, infrared cameras, thermocouples, density gauge, weather station	Process 'as constructed' (2)

** The numbers indicate the construction night (night 1 and night 2)*

Questionnaire survey

Before the construction task started, a questionnaire survey was conducted with operators on how they planned to conduct their tasks. The questionnaires aimed to make the planned process explicit regarding certain parameters that could be measured during actual construction. The researcher explained the context of the questions to the operators and the operators individually completed the questionnaires.

Two questionnaires were conducted: one for all the operators of the asphalt team, and one about compacting operations specifically for the roller operators. The purpose of these questionnaires was to explicate the operators' planned processes. At first, it was difficult for the operators to answer these kinds of questions because usually they do not think explicitly about these parameters. Normally, they instinctively manage them based on their experience and skills. Nevertheless, the operators tried to verbalise their thoughts.

The questions addressed to all the operators were about: (1) the cooling process of the asphalt mixture, (2) the cooling process during paver stops, and (3) general aspects, such as the optimal paver speed, the expected difference between the surface and in-asphalt temperature given a specific asphalt mixture, layer thickness and weather conditions. The questions directed at the roller operators alone were about: (1) their own planned process and (2) the process of their colleagues. The level of analysis of these questions covered the number of roller passes and the temperature window they planned to compact in. The questions posed are shown in Appendices 1 and 2.

Monitoring and observing the construction process

The actual working methods and operational strategies were monitored and explicated 'as constructed' (concrete experiences). We used the previously developed 'Process Quality improvement' (PQi) measurement framework (Miller 2010) to map the actual working methods and make the construction process explicit. In this framework, the operational activities are made explicit using several technologies, such as Differential GPS (D-GPS) to record machinery movements, and a laser linescanner, infrared cameras and thermocouples to record asphalt temperatures during the construction process. Both of these are important parameters in determining asphalt quality. In some locations, the changes in density after each roller pass and the cooling process of the asphalt mixture were measured. Also, data were collected about the weather and all the essential events undertaken during the process are recorded in a logbook to aid better understanding and to place things in a proper context. The aim of the PQi-framework is the improve the 'process quality' by closely monitoring asphalt construction works and making operational behaviour explicit.

This framework had already gone through various implementation phases (Miller, 2010). First, the technologies were introduced and tested. Having identified the useful technologies, a structured framework to collect systematically the same set of variables in various projects was developed. Finally, this framework was scaled-up (broad implementation) to eleven contractors in the Netherlands so that we could start to generalise about the implementation of the framework. More information about the technologies used and the systematic way in which data were collected, analysed and mapped have been described in Miller (2010). The preliminary results were presented at ARCOM 2008 (Miller *et al.* 2008).

Feedback session

With measurements made and the asphalt construction process made explicit, we then used feedback sessions to help understanding the team's views of the key process parameters monitored, i.e. the asphalt temperatures and compaction variability, as well as to develop further insights into the construction processes.

The monitored data were visualised in a structured format using Matlab, AsphaltOpen and MS Excel so that the information would be understandable to the asphalt team (Miller *et al.* 2011). This explicit data, converted into a series of visualisations and animations, was combined with the operators' viewpoints to explore the perspective of those closest to the process (the construction teams). During these sessions, the researchers acted as facilitators who only asked questions, generated discussions and challenged individuals to think differently. Thus, a participative dialogue inquiry was undertaken, rather than a sender/receiver approach where the researchers would have expounded on what was found and the asphalt team listened. For many operators, the feedback session was a first opportunity to study and reflect on the results of their own operational practices (in the form of the animations, temperature and compaction plots) based on an explicitly monitored process and discuss these practices as a team.

All the members of the construction team attended the feedback session: the site supervisor, paver operators, screed operators, roller operators, and general workers. Also attending were the laboratory technicians responsible for density measurements, the field engineers, the responsible project managers, and the regional asphalt managers/directors.

The feedback session was recorded with a voice-recorder and transcribed afterwards. The results were coded into various themes as they related to operational behaviour and to the key construction parameters presented at the feedback session.

4.5 Learning-cycle results - Dutch highway project

Project description

The object in the case study was the construction of the A15 highway as part of improving the connection between the Port of Rotterdam and the rest of the country. A consortium of three contractors was responsible for not only the construction but also for maintenance until 2035. Therefore, controlling the process and the quality was essential to prevent problems (shortcomings) during the maintenance period. Construction work took place overnight (between 11 pm and 6 am) and there was a lot of pressure on the project. In response, the contractor had increased the production from 2,000 up to 3,000 tonne per night. The carriageway was approximately 15 metres wide and about 1,000 metres was laid each night. The 70 mm thick asphalt layer was constructed using an AC 16 bind (40/60 pen). During both the nights surveyed, the same asphalt team was involved in constructing the asphalt layers. The construction took place under relatively mild circumstances: 8-10 °C and 3-7 km/hr wind speed. The asphalt plant was approximately 25 km from the construction site but there were enough trucks for logistics not to be a problem.

The full experiential learning cycle, for both researchers and operators, is discussed below based on the explicated process.

Concrete experience

The laying temperature of the asphalt mixture, the cooling process and temperature variability are key quality parameters (Miller, 2010). Despite this, operators receive virtually no information during the construction process about these temperatures and their variability. So, in general, operators estimate the temperatures based on their experience and relate this to the weather, the specific mixture and layer thickness and then decide on their rolling process.

Before the measurement process, questionnaires were distributed among seven operators seeking their estimates of the temperatures. Then, during construction, four sets of measurements were made using thermocouples and IR-cameras to monitor the cooling process 'as constructed'. The operators' predictions and the measurements are shown in Table 4.2.

Table 4.2: Predicted and actual asphalt temperatures and cooling rates of measurement night 1

Parameter	Predicted range (7 operators)	As constructed (4 measurements)
Cooling until 120 °C (min.)	10-30	8-17
Cooling until 90 °C (min.)	24-60	22-38
Cooling until 60 °C (min.)	30-90	57-80
Difference surface and in-asphalt temperature (°C)	17-25	8-15
Temperature drop truck change (°C)	5-8	5-10
Temperature drop during 3 min. paver stop (°C)	10-12	10-20
Temperature drop during 7 min. paver stop (°C)	14-20	25-35
Temperature drop during 15 min. paver stop (°C)	20-30	35-50

Interestingly, the measured cooling times to 120 °C, 90 °C and 60 °C all correspond reasonably well with the operator's predictions. However, the range of predictions was certainly wide. For example, one operator predicted that cooling to 60 °C would take 30 minutes, while another predicted 90 minutes. Such differences certainly influence decisions regarding the operational rolling strategy.

The difference between the surface and the in-asphalt temperatures was slightly over-estimated by the operators. This is important because the operators' decisions are mainly influenced by what they believe the in-asphalt temperature to be while, during the construction process, it is mainly the surface-temperature that is measured. Temperature drops during truck changes and paver stops were accurately predicted for short stops, but underestimated for longer (7 and 15 minutes) stops.

In addition, the questionnaires sought information on the planned operational strategies regarding the number of roller passes and the temperature windows in which one could compact before the measurement phase. During the construction process, the actual number of roller passes and the prevailing temperatures when compacting were determined using D-GPS, infrared cameras and thermocouples.

The planned operational strategies and the actual operational strategies are shown in Table 4.3. The data show that operators were able to predict the number of roller passes to be made by their own roller quite accurately, but predicting the number of roller passes their colleagues would make appeared difficult. For example, operator 3 expected to make five or six roller passes himself, and during the measurement night he made between four and seven passes on the various parts of the new surface. However, the same operator predicted that the other operators would complete ten roller passes but, in practice, operator 1 made four to six roller passes and operator 2 made seven to nine passes. The data also show that the temperature windows were somewhat difficult to predict, especially for the second roller.

Table 4.3: Expected and actual number of roller passes and temperature windows for compaction of measurement night 1

Parameter	**Prediction operator 1**	**Prediction operator 2**	**Prediction operator 3**	**As constructed (4 measurements)**
Number of roller passes Roller 1	2-3	2-3	10	4-6
Number of roller passes Roller 2	4	6-8	10	7-9
Number of roller passes Roller 3	3-4	2-3	5-6	4-7
Temperature window Roller 1	150-120 °C	140-120 °C	145-90 °C	150-125 °C
Temperature window Roller 2	130-90 °C	110-80 °C	90-70 °C	130-95 °C
Temperature window Roller 3	90-60 °C	70-50 °C	70-50 °C	90-60 °C

The analysis shows that the estimates, based on 'concrete experience', made by the operators correspond quite well with the process 'as constructed' in terms of their own operations (albeit that the estimates covered wide ranges). However, it was clearly difficult for operators to estimate what their colleagues were doing during the construction process. This makes it difficult to anticipate during the process and, because asphalting is a collaborative process, this will negatively influence controls employed to manage the process.

Reflective observation

A key step in explicit method-based learning is providing feedback to the operators, here to the asphalt team and for them to learn from this feedback (Kolb, 1984; Miller, 2010). The measured data were provided to the asphalt team during the feedback session, so that they could reflect on their own operations. These sessions enabled teams to determine improvements in the asphalting process, both in their individual tasks and in their collaborative work. Here, the measured quantitative data are used to make the operational behaviour explicit. The qualitative data from the feedback sessions tells the story from the operators' viewpoints. The session lasted approximately one hour. The results from measuring the process 'as constructed' were printed out and given to everybody so they could look at the findings themselves. This included the asphalt team, project managers, people involved in the preparation and technologists. The observations and reflections are summarised in Table 4.4.

Table 4.4: Observations and reflections of the operators of the asphalt team

Topic	Observation	Reflection asphalt team
Initial surface temperature	In general, the surface temperature behind the paver was 160 °C. During a truck change it cools by 5-10 °C. If the paver has to stop, the temperature decreases quickly (by up to 40 °C).	It is well-known that the temperature decreases by 5-10 °C during truck changes. The rapid temperature drop by 40 °C during paver stops was more than expected and underestimated. If they are aware of lower temperatures, they will start compacting more quickly.
Cooling	The predictions of the operators agreed well with the measured cooling curves. Nevertheless, the range of predictions is rather large.	The differences in predictions are mainly caused by the variations in experience. Predictions by inexperienced operators are the least accurate.
	The variability in the cooling curves is rather large, making it difficult to predict the temperature during the process.	The operators knew this and stressed that this makes their work difficult. Real-time temperature information would certainly help the operators to improve the quality of their operations.
Compaction strategy	Operators can fairly accurately predict the passes they will have to make but are less good at predicting the passes their colleagues will make.	It is difficult enough to do their own compaction consistently with so many changing variables, such as weather, layer thickness and temperature. Real-time info about their colleagues work and results could improve quality.
	The influence of the third roller on the final density is unclear. There is hardly any change in density despite the large number of roller passes.	Normally only two rollers are used in such projects rather than three. However, here, the project consortium insisted that three rollers were used to compact the asphalt.
Cores and quality	The correlation between the on-site nuclear measured density and the core density determined in the laboratory is good (within 1%).	The correlation is rather good, but a technician is not always present at the site and sometimes at the wrong times, such the end of the night. This can be improved.
Paver speed	The speed of the paver is higher than in many other projects and above the expected speed.	The increased speed of the paver is not the operators' choice, but stipulated by the consortium due to production pressures.
	Interesting in reasoning is that, if the paver increases speed, the rollers have to work faster, but should be further away from the paver to operate in the same temperature window.	The asphalt team found this reasoning difficult to understand. Training that address various scenarios could possibly help to improve this understanding. This training may be done in a 'asphalt simulator' in a 3D software environment.
Monitoring	The measurements provided the asphalt team with more information and formed a good basis for reflecting on the process.	The data often confirmed the team's gut-feelings. To understand the process better, more measurements should be conducted with various mixtures and different conditions.

Abstract conceptualization

The observations and reflections were distilled into 'abstract concepts' that helped produce plans for action that could be 'actively experimented' with during the second night of study. Plans at the operational, project, organisational and research levels were distinguished:

Operational level (asphalt team)

- The asphalt temperature is important throughout the whole construction process. Therefore, asphalt temperature information should be available in real-time and communicated between the technologists and the operators.
- Currently, asphalt technologists only systematically measure the density during compaction, plus ad-hoc temperatures. These technologists should also systematically measure the temperature and the number of roller passes and communicate these with the operators.
- The three-drum roller (the third roller in the process) is used to create an even surface. This has little influence on the density of the asphalt mixture but, if used at too low an asphalt temperature, could create micro-cracks. Although, it is well-known that the purpose of this finishing roller is to make the surface even rather than increase the density, it remains unclear how these additional roller passes at lower temperatures influence the final mechanical properties other than the density. This requires additional research under better controlled circumstances. Nevertheless, the asphalt team proposed making fewer roller passes with the three-drum roller during the next measurement session.

Project management level (work preparation and coordination)

- The managers realise that asphalt temperature is important for the operators. They also acknowledge that real-time information is essential to improve the process. The managers now consider that buying infrared pistols for every roller operator (a low-cost option) would be worthwhile and they will further try to convince the company to buy high-end equipment to continuously monitor real-time temperatures.
- The managers also recognise that it is difficult for the three-drum roller operator to see where he has been. They acknowledge that GPS-based equipment could help to resolve this problem. However, they argued that this would be a significant investment and required more support from within the company and the consortium. The data

collected could help convince people about the need for new equipment.

Organisational level (company)

- At the organisational level, it was acknowledged that production pressures could lead to communication and quality issues, especially if there is little feedback. For example, while a higher speed may be possible, the operators lack experience of working at higher speeds. Training and scenario-playing could possibly improve this understanding and experience.
- There is hardly any feedback between the laboratory and the technologists, despite both conducting density measurements. Feedback cycles should be included in quality control to compare the on-site nuclear-measured density and the lab-determined density so as to improve instructions and guidance for roller operators.

Research level (Research and Development)

- The data collected should all be geo-referenced. Using geo-referenced data creates a historic record of how the road was constructed, how it behaves during usage, and where early damage might originate.
- Using the PQi framework, density measurements are taken after every roller pass. However, adopting this strategy makes it impossible to understand what happens with the asphalt between operations. Therefore, during the next testing night, measurements should also be taken between the roller passes.
- Providing the individual operators with the graphical data on paper in the feedback sessions worked well. Previous feedback sessions had been held using a beamer but operators seem to be able to focus better when they have all the graphs and information in front of them.

The action plans for the project management and organisational levels have more of a mid- to long-term perspective, whereas most of the operational-level plans could quickly be made operational. During the second night of measurement, some of the short-term action plans were experimented with as discussed in the following section.

Active experimentation

During the second measurement night, questionnaires were again used to establish how the operators planned to carry out their work. The construction process was again monitored and observed. These plans were compared to the predictions made for the first night. Two plans drawn up during the abstract conceptualization phase were experimented with during the second night, namely:

(1) fewer passes with the three-drum roller combined with density measurements between roller passes; and

(2) feedback and greater communication during the process to see if this led to improved predictions and understanding of the process.

Figures 4.3 and 4.4 show the monitored roller passes and density progression for the different type of rollers on night 1 and night 2 respectively. These figures show that the three-drum roller made fewer roller passes during the second measurement night (two compared with seven on the first night); an aspect discussed during the feedback session. Figure 4.4 also shows the density measurements made between the roller passes (the circular markers).

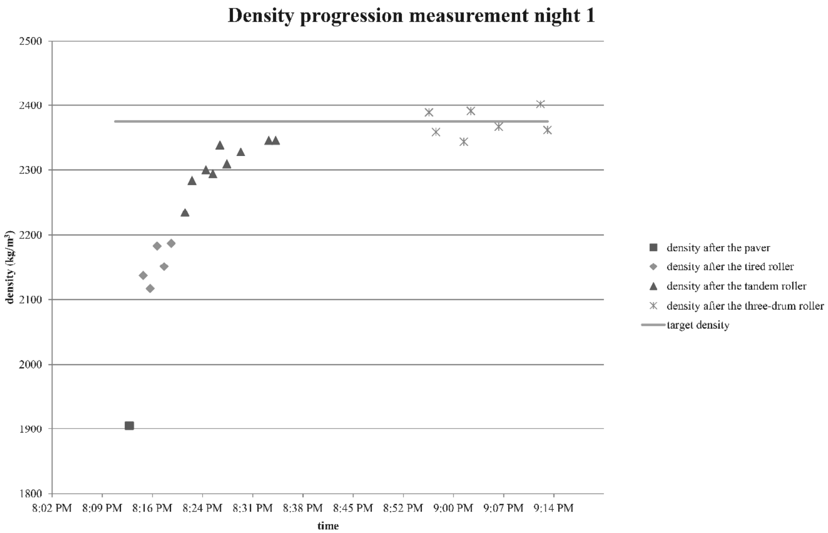

Figure 4.3: Density after each roller pass of the first measurement night

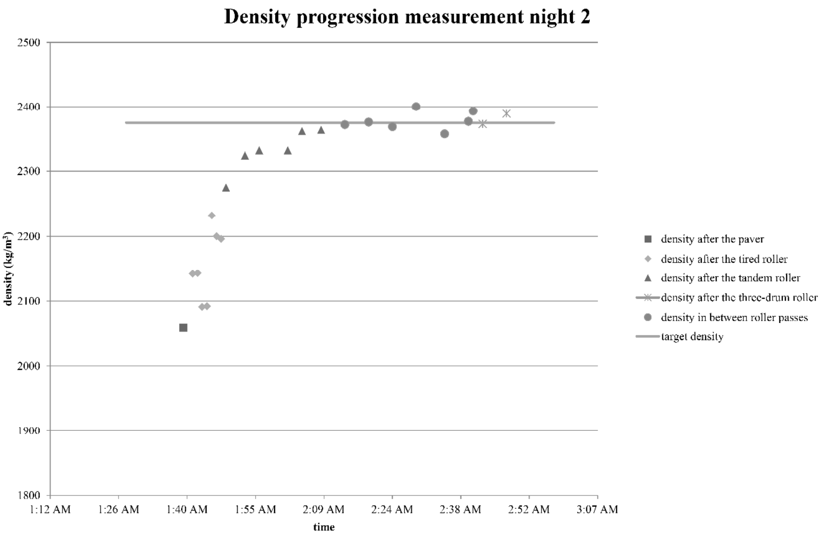

Figure 4.4: Density after each roller pass of the second measurement night

These measurements show that, even between the roller passes, the asphalt mixture is still settling and expanding. As such, measuring between the roller passes does provide valuable knowledge about the asphalt behaviour during compaction. This observation is in line with ter Huerne (2004) and Asphalt-Institute (2007) who also reported the plastic-elastic behaviour of asphalt during compaction.

We do not know which of the compaction strategies is better since no mechanical properties were determined as this was not the focus of the research. However, this example shows that, based on the explicated process, it is possible for operators to change their behaviour and to experiment actively. Based on the operators' experimentation, the new process can then be either adopted or rejected.

The second element of the active experimentation was to test if feedback and greater communication during the process would lead to improved predictions and understanding about the process.

More intensive communication was observed during the second measurement night (mainly as a result of its value being recognised during the organised feedback session, rather than through instructions to operators). Roller operators communicated about temperatures and the number of roller passes undertaken. The technologist also communicated in more detail. In addition to the traditional reporting of density, the number of roller passes and the temperatures were also communicated.

The findings related to the predictions of the operators and the actual constructed processes on the second night are shown in Tables 4.5 and 4.6. Based on these questionnaires and measurements, we conclude that, following the feedback session, the operators had improved their predictions of temperatures, cooling and number of roller passes when compared to the first measurement night. The predictions made by the operators regarding temperature and cooling are now all within the range of those measured during actual construction and also fall within smaller bands. In terms of the number of roller passes and the temperature windows for compaction, most of the predictions corresponded with, or were very close to, the actual construction process.

Table 4.5: Predicted and actual asphalt temperatures and cooling rates of measurement night 2

Parameter	**Prediction range (7 operators)**	**As constructed (4 measurements)**
Cooling until 120 °C (min.)	10-20	12-17
Cooling until 90 °C (min.)	20-40	19-29
Cooling until 60 °C (min.)	40-80	47-56
Difference surface and in-asphalt temperature (°C)	10-20	7-15
Temperature drop truck change (°C)	5-10	5-10
Temperature drop during 3 min. paver stop (°C)	10-20	10-20
Temperature drop during 7 min. paver stop (°C)	20-40	20-30
Temperature drop during 15 min. paver stop (°C)	30-60	30-50

Table 4.6: Expected and actual number of roller passes and temperature windows for compaction of measurement night 2

Parameter	**Prediction operator 1**	**Prediction operator 2**	**Prediction operator 3**	**As constructed (4 measurements)**
Number of roller passes Roller 1	6-7	3-4	5	4-7
Number of roller passes Roller 2	7-8	5-6	6	6-7
Number of roller passes Roller 3	4	2-3	2-3	2-4
Temperature window Roller 1	150-120 °C	150-130 °C	150-130 °C	150-125 °C
Temperature window Roller 2	130-80 °C	130-90 °C	130-90 °C	135-90 °C
Temperature window Roller 3	70-50 °C	70-50 °C	70-50 °C	70-60 °C

4.6 Reflection and discussion

The pragmatic aim of this research was to instigate a change towards explicit method-based learning amongst paving practice. To encourage a change towards method-based learning, the learning model of Kolb (1984) was adopted and ‘monitoring the process (explicating)’ was added as an additional step in this learning cycle. Using various technologies, such as GPS, laser, and infrared, it has become possible to monitor key parameters and operations in the construction process and explicitly map them. This enables a change from implicit to explicit learning and hence could see of breaking down of the barriers to technology adoption.

By explicating the 'as constructed' process, it became possible to have meaningful discussions with the team’s operators in a feedback session, and this helped unravel the intentions and reasoning of the chosen strategies. Transparency in the process and operational choices were created using these technologies and well-designed visuals helped individual operators in sense making about the construction processes and their interdependencies. Some roller operators seem to be alone on the ‘island of their machine’ during the construction process and focused solely on their individual task. However, asphalt paving is a collaborative task (Asphalt-Institute, 2007), and therefore, while individual learning is relevant, learning as a team is as vital. For example, a field engineer may be able to offer improved guidance to operators and the operators can improve the quality of their operations. Both an explicated process and an opportunity to discuss the process during feedback sessions are helpful in this team-learning process. Further research may develop other and better methods for improved collective and collaborative learning.

The introduction of our approach, including the use of new technologies, helped to break through the vicious ‘no understanding – no adoption’ circle, in which the failure to adopt technologies can be attributed to insufficient understanding of operational strategies and insufficient understanding of operational strategies because the technologies are not adopted. The use of these new technologies has become feasible as ICT-technologies have become increasingly available and affordable. However, having data gathered in a structured and systematic way and then synthesised with the needs of the practitioners proved very helpful in creating an improved appreciation of the value of the technologies.

In addition to the framework proposed by Miller (2010) to monitor the on-site processes using various technologies, we introduced questionnaire surveys to determine the process planned by the operators. This helped us in analysing the differences between what they initially planned and what they actually did.

In conclusion, the technologies and the questionnaire surveys were invaluable in enriching the data and opening communication channels to facilitate a transition towards learning based on an explicit construction process. This is a valuable contribution in demonstrating the successful application and use of the learning model of Kolb (1984) in the construction industry.

The demonstration of the action research strategy with alternate steps of technology introduction, explicating operational strategies and undertaking feedback with operators, showed that this strategy is applicable and helpful in the quest for improved learning methods and competencies in practice. Through monitoring the process (explicating) and discussing operational choices with the asphalt team, the tacit knowledge represented in the everyday practice of operators becomes explicit. This research strategy provides an opening for the further development of process tools and a better understanding of the operational strategies. It also demonstrated the importance of combining quantitative process data with qualitative heuristics gleaned from operators. It helped uncover the enormous wealth of tacit knowledge and experience within the operators.

The adopted experiential learning lens applied to the act of learning is not dissimilar to the constructionism view of learning, which could also be explored in further research. The constructivist theories of psychology view learning as the reconstruction rather than the transmission of knowledge (Papert and Harel, 1991). Constructionist learning is motivated by the theory that individual learners construct mental models to understand the world around them, meaning that learning is most effective when people are active in making tangible objects in the real world (learning-by-making). In this learning-by-making view, it would also be relevant to examine how knowledge is assembled through the act of performance and how craftsmanship as described by Sennett (2008) influences performance and learning competencies.

The explicit method-based learning approach adopted may also be applicable to other traditional experience-driven practices in the construction industry. For example, in the sub-surface domain (i.e. laying pipes, cables and sewers), where the process is similarly not explicit, multiple stakeholders influence the process and coordination is becoming increasingly important. Technologies to explicate the location of cables and sewers could help to improve the coordination and scheduling of projects. Further research is also planned to study behavioural changes after a second or further learning cycle. The learning styles defined by Kolb (2005) for various types of people could be useful in studying these learning cycles. Knowing and understanding the different learning styles may shorten the learning curve.

In addition, it has been observed that certain asphalting teams perform better than others under certain circumstances. Further research is planned to understand why certain teams perform better than others. A possible lens to investigate this is the perspective of 'mindful organizing' (Weick *et al.* 1999; Weick and Sutcliffe, 2007) or 'High-Reliability Crews' (Mitropoulos *et al.* 2009). Identifying the rules and work practices of high-performing asphalt crews could help to achieve higher levels of production, quality and safety across the sector. This would be a valuable step towards improved process and quality control.

Finally, if the construction process is explicit, and good and poor operational strategies can be distinguished, then opportunities for training in a virtual construction site arise (Vasenev *et al.* 2012; Vasenev *et al.* 2013). Similar to training tools such as flight-simulators, roller-simulator serious 'games' could be developed that draw directly on actual monitored projects and the discussions involving operators and teams around the operational strategies.

4.7 Conclusions

Various changes are taking place in the construction industry. Integration of maintenance, lifecycle involvement and longer guarantee periods make it increasingly important for contractors to control the construction process and improve quality control. However, current construction processes rely heavily on the skills and on-site experience of operators. This essentially results in individual implicit learning and lengthy learning cycles.

In this research, the experiential learning theory of Kolb (1984) was introduced to usher in a change towards explicit method-based learning. An additional step, monitoring on-site construction processes (explicating), was added to the learning cycle as part of moving from implicit to explicit learning and its merits have been demonstrated in the asphalt construction industry. On-site processes were monitored with new technologies to build a data-rich understanding of the process. Key processes and factors were explicated using D-GPS, a laser linescanner and infrared cameras. Questionnaire surveys, interviews and feedback sessions were used for sense making and learning about the construction processes for both individual operators and teams.

The introduction of Kolb's learning cycle fused with on-site data collection was critical in explicating the tacit knowledge and implicit processes. The adopted learning framework was shown to be relevant, applicable and useful in highway construction. The research demonstrated the value of an engaged research approach, as well as the potential for introducing new sensor and ICT technologies in current traditional working practices.

A rigorous, structured and systematic data collection process was essential in using these technologies and in the engaged research approach. The explicit method-based learning framework led to improved awareness of the quality and value of communications with and within the asphalt team. It responded to the lack of explicit learning and reflection in the construction industry. It is a method that can develop the learning and reflective competencies of both individuals and teams. Finally, the research approach and the method-based learning framework offer opportunities for making experience-driven practices more professional in the construction industry.

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Appendix 1: Questionnaire survey for all the operators and the field engineers (translated from Dutch)

	Questions for all the operators and the field engineers
0	Project Date Asphalt mixture Position Years of experience
1	How long do you expect it will take the in-asphalt temperature to cool down until 120 °C (in minutes)?
2	How long do you expect it will take the in-asphalt temperature to cool down until 90 °C (in minutes)?
3	How long do you expect it will take the in-asphalt temperature to cool down until 60 °C (in minutes)?
4	What is the optimal paving speed according to you (in meters per minute)?
5	What is the average difference between the surface temperature and the in-asphalt temperature during the construction process according to you?
6	How much will the surface temperature drop during a truck change (in °C)?
7	How much will the surface temperature drop during a paver stop of 3 minutes (in °C)?
8	How much will the surface temperature drop during a paver stop of 7 minutes (in °C)?
9	How much will the surface temperature drop during a paver stop of 15 minutes (in °C)?
10	What is the target density and what are the most important points of interest for this specific asphalt mixture?

Appendix 2: Questionnaire survey for the roller operators (translated from Dutch)

Questions for all the roller operators	
0	Project Date Asphalt mixture Which roller operator Years of experience
1	How many roller passes do you expect the different rollers will make (in number): Pneumatic tired roller (roller 1) Tandem roller (roller 2) Three-drum roller (roller 3)
2	In which temperature windows do you expect these roller passes will be conducted (between .. °C and .. °C): Pneumatic tired roller (roller 1) Tandem roller (roller 2) Three-drum roller (roller 3)
3	What density progression do you expect the different rollers will make (in percentage degree of compaction): Pneumatic tired roller (roller 1) Tandem roller (roller 2) Three-drum roller (roller 3)
4	What is the compaction distance of the different rollers behind the paver (between .. meter and .. meter): Pneumatic tired roller (roller 1) Tandem roller (roller 2) Three-drum roller (roller 3)

Chapter 5

Aligning laboratory and field compaction practices - the influence of compaction temperature on mechanical properties[4]

The approach used to identify a compaction temperature in the laboratory, based on binder viscosity, provides a single compaction temperature whereas, on-site, a roller operates within a temperature window. The effect on the density and mechanical properties of rolling during a temperature window remains unclear. Consequently, asphalt concrete binder mixtures were compacted in different temperature windows in the laboratory using a Roller Sector Compactor, and the observed phenomena were then compared with field study observations. The results show that while similar densities can be achieved in a broad range of temperature windows, other mechanical properties such as fracture energy may decline by up to 30% if compacted outside the optimum temperature window. These results indicate that a compaction temperature window should form part of mix design and quality control. The paper proposes specifying a compaction window based on temperatures and the resulting mechanical properties, rather than a single compaction temperature.

Keywords: Asphalt, compaction, cracking resistance, density, fracture energy, temperature.

[4] This chapter has been submitted after a revision and is under review at the *International Journal of Pavement Engineering* as: Bijleveld, F.R., Miller, S.R., de Bondt, A.H., Dorée, A.G. Aligning laboratory and field compaction practices - the influence of compaction temperature on mechanical properties.

5.1 Introduction

Asphalt paving companies require deeper insights into the relationships between compaction operations undertaken on a construction site and the resulting mechanical properties of the constructed asphalt layer (Kassem *et al.* 2008, Leiva *et al.* 2008, Bijleveld 2010). Although the impact and importance of the on-site compaction process on the final quality of the asphalt pavement is recognised, both in scientific journals and in practice, this field is still in its academic infancy. Miller (2010) concluded that the current literature mainly concerned asphalt characteristics from a material perspective, and that only limited attention had been given to systematically mapping and analysing the effects of the construction process on the quality of the asphalt layer. As such, little is known about how operations on-site impact on asphalt quality.

In current practice, rolling strategies are generally determined on a project-by-project basis, and to an extent by trial and error, using the experience of the operators (ter Huerne 2004, Bahia *et al.* 2006, Schmitt *et al.* 2009, Miller 2010). However, the chosen strategies can quickly become outdated if the variables change or new asphalt mixtures are introduced. This makes it difficult to determine the relationship between on-site compaction operations and the resulting mechanical properties. In addressing one aspect, this paper focuses on the influence of asphalt temperature during the compaction process on the resulting mechanical properties.

Several technologies have been developed to monitor asphalt temperatures during lay-down and compaction using thermal cameras, laser-linescanners and thermocouples (Stroup-Gardiner *et al.* 2000, Ulmgren 2000, Lavoie 2007, Miller 2010). Although some of the technologies have progressed into industrial applications, it seems that few have been accepted widely by the industry and used on-site. This is due to insufficient understanding of the process and a lack of evidence of added value. Appreciating the influence of compaction temperatures on the final mechanical properties could enhance this technology adoption process.

A basic assumption in the literature is that the compaction temperature is a key determinant of pavement quality (NAPA 1996, Asphalt-Institute 2007). The traditional laboratory approach to selecting a compaction temperature is to identify the binder viscosity and then checking this against corresponding binder viscosity - compaction temperature charts. The asphalt mixture is then compacted at this temperature using a standard procedure, and the resulting density and mechanical properties then measured. This laboratory simulation is dissimilar from the compaction process in practice, where successive roller passes are undertaken, while the asphalt is cooling, until the target density is reached. Non-destructive density measurements and operator observations are used to decide when the target density has been reached, and that no further roller passes are required. Thus, while the existing laboratory approach uses the binder viscosity to determine a single optimum compaction temperature, the on-site roller operator has to determine a temperature window in which to compact as the asphalt cools during construction. As such, it is hard to give operators appropriate guidelines about the temperature window in which they should compact.

The different approaches to determining compaction temperature(s) have consequences for the resulting density and mechanical properties, the significance of which remain unclear. This paper specifically addresses the influence on the density and mechanical properties of compacting at various asphalt temperatures, and suggests a methodology for better aligning laboratory and field compaction in terms of asphalt temperatures. The various approaches and the focus of this study are shown in Figure 5.1.

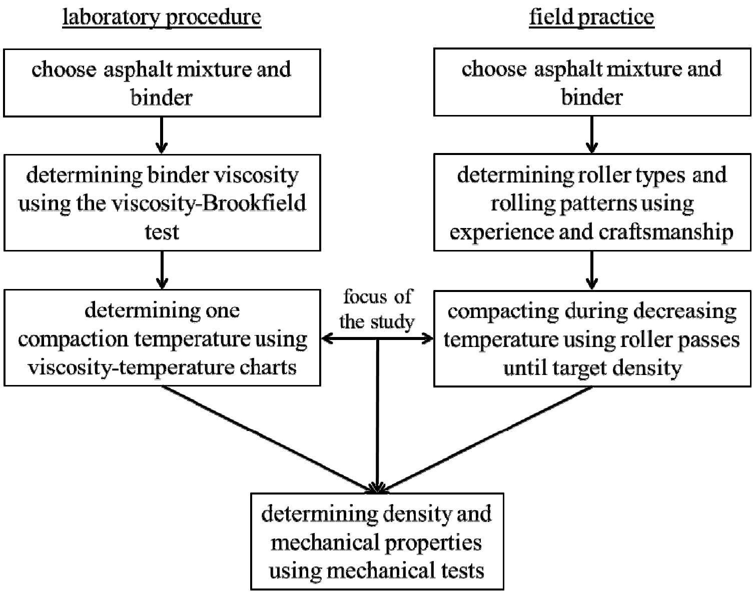

Figure 5.1: Laboratory procedure and field practice for determining density and mechanical properties

Previously, Timm *et al.* (2001) argued that there is an ideal temperature window within which to compact an asphalt mixture that will result in a high probability that the desired mechanical characteristics will be achieved. Depending on the cooling rate of the asphalt mixture, this means that there is also an optimum time window in which to compact. If the asphalt mixture is compacted outside these windows, the asphalt mixture will be compacted at too low or at too high temperatures. These conditions are illustrated in Figure 5.2 that schematically shows the changing temperature of the mixture as a function of time. For different mixtures and under different conditions, the ideal compaction window will shift along the timescale.

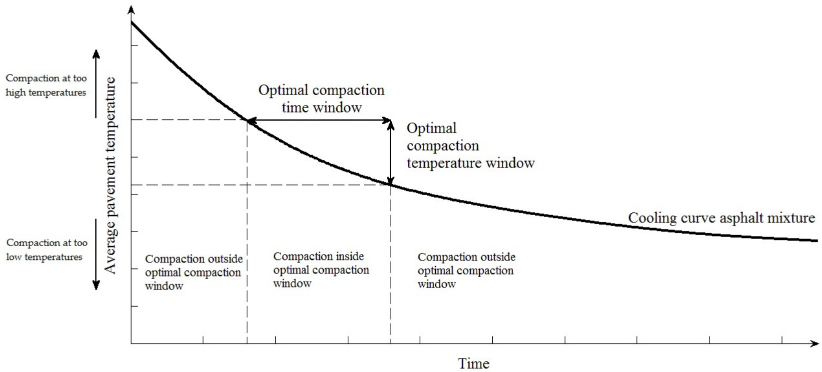

Figure 5.2: Cooling of the asphalt mixture over time and the optimal compaction window (after Timm et al. 2001)

This study focuses on the consequences for the mechanical properties of compacting an asphalt mixture outside its optimum temperature window. The objectives of this study are: (1) to increase understanding of how compaction temperature influences the mechanical properties of an asphalt layer; and (2) to develop improved laboratory compaction procedures that more closely simulate field compaction as a step towards better informing and guiding roller operators.

A two-fold approach is used to achieve these objectives. First, experiments were conducted in the laboratory. Second, the compaction process was monitored on a construction site to determine whether the phenomena observed in the laboratory also occur in practice. Note that the goal of the field study was not to relate laboratory and field results but to determine whether the phenomena observed in the laboratory also occur in practice. In investigating the effects of compaction temperature, an AC16 binder mixture was compacted at various temperatures and the resulting densities and mechanical properties then measured.

5.2 Background

The Asphalt-Institute (2007) defines compaction as the process of compressing a given volume of asphalt into a smaller volume. The result is an asphalt mixture with a certain density. Achieving a specific density optimises the mixture's desired characteristics including its strength, durability and resistance to deformation 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, the asphalt mixture can deform under everyday loads leading to rutting and cracking.

Asphalt compaction is achieved through loading the mixture, in practice through successive roller passes. A material that is loaded tends to deform, and this deformation is resisted by counter pressures and internal cohesion (van Stek and Linden 1992). To increase density, the aggregate has to be pushed closer together and this can only be achieved if excessive air is driven out. In loading a relatively uncompacted material, the particle arrangement will change, the volume will reduce and the density increase. In this process, the fluid in the asphalt mixture lubricates the contact areas between the particles and eases their sliding against each other (ter Huerne 2004). During this process, the angularity of the fine aggregate critically influences the mixture properties (Bahia and Stakston 2003). In essence, the task of roller compactors is to reduce the void content to the desired level and achieve an even surface (Asphalt-Institute 2007).

The roller compaction process can be divided into three phases (ter Huerne 2004, Asphalt-Institute 2007, Bijleveld 2010, Miller 2010): (1) breakdown rolling, where particles are re-arranged and air expelled; (2) intermediate rolling, where the asphalt mixture behaves differently due to its increasing stiffness and the viscoelastic behaviour of the mixture, and sometimes the mixture begins to act tender (Faheem *et al.* 2007); and (3) finish rolling, where the mixture is compressed further until the target density is achieved. From an operational perspective, these phases can be characterised by the types of roller used and the timing and temperature of the compaction process.

Both researchers and practitioners accept that the temperature of the asphalt mixture during the compaction process is critical for the pavement quality (Chadbourn *et al.* 1998, Timm *et al.* 2001, Willoughby 2003, Delgadillo and Bahia 2008, Masad *et al.* 2009, Schmitt *et al.* 2009). Some suggest that compaction should be completed within a specific temperature range, such as between 90 and 100°C (Floss 2001), others specify either a maximum temperature, generally around 130°C, (Commuri and Zaman 2008) or a minimum temperature of say between 70 and 80°C (Alexander and Hughes 1989, van Dee 1999). If the compaction temperature is too low, the bitumen is unable to lubricate the mixture, resulting in an open surface that is vulnerable to ravelling. Conversely, if the mixture is too hot, the binder can be too fluid and the resulting aggregate structure weak because the roller loads displace the material rather than compact it, increasing the likelihood of cracking (Kari 1967, VBW-Asfalt 2000).

In response to these concerns, researchers have developed tools to predict the cooling rate of an asphalt mixture and with that take cognisance of asphalt temperatures during compaction. Chadbourn *et al.* (1998) and Timm *et al.* (2001) developed Windows-based computer programs, PaveCool and CalCool, to predict the asphalt cooling process. The outputs include the theoretical cooling rate for a specific mix and recommended starting and stopping times for compaction after laying down the material. Since then, researchers have developed practical guides to estimate compaction windows based on local conditions (Wise and Lorio 2004, Mieczkowski 2007, Park and Kim 2013). Although these models provide information about asphalt temperatures throughout the duration of the process, they do not provide operators with guidance regarding temperature windows.

The optimum compaction temperature has traditionally been determined by plotting a log-log graph of bitumen viscosity against temperature, with the ideal compaction temperature coinciding with a viscosity of 0.17 Pascal-second (Corlew *et al.* 1968). Following this, Jordan and Thomas (1976), Daines (1985) and Luoma *et al.* (1995) developed tools to predict an optimum temperature window in which to compact, i.e. the starting and finishing temperatures between which to compact. The associated levels of viscosity were determined based on practical factors and experience, and this approach seemed to work well. However, Decker (2006) and Bahia *et al.* (2006) argued that determining compaction temperatures through viscosity-temperature plots was no longer appropriate since these traditional approaches sometimes indicate unreasonably high temperatures. Practical experience over the last twenty years in the Netherlands using modified bitumen confirms this (Sullivan and de Bondt 2009).

As such, there is a need for a greater understanding of the relationship between the asphalt temperature during compaction and the resulting mechanical properties. It is attractive to evaluate effects in a laboratory setting, where variables can be controlled and isolated. Various studies have indicated that, of the laboratory options, roller compactors most closely reflect field compaction (Renken 2002, de Visscher *et al.* 2006, Muniandy *et al.* 2007, Bijleveld 2010, Mollenhauer and Wistuba 2013, Airey and Collop 2014, Plati *et al.* 2014, Wistuba 2014). The advantages of roller compactors are that they can be pre-heated and can produce relatively large asphalt slabs, typically 500 mm by 500 mm or 700 mm by 500 mm. As such, several test specimens can be created simultaneously in a single slab.

Muniandy *et al.* (2007) conducted experiments with Stone Mastic Asphalt slabs using a roller compactor. A compaction procedure was developed that involved 75 passes with 8 kg/cm2 of pressure to achieve their targeted air voids of 4%. This pressure is not dissimilar to that exerted by rollers in the field. However, the number of passes they used is much higher than typical field compaction and, further, the latter only aims to achieve a target density. Mollenhauer (2009) developed a two-step standardised laboratory compaction procedure using a roller compactor. First, a position-controlled compaction procedure, simulating the paver, is applied to achieve a certain thickness and density. This is followed by a force-controlled compaction procedure to simulate compaction using rollers. Based on the procedures developed by Mollenhauer (2009), research into more accurately simulating field compaction in the laboratory is currently being undertaken by Paffrath *et al.* (2012). However, these procedures do not explicitly take compaction temperatures into account, nor involve a realistic number of roller passes that reflects field practice. More importantly, the existing laboratory compaction procedures offer no clear guidelines for operators.

Overall, asphalt temperatures during compaction are widely acknowledged as crucial for asphalt quality. Considerable research effort has been put into predicting asphalt temperatures throughout the process, but less effort has gone into using asphalt temperatures to provide better guidelines for roller operators. In response, this research focuses on analysing the effect that compacting at various temperatures has on the asphalt's mechanical properties, and on aligning laboratory and field compaction processes to provide operators with guidelines on the optimum compaction window.

5.3 Materials

The empirical research, incorporating both laboratory experiments and a field study, was conducted using an AC16 Base mixture with a 16 mm maximum size coarse aggregate, 4.5% bitumen by mass (pen 40/60) and without recycled asphalt. This mixture was chosen since it is frequently used under less than ideal circumstances in the Netherlands. The reason for choosing a mixture without recycled asphalt was to increase the homogeneity of the mixture. Table 5.1 lists the materials in the asphalt mixture and Table 5.2 shows the aggregate gradation. The target density of the mixture is 2360 kg/m^3. All the materials were ordered as a single batch to minimise the risk of excessive variability in the raw materials.

Samples were taken to determine the penetration grade and the Ring & Ball temperature of the bitumen, and the results showed little variability. The penetration grades of the tested samples were in the range of 50.0-55.0 mm and the softening points between 50.6 and 51.3 °C.

Table 5.1: Raw material composition

Material	Percentage (by total mass)
Bestone 4/8	22.1
Granite 8/16	35.4
River sand	28.9
Sea sand	7.3
Wigras 40K (filler)	6.3
Bitumen 40/60	4.5

Table 5.2: Aggregate gradation

Sieve size (mm)	Percentage passing sieve
16.0 mm	96.7
11.2 mm	75.6
8.0 mm	65.0
5.6 mm	51.1
4.0 mm	45.4
2.0 mm	43.0
500 µm	35.6
180 µm	15.2
63 µm	6.0

5.4 Experimental design and setup

Laboratory experiments were conducted, and then followed up by a field study, to determine the effect of asphalt temperature during compaction on the resulting density and mechanical properties. Compaction temperatures were varied and the resulting density and mechanical properties analysed. The subsections below describe the design of the experiments for both laboratory and field.

Laboratory experiments

All the test materials were produced in the laboratory. Each slab required 47.2 kg of material based on the target density of 2360 kg/m^3 and the targeted slab dimensions of 500 mm by 500 mm and 80 mm thick. The materials were mixed at 180 °C for 3 minutes using an 80 kg mixer. The roller compactor shown in Figure 5.3 was used to compact the asphalt mixtures according to European Standard EN 12697-33.

Figure 5.3: Rolling compactor WSV-2008-KW50/500 and the resulting 500 mm² slab

In compacting the asphalt mixture to produce slabs, two alternative compaction procedures were applied using a Roller Sector Compactor:

- Position-controlled compaction: compacting until the desired thickness is achieved (in our case 80 mm);
- Force-controlled compaction: compacting using a specified force (in our case 15 one-directional passes applying 0.30 kN/cm).

In total, 18 slabs were produced, 12 using the position-controlled procedure and 6 applying the force-controlled procedure. The settings for the Roller Sector Compactor are shown in Tables 5.3 and 5.4 for the position-controlled and the force-controlled compaction procedures respectively. These settings are based on the compaction procedures developed by Mollenhauer (2009). The literature suggests that it is important to compact the asphalt mixture in distinct phases in order to achieve a certain particle orientation and to expel the trapped air. The asphalt slabs produced using the height-controlled procedure were compacted in two phases, first to a height of 84 mm using a relatively low force and, in a second phase, to 80 mm using a larger force. The force-controlled compaction procedure was divided into a pre-compaction phase, a smoothing phase (to simulate screed levelling) and finally the main compaction phase.

Table 5.3: Settings for the position-controlled compaction procedure

Required settings for position-controlled procedure	**Chosen setting**
Starting load (as a line-load)	0.04 kN/cm
Moving speed of the mould	240 mm/s
Pause of the mould at the turning point	0.2 s
Loading speed / height decrease of the segmented slab	1st phase: 1.60 mm per roller pas 2nd phase: 0.30 mm per roller pass
Maximum allowed load	1.00 kN/cm
Final height of the slab	1st phase: 84 mm 2nd phase: 80 mm
Number of passes after final height is reached	15 passes (one directional)
Temperature of the mould and segment	80 °C

Table 5.4: Settings for the force-controlled compaction procedure

Required settings for force-controlled procedure		**Chosen setting**
Starting load (as a line-load)		0.04 kN/cm
Moving speed of the mould		240 mm/s
Pause of the mould at the turning point		0.2 s
Pre-compaction	Loading speed of the segmented slab	0.1 mm per one-directional pass
	Pre-compaction starting load (line-load)	0.1 kN/cm
	Number of passes applying pre-load	2 one-directional passes
	Unloading speed of the segmented slab	0.1 mm per one-directional pass
Smoothing	Load during smoothing-phase (line-load)	0.02 kN/cm
	Number of roller passes during the smoothing-phase	15 one-directional passes
Main compaction	Main compaction load (as a line-load)	0.30 kN/cm
	Number of passes to reach the main-compaction load	15 one-directional passes
	Number of passes to unload	15 one-directional passes

The slabs were compacted at mixture temperatures varying from 80 °C to 170 °C and afterwards placed in one of four categories: slabs compacted in the temperature ranges of 80-100 °C, 100-135 °C, 135-155 °C and 155-170 °C. The asphalt temperature was measured using three thermocouples inserted in the side of the slab at different heights.

During the compaction process, the number of roller passes and the force per roller pass are automatically recorded and, using those parameters, the total compaction energy can be derived from Equation (1).

$$E_{tot} = \sum_{i=1}^{n}(P \cdot t) \tag{1}$$

where:

E_{tot} = Compaction energy (Nm)

n = number of the roller pass

P = force per roller pass (N)

t = decrease in layer thickness per roller pass (m)

Nine cores, each 100 mm in diameter, were removed from each of the 500 mm square slabs and their densities and certain mechanical properties measured. The densities of the cores were determined according to EN-12697-9. An indirect tensile strength (ITS) test was carried out on six cores, providing an indication of the resistance to cracking (NAPA 1996), and a cyclic triaxial compression (CC) test on the other three, providing an indication of the resistance to rutting (Erkens 2002). These tests were chosen as they determine parameters that are relevant to the typical damage seen with this kind of mixture (with base and binder layers).

The ITS tests were conducted according to EN-12697-23. The specimens were conditioned at 5 °C for four hours so that the results could provide information about thermal cracking (NAPA 1996). The indirect tensile strength (ITS), the work of fracture (W_f) and the fracture energy (G_f) are derived from this test. The fracture energy was calculated according to the RILEM TC 50-FMC specification (1985). The ITS-data were computed according to the EN Standard, and the work of fracture (W_f) was computed as the area under the load-displacement curve (Equation 2) and the fracture energy (G_f) was obtained by dividing the work of fracture by the ligament area (Equation 3), a procedure in line with Wen (2013).

$$W_f = \int_{0}^{\alpha} P \cdot du \tag{2}$$

where:

W_f = Work of fracture (N.mm)

P = load (kN)

u = displacement (mm)

$$G_f = \frac{W_f}{D \cdot H} \quad (3)$$

where:

G_f = fracture energy ((N.mm)/mm^2)

W_f = work of fracture (N.mm)

D = diameter of the specimen (mm)

H = height of the specimen (mm)

The CC tests were conducted according to the national standard established in the Netherlands (test 62) loaded with a periodical loading pulse using the Nottingham Asphalt Tester (NAT). The confining pressure (0.05 MPa) was applied by putting the specimen in a rubber socket and applying a vacuum to the specimen. To reduce friction, two layers of plastic with silicon oil between them were placed on both the top and the bottom of the asphalt specimens (Erkens 2002). The specimens were conditioned at 40 °C for four hours and then 10,000 400 ms per second pulses of 0.45 MPa were applied. The analysis revolves around comparing the cumulative plastic strains.

Field study

The phenomena observed in the laboratory were then checked against those obtained in a practical setting during a field study. The field study took place in the town of Dirkshorn in the north of the Netherlands. The surfacing of a 1600 m^2 area surrounding an agricultural warehouse formed the setting for the field study. The underlying layer consisted of a well-compacted 350 mm of recycled concrete granulate. The asphalt was produced at an asphalt plant approximately 8 km from the construction site.

Bulk compaction of the asphalt layer was undertaken using a 10 tonne combination tandem roller with all the joints further compacted using a small 2.5 tonne tandem roller. The combination roller had four pneumatic tyres on the front and a steel drum roller at the rear. The design of this pneumatic-tyred roller (PTR) provides a kneading action through the tyres. PTRs can be used in the breakdown or intermediate compaction phases (Asphalt-Institute 2007). These rollers usually cause deformation that are removed in the final, finish rolling, stage. However, with a combination roller, any such deformations are removed immediately by the steel drum mounted at the rear.

During the field study, the following measurements were taken:

- The movements of the paver and rollers were monitored using high-accuracy D-GPS equipment in order to determine the stops of the paver and the number of roller passes;
- The surface temperature behind the screed of the paver was continuously measured to determine the initial lay-down temperature using a laser linescanner;
- The in-asphalt and the surface temperatures were measured using thermocouples and an infrared camera at static points alongside the paving lanes to determine the cooling curve of the asphalt mixture throughout the process. At these points, the density was measured after every roller pass using a nuclear gauge.

Three lanes, each 86 metres long, were surfaced alongside each other with an 80 mm base layer (AC 16 Base 40/60 pen without RAP). Given the aim of studying the influence of compaction temperature on density and mechanical properties, the compaction process had, to some extent, to be guided. Here, the compaction temperatures and time frames were specified, with roller operators instructed when to start and when to finish compacting. The compaction of Lane 1 took place while the asphalt was within a temperature range of 150 to 90 °C. Lane 2's compaction took place between 130 and 80 °C, and the compaction of Lane 3 took place between 100 and 50 °C. Immediately after construction, 14 cores were extracted from each lane to evaluate their properties. As with the laboratory specimens, the cores were trimmed to a diameter of 100 mm and height of 60 mm. Next, in the laboratory, the densities of the specimens were determined, and ITS tests conducted to determine their resistance to cracking.

Figure 5.4 summarises the laboratory and field tests undertaken.

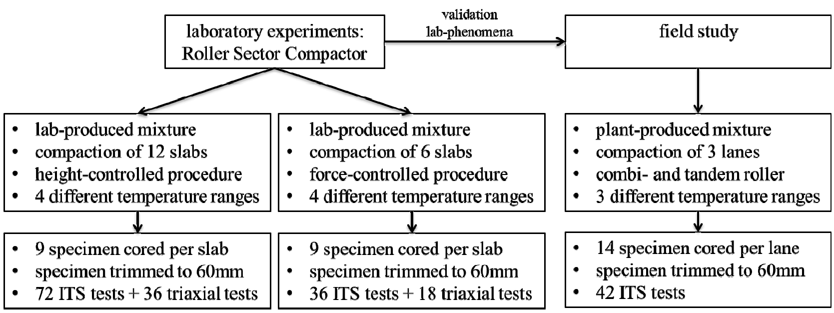

Figure 5.4: Laboratory and field study overview

5.5 Laboratory experiments and field study results

The effects of the various compaction temperatures on the compaction effort and energy, the viscoelastic mix behaviour, the resulting density and the mechanical properties are described for both the laboratory experiments and the field study. The temperature variability during the compaction processes is also addressed.

Note that no direct comparison is made between the results of the laboratory experiments and those stemming from the field study for two reasons. First, because the field-study mixture appeared coarser than the mixture used in the laboratory and, second, because it rained heavily the night before the field study and the granular base layer was somewhat saturated. This situation means that the validity of comparing field study and laboratory results would be questionable. Here, we would emphasise that the purpose of the field study was not to accurately determine a relationship between laboratory and field results but rather to study whether the phenomena observed in the laboratory took place in practice.

Results of laboratory experiments

Asphalt temperature variability during compaction

In the laboratory, three thermocouples were used to measure the bottom temperature, the in-asphalt temperature and the surface temperature of each slab. Afterwards, the temperature variation within the slab was analysed. The maximum temperature difference measured within a single slab was 14 °C. The average temperature spread within a slab was 9 °C, with the standard deviation of the single slab measurements varying between 2 and 8 °C, and averaging 5 °C.

In the position-controlled compaction process, the average number of roller passes per compaction phase was 28 (one-directional passes of approximately 2.3 sec per pass). As such, each compaction phase in the laboratory took approximately one minute. During this compaction process, the asphalt mixture cooled on average by 2 °C.

Effect of compaction temperature on compaction energy

Figure 5.5 illustrates the compaction energy (in Nm) for the various compaction temperatures used with the position-controlled compaction procedure. It can be seen that, as the compaction temperature decreases, the required compaction force and compaction energy increase. The most obvious explanation for this is that cooler bitumen is more viscous and, as a consequence, more force is necessary to bring the particles closer together.

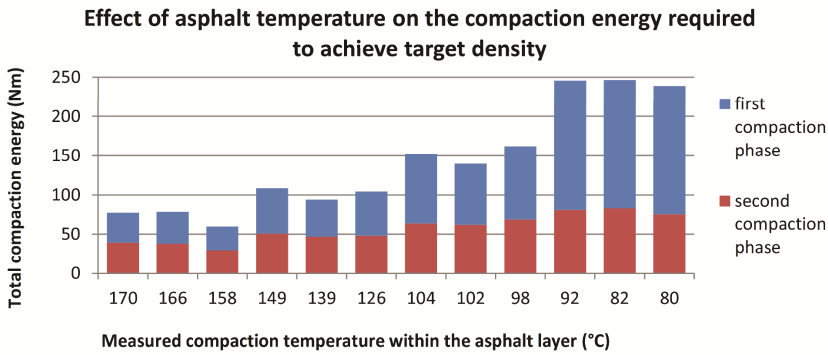

Figure 5.5: Compaction energy for different laboratory compaction temperatures

At low temperatures, a large force and considerable energy were required to achieve the target density. Using the Roller Sector Compactor, forces above 30 kN could be achieved. It should be noted that such forces are currently not a realistic option in practice, and that this situation seems unlikely to change given current roller compaction technology. As shown in Figure 5.6, where the maximum load is plotted for different compaction temperatures, forces of such a magnitude are required if compaction starts below 110 °C. At compaction temperatures above 150 °C, the required force has dropped to such an extent that, in a practical situation, it would be necessary to use a light roller to avoid the bitumen being squeezed out of the skeleton and coming to the surface.

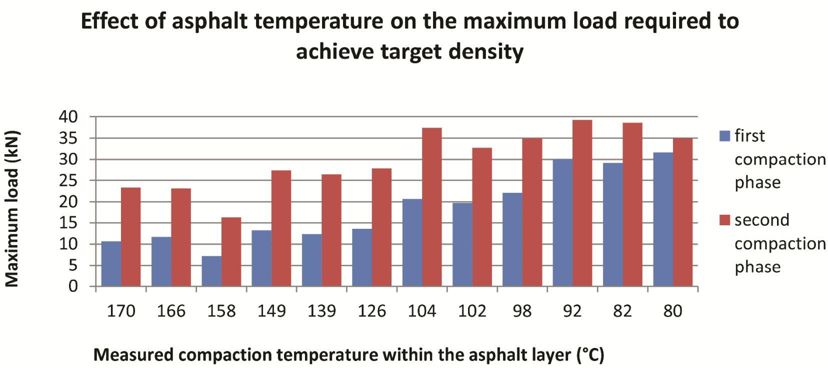

Figure 5.6: Peak load for different laboratory compaction temperatures

It is generally accepted that an asphalt mixture exhibits both viscous and elastic characteristics (Figge 1986, van Stek and Linden 1992, VBW-Asfalt

2000, ter Huerne 2004, Asphalt-Institute 2007). This was also apparent in the laboratory tests. Although the samples in the laboratory were compacted to a thickness of 80 mm, the measured heights, after cooling and conditioning, were found to vary between 81.5 and 82.5 mm.

The thicknesses of the laboratory samples were again measured after 110 hours, and had not changed from those measured after 23 hours. From this, the conclusion was drawn that any viscoelastic behaviour is complete within 23 hours of compaction. An analysis of how the layer thickness varies with compaction temperature shows that viscoelastic behaviour is greater at higher compaction temperatures. However, the measurements were not sufficiently precise to determine an exact relationship.

Effect of compaction temperature on density and mechanical properties

The densities of the specimens at the applied compaction temperatures are shown in Table 5.5. The results show that the target density (2360 kg/m^3) could be achieved at all compaction temperatures, even down to 80 °C. The densities within a single slab, based on nine sample cores, were found to be reasonably homogenous. The standard deviation of density within one slab varied between 4 and 12 kg/m^3.

The test results also show that the position-controlled compaction procedure produces samples with higher densities than the force-controlled compaction procedure. This difference can be attributed to the maximum allowable loads applied to the asphalt mixture, which was higher with the position-controlled compaction procedure (1.00 kN/cm) than during force-controlled compaction (0.30 kN/cm).

Table 5.5: Variability between field and (laboratory specimens)

Experiment	**Compaction temperature (°C)**	**Density (kg/m^3)**
position-controlled	170	2363
	166	2365
	158	2381
	149	2367
	139	2365
	126	2360
	104	2386
	102	2389
	98	2387
	92	2390
	82	2367
	80	2368
Summary position-controlled	Density range (12 slabs)	2360-2390
	Average density (12 slabs)	2374
	SD density per slab (9 cores)	4-12

Experiment	Compaction temperature (°C)	Density (kg/m^3)
Force-controlled	169	2351
	166	2349
	140	2372
	138	2370
	89	2340
	88	2357
Summary force-controlled	Density range (6 slabs)	2340-2372
	Average density (6 slabs)	2356
	SD density per slab (9 cores)	8-11

** SD corresponds to the standard deviation*

From the mechanical tests, it can be concluded that, although the target density can be achieved at all the temperatures tested, the measured mechanical properties vary with the compaction temperature. The sensitivity is illustrated in Figure 5.7 where the fracture energy is plotted against compaction temperature for the position-controlled slabs. The test results for the force-controlled compacted samples are not shown but produced a similar trend. From the test results, it is clear that the samples compacted in the 135-155 °C temperature range have a significantly higher fracture energy than samples compacted at either higher or lower temperatures. The fracture energy of the samples compacted in the 135-155 °C range is approximately 1.0-2.0 $N.mm/mm^2$ (or 20-30%) higher than the cores compacted at other temperatures. The fracture energy and the small differences in density were analysed and the differences in fracture energy could not be explained by the small differences in density between the slabs. Thus, it is apparent that while it is possible to achieve the target density while starting the compaction process at temperatures outside the 135-155 °C temperature range, this might well reduce the potential fracture energy by as much as 30%.

The results of the triaxial cyclic compression tests showed a relatively high standard deviation in cumulative axial strain within a single slab compared to the differences between slabs. The values for the cumulative axial strain were between 3.6% and 4.4% of the permanent deformation, while the standard deviation within one slab was up to 1.1% of the permanent deformation. This made it impossible to discern a clear relationship between compaction temperature and resistance to rutting. This issue, of a large variation in permanent deformation values, was similarly raised by de Visscher *et al.* (2006). A useful aim for future research would be to improve the sample preparation and test procedures to minimise experimental variation; a goal achieved by Muraya (2007) for gyratory compaction.

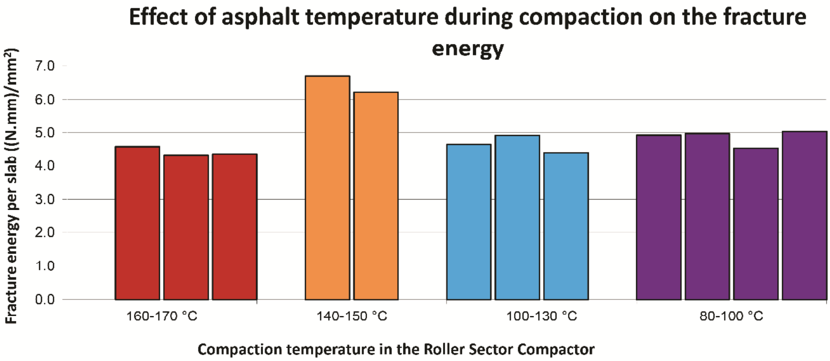

Figure 5.7: Fracture energy for different laboratory compaction temperature ranges

Results from field study

<u>Asphalt temperature variability during compaction</u>

During the field study, the asphalt temperature was monitored at various points throughout the entire construction process: at the asphalt plant, at the asphalt truck as the mix was released into the paver hopper, and behind the paver screed. The average temperature at the plant was determined to be 161 °C. The construction site was 8 km from the plant, with typical journey times between 10 and 15 minutes. The asphalt temperature, as the mixture was released into the hopper, was measured with an infrared pistol. The average temperature for Lane 1 was 165 °C, for Lane 2 it was 157 °C and for Lane 3 it was 156 °C.

The analysis of the GPS measurements showed that the paver had operated at a consistent speed of approximately 4.5 metres per minute across all lanes. However, six paver stops were observed for asphalt truck changeovers and an analysis of the laser-linescanner results showed that the surface temperature had cooled to approximately 135 °C during the stops. Rainfall also caused the surface temperature to drop to approximately 135 °C at some locations, while the in-asphalt temperature remained at approximately 165 °C. No cores were extracted at locations where excessive temperature differences were observed.

Further analysis of the GPS measurements showed that the operators of both rollers had approached compaction in a consistent manner. The operator of the combination roller concentrated on bulk compaction, and the small tandem roller was used on all joints and in small areas. Despite the apparent consistency in roller patterns, it appeared that a few metres at each end of the lanes received fewer roller passes than the rest of the lanes. Given this situation, cores were not extracted from the ends of the lanes.

Effect of compaction temperature on density progression

Field measurements were taken using a nuclear density gauge to assess density progression during the compaction process. The density progression and the cooling of the asphalt mixture over time for Location 1 within Lane 1 are shown in Figure 5.8. The results show that the density first increases, then slightly decreases and, once a certain temperature is reached, again increases on successive roller passes. This is probably due to the viscoelastic behaviour of the mixture, where the material springs back and the density reduces. The plotted results are typical of all the three lanes that were monitored. The density progression during compaction, which is not dissimilar to that in the laboratory experiments, shows that it is still possible to achieve the target density at lower asphalt temperatures although compaction becomes progressively more difficult.

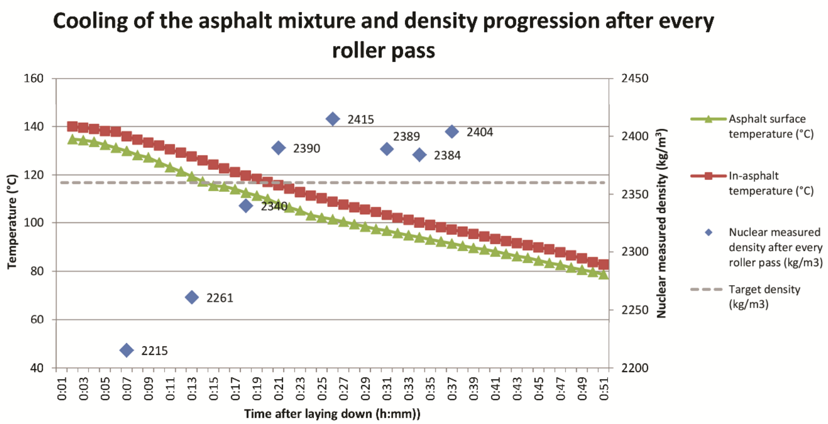

Figure 5.8: Sample cooling curves and density progression after successive roller passes in the field study

Effect of compaction temperature on density and mechanical properties

The samples taken from the field and analysed in the laboratory show that the density for the three lanes varied between 2322 and 2369 kg/m^3. These values are within the performance-based specification range. This shows that also in practice the desired density can be achieved in different compaction temperature windows.

Further, the samples taken from the field show that, even though the target density is achieved, the Indirect Tensile Strength (ITS) and fracture energy can vary significantly depending on the compaction temperature. The lane in which the operators started the compaction process, when the asphalt mixture was at approximately 150 °C, showed significantly better results for resistance against cracking, with a 10-25% higher ITS, than the lanes where the compaction process started at 130 °C or 100 °C, as shown in Figure 5.9. As with the laboratory results, these differences in ITS values could not be explained by the small differences in density.

Thus, similar patterns to those observed in the laboratory were found in the field study. Given the effects of the compaction temperature on the asphalt's mechanical properties, the temperature during compaction is clearly an important parameter in determining the resistance to cracking, at least for this specific asphalt mixture.

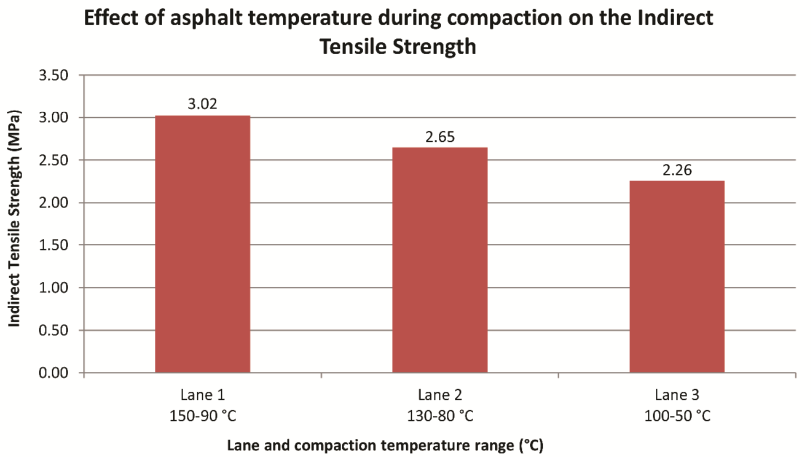

Figure 5.9: Indirect Tensile Strength for compaction temperature ranges in the field study

5.6 Reflection and discussion

Both the laboratory and field results show that, depending on the compaction temperature, mechanical properties can vary significantly despite the target density being achieved. One possible explanation is that the weight of the roller leads to micro-cracks being created. The results show that the compaction process when using an AC 16 Base (with conventional bitumen 40/60 pen) should ideally start when its temperature is in the range of 135-155 °C. If the compaction process starts outside this window, it is still possible to achieve the target density but a lower fracture energy should be anticipated, possibly by up to 30%. As a consequence, the layer may deteriorate more rapidly than expected, leading to higher repair costs for as well as possible penalties for road closures. These findings have practical consequences for the industry and implications for asphalt compaction theory.

Practical consequences for the paving industry

It is apparent that an asphalt team needs to be aware that compaction outside the optimum compaction window can significantly impact on quality. However, there are other aspects of the process and other disciplines that should heed these results. The significance of our findings should be considered when specifying an asphalt mix or planning logistics. A designer of a mixture should take into account that the quality will be influenced by the compaction temperature and thus include the sensitivity to temperature differentials in the mix and in the pavement design. A planner of the logistical process should recognise that delays in asphalt delivery could lead to lower lay-down temperatures, which could result in compacting outside the optimum window. To reduce these risks, a planner could opt to use an additional asphalt truck or choose to use a Material Transfer Vehicle in order to reduce temperature differentials.

Further, the results are relevant to quality control. If only the density is used as a criterion, any reduction in quality due to compacting outside the optimal temperature range will go undetected. For quality purposes, the compaction temperature needs to be monitored during the process. Nowadays, suitable equipment for monitoring temperatures during the process is widely available, and becoming increasingly affordable, such as laser-linescanners, infrared cameras and thermocouples (Ulmgren 2000, Lavoie 2007, Miller *et al.* 2011,Vasenev *et al.* 2012), and rollers can be tracked using GPS to determine the number of roller passes applied at each location (Krishnamurthy *et al.* 1998, Miller 2010, Gallivan *et al.* 2011). By adopting such enhanced process and quality control, a higher asphalt quality can be achieved.

The results of this study are also important within the context of accepting a completed project. If a client accepts a project without recognising that the compaction temperature can significantly affect the pavement quality, they may accept a road that fails to match up to the intended quality goals. To reduce this risk, a client could stipulate that the contractor must monitor compaction temperatures and pass this information over in a delivery file. Including contractual requirements regarding the monitoring of key parameters would reduce the risk of accepting a poorly constructed deliverable.

Implications for asphalt compaction theory

The experimental results show that the temperature of the mixture when compaction starts significantly influences the pavement quality. For this reason, the compaction window for rollers should be based on the compaction temperature and the associated mechanical properties, rather than solely on bitumen viscosity and density – the latter is common practice (Corlew *et al.* 1968, Jordan and Thomas 1976, Luoma *et al.* 1995, Asphalt-Institute 2007). This conclusion is in line with those of Decker (2006) and Bahia *et al.* (2006) who similarly postulate that determining the compaction temperature from viscosity-temperature plots is no longer sufficient. Some researchers have suggested that compacting at lower temperatures is possible, but have only considered density as a criterion (Kearney *et al.* 2006, Schmitt *et al.* 2009). The results of this study show the importance of distinguishing between achieving the target density and achieving the intended mechanical properties. Achieving the target density may indeed be possible at lower temperatures, but the mechanical properties would likely suffer.

5.7 Future work

This study has demonstrated that it is possible to incorporate the compaction temperature in laboratory compaction procedures when using laboratory roller compaction equipment. However, test specimens are compacted in a relatively narrow temperature range, whereas field compaction takes longer and is therefore conducted across a wider temperature window. A challenge for future research is to develop new laboratory compaction procedures based on determining a temperature window rather than a single temperature and then controlling the frequency of roller passes while the asphalt cools. If it were possible to alternate asphalt cooling with roller passes, one could more closely simulate field compaction. This would be much more efficient than running trial-and-error experiments during real construction projects, and could lead to clearer guidelines for roller operators.

Further, laboratory procedures need to be improved to reduce the variability in density within and between slabs. This could possibly be achieved by automating the filling of the mould with the asphalt mixture related to the pre-compaction of the paver and by standardising mixing techniques to achieve homogeneous asphalt mixtures.

Further research should also be devoted to conducting experiments to determine the effects of various compaction strategies, as observed during real construction projects, on the pavement's asphalt quality for various asphalt mixtures. Roller compactors may play an important role in this future laboratory-based research since they more closely simulate field compaction and, according to de Visscher *et al.* (2006) and Mollenhauer and Wistuba (2013), produce slabs that are more representative, in terms of composition and internal structure, of full-scale constructions. This claim could be validated by using X-ray imaging to determine particle distribution at a range of compaction temperatures.

5.8 Conclusions

The standardised approach to determining the ideal temperature for asphalt compaction in the laboratory fails to reflect the actual field compaction process. The existing approach in the laboratory, based on binder viscosity, provides a single compaction temperature, whereas the on-site roller operator has to determine a temperature window in which to compact. The different approaches have consequences for the resulting density and mechanical properties. However, the significance of these consequences is unclear and this makes it difficult to provide appropriate guidelines to roller operators.

This paper has focused on the relationship between the asphalt temperature during compaction and the mechanical properties of the asphalt layer. This relationship was assessed in the laboratory using a Roller Sector Compactor and in a field study. In the latter, the rollers were tracked using D-GPS and the asphalt temperature monitored using a laser-linescanner, infrared cameras and thermocouples. The results show that the compaction process should ideally start within a certain temperature window. If the compaction process starts outside this temperature window, it is still possible to achieve the target density, but the asphalt's mechanical properties will suffer. In our tests with a representative base layer, compacting outside the optimum compaction window could decrease the fracture energy by up to 30%. This exposes a contractor to the risks associated with a shortened pavement lifespan and possible extra maintenance costs. The risk for clients (infrastructure agencies), if their prime criterion for acceptance is density, is that they accept substandard work that does not fulfil all their quality goals. Practice needs to be aware of the significance of asphalt temperature during compaction. Improved designs and enhanced quality control are feasible, and could be used to achieve a higher asphalt quality. In terms of asphalt compaction theory, the paper proposes defining roller compaction windows based on a temperature range, and the resulting mechanical properties, rather than on bitumen viscosity at a single compaction temperature and the desired density.

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Chapter 6

Including asphalt cooling and rolling regimes in laboratory compaction procedures[5]

Given the various changes occurring in the asphalt construction industry, improved process and quality control is becoming essential. The significance of appropriate rolling and compaction for the quality of asphalt is widely acknowledged and vital for improved process control. But what constitutes appropriate rolling and what are appropriate instructions for operators? Existing laboratory procedures generate a single compaction temperature based on binder viscosity. However, in practice, roller operators choose various windows in terms of both time and temperature for compaction activities. This makes it difficult to design the compaction process and give proper instructions to operators.

This research project has aimed to (1) develop laboratory compaction procedures that take account of asphalt cooling during compaction and (2) determine the effects of different compaction strategies on the asphalt quality. Field compaction processes for two mixtures, an AC 16 base/bind and SMA 11 surf, were simulated in the laboratory using different temperature windows and applying different rolling regimes using a slab compactor and a 2.5 ton roller to produce 500 mm square slabs. The resultant densities and Indirect Tensile Strengths (dry and retained) were assessed based on 16 cores drilled from each slab.

The experimental results show that it can be important to design rolling strategies within clearly defined temperature windows. If an SMA 11 surf is compacted outside the optimal temperature window, or using a sub-optimal rolling strategy, the density may drop by 30 kg/m^3 and the Indirect Tensile Strength fall by up to 10%. Such experimental results are vital if one is to design appropriate rolling regimes and give appropriate instructions to roller operators. Also, the results can help to close the gap between field processes and laboratory compaction techniques. Overall, the results reflect a valuable step in the quest toward improved process and quality control.

Keywords: Asphalt temperature, cooling, compaction, density, indirect tensile strength.

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6.1 Introduction

The final stage of the asphalt road construction process remains a grey area when it comes to quality control. Although substantial research effort is put into creating a mix with the desired characteristics, the actual compaction sequence, once this is delivered to a site, primarily depends on the experience and gut feelings of the roller operators. This unknown element in quality control is of increasing concern to contractors. The search is on for properly validated compaction procedures because significant changes are occurring in the asphalt construction industry that result in new roles for agencies (clients) and contractors. In particular, agencies are shifting toward service-level agreements with lengthy guarantee periods. With these new roles and contracts, contractors are directly confronted with any quality shortcomings that appear during the guarantee period. As such, it is important for contractors to professionalize their operations and improve process and quality control during construction. The current asphalt construction process is mainly based on experience and craftsmanship, and is still mostly carried out without the use of high-tech instruments to monitor key process parameters, and little research effort has been put into the systematic mapping and analysis of construction processes (Miller 2010). Therefore, contractors have little knowledge of what actually transpired during construction and how the operations were carried out. It is therefore near impossible to relate the operations to quality parameters, to identify poor and good practices, and thus also to improve process control.

In the current technological age, various technologies are being developed to make construction processes explicit in real-time by both geodetic companies (Trimble, Topcon) and machine manufacturers (Bomag, Wirtgen, Ammann, Dynapac, Caterpiller). Using modern technologies, it becomes possible to make the construction processes explicit and systematically monitor, map, and analyze on-site processes. Several studies have demonstrated, using these technologies, that there is significant variability in both construction processes and key parameters (Krishnamurthy *et al.* 1998, Miller 2010, Bouvet *et al.* 2011, Gallivan *et al.* 2011). To reduce this variability, it is essential to change from the current experience-based working methods toward a more method-based working. To enhance this change, it is vital to design and specify the optimum construction process before actual construction. However, it is difficult to relate the various construction processes to quality parameters in field projects given the many changing variables. Ideally, one would like to design the construction process in advance within the laboratory. However, procedures to design on-site construction processes within the laboratory are lacking and thus there remains a lack of appropriate instructions for operators. If the process could be designed in advance in the laboratory, better instructions could be provided for on-site operators.

This paper focuses on the compaction process in the laboratory (a process which on-site uses rollers). The existing laboratory compaction procedures mainly generate a single optimum compaction temperature based on binder viscosity. However, in practice, roller operators use a range of time and temperature windows for compaction (observed using GPS tracking and on-site measurements). This paper proposes a procedure to accommodate asphalt cooling and compaction rolling regimes in laboratory compaction procedures. The paper starts with a literature review of research addressing asphalt compaction, followed by the objectives and approach followed in this research. Next, the compaction procedures and materials used will be described, followed by the experimental results. The paper concludes by addressing the implications of the findings for the asphalt industry and considering opportunities for future research.

6.2 Literature asphalt compaction

Asphalt compaction

An extensive literature review by Miller (2010) concludes that the majority of the literature deals with the characteristics of asphalt from the perspective of a construction material and that only about 5% of the asphalt-related journals deal with asphalt laying and compaction operations. Further, in this small research area, the studies have been conducted in separate niche areas such as ‘temperature variability’, ‘temperature segregation’, and ‘compaction problems’. Nevertheless, this literature (Elhalim *et al.* 1993, Asphalt-Institute 2007, Miller 2010) has identified two important facets within the construction process that are important for the final quality of the asphalt pavement: (1) compaction operations; and (2) the asphalt temperature during these compaction operations.

First, there are the compaction operations: inadequate compaction in vital areas of the road section can lead to premature failure. Roller operators have a limited window of opportunity to carry out their operations if they are to reach a certain quality level (Kari 1967, Daines 1985, Chadbourn *et al.* 1998, Floss, Timm *et al.* 2001, Delgadillo and Bahia 2008, Kassem *et al.* 2008). They have to take into account a number of factors including the temperature of the existing surface, the initial material temperature, the thickness of the layer, and the weather conditions. Further, the operators have to perform their tasks under frequently changing site conditions involving wind, rain, and layer thickness (Daines 1985, Chadbourn *et al.* 1998, Miller 2010). This all contributes to compaction being a complex task.

The second facet is the temperature of the asphalt mixture during the paving and compaction phase. In the asphalt paving industry, both researchers and practitioners recognize that the temperature of the asphalt mixture during compaction is an important determinant of the final quality of the pavement (Chadbourn *et al.* 1998, Stroup-Gardiner 2000, Floss 2001, Timm *et al.* 2001, Willoughby 2003, ter Huerne 2004, Schmitt *et al.* 2009, Miller 2010). Some authors suggest that compaction should be completed in a specific temperature range such as between 90 °C and 100 °C (Floss 2001) or have specified either maximum temperatures of about 130 °C (Commuri and Zaman 2008) or minimum temperatures between 70 and 80 °C (Corlew and Dickson 1968, van Dee 1999). If the material temperature is too low during compaction, the bitumen can no longer lubricate the mixture resulting in an open surface. If the temperature is too high, the binder is too fluid and the resulting aggregate structure is weak as the roller loads will simply displace or "shove" the material rather than compact it, cracks may originate behind the rollers, and the rollers sink into the mixture. Kari (1967) describes these minimum and maximum temperatures as understressed and overstressed situations.

Traditionally, the optimal compaction temperature has been determined by plotting log-viscosity vs. log-temperature, and the ideal compaction temperature coincided with a bitumen viscosity of 1.7 poise (Corlew and Dickson 1967). Subsequently, Jordan and Thomas (1976) and Luoma *et al.* (1995) developed tools to predict a temperature window, and the starting and ending temperatures at which to compact. Later, Chadbourn *et al.* (1998) and Timm *et al.* (2001) developed Windows-based computer programs (PaveCool, Calcool, and Multicool) that produced solutions that predicted the pavement cooling phenomenon and suggested starting and stopping times for compaction. The main problem with these methods is that they are based on viscosity and density rather than final quality characteristics such as resistance against fatigue, rutting, and cracking. Decker (2006) argues that determining the compaction temperature through viscosity-temperature plots is no longer appropriate with more viscous bitumens since these can have a higher compaction temperature leaving insufficient time to compact the mixture. Similarly, Bahia *et al.* (2006) showed that these traditional approaches indicated unreasonably high temperatures for modified asphalts.

In conclusion, the compaction process and the temperature during this process are key determinants of the final quality of the pavement. However, how the density and mechanical properties of the pavement are influenced by the various operational compaction strategies remains unclear.

Simulation of field compaction in the laboratory

Several studies have shown that conventional laboratory compactors, such as Marshall compactors, vibratory compactors, and gyratory (kneading) compactors, do not truly simulate the compaction in the field. In the last decade, a new type of compactor has entered the laboratory asphalt compaction market – the rolling compactor (EN 12697-33) - that produces relatively large slabs. The principle of these compactors is a segmented roller that moves back and forth across the mixture in a mold to produce relatively large slabs, often 500 mm by 500 mm.

From various studies, it has become clear that rolling compaction is closest to field compaction (Renken 2002, de Visscher *et al.* 2006, Muniandy *et al.* 2007, Bijleveld 2010, Paffrath *et al.* 2012). Also, the instrument can be pre-heated and can produce several test samples at the same time, and this diminishes variability between subsequent tests. The University of Wuppertal has conducted research so as to be better able to simulate, in the laboratory, field compaction and more accurately simulate pre-compaction (Paffrath *et al.* 2012). These new laboratory compactors are available on the international market. Companies in Europe, including BPS Wennigsen and Infratest Testing Systems in Germany (who have sold 66 machines worldwide since 2006) have developed several compactors as has IPC Global based in Australia. However, less research effort has been put into determining relationships from an operational (process) perspective related to the final mechanical properties of the asphalt mixture. As a result of these studies and developments, we believe that rolling compaction has now reached a stage where it can play an important role in simulating the field compaction process, and with that in the design of improved compaction procedures. The next section discusses the objectives of this research and the approach followed.

6.3 Objectives and approach

The objectives of this research were: (1) to develop laboratory-scale compaction procedures that include asphalt cooling; (2) to develop laboratory procedures to imitate actual rolling regimes with various rollers; and (3) to compare the compaction procedures used in various laboratories using different compaction methods. Overall, the aim was to improve understanding of operational strategies and narrow the gap between field compaction and compaction in the laboratory. The objective of this paper is to demonstrate the merits of the developed compaction procedures and the range of experimental results when the compaction procedures were varied.

To achieve the objectives, three experiments were designed and conducted. In these experiments, some elements of the compaction process were varied and quality parameters were determined. More specifically, the temperature window and the roller types used for compaction were varied (the independent variables) and the quality of the finished product was determined in terms of density and Indirect Tensile Strength (ITS) (the dependent variables).

The 'temperature window' variable warrants further explanation. From the literature review, it is clear that the traditional approach to specifying the compaction temperature from laboratory tests results in a single compaction temperature based on viscosity whereas, during field compaction, subsequent roller passes are made while the asphalt mixture cools, resulting in a temperature window. Timm *et al.* (2001) put forward the idea that there is an ideal window of temperatures in which to compact the asphalt mixture and, if this is met, then it is highly likely that the desired mechanical characteristics will be achieved. Depending on the cooling rate of the asphalt mixture, this also means that there is an optimal time window in which to compact. If the asphalt mixture is compacted outside these windows, the asphalt mixture will be understressed (if the mixture is compacted at too low temperatures) or overstressed (if the temperatures are too high). Figure 6.1, which shows schematically the temperature of the mixture as a function of time, illustrates these conditions.

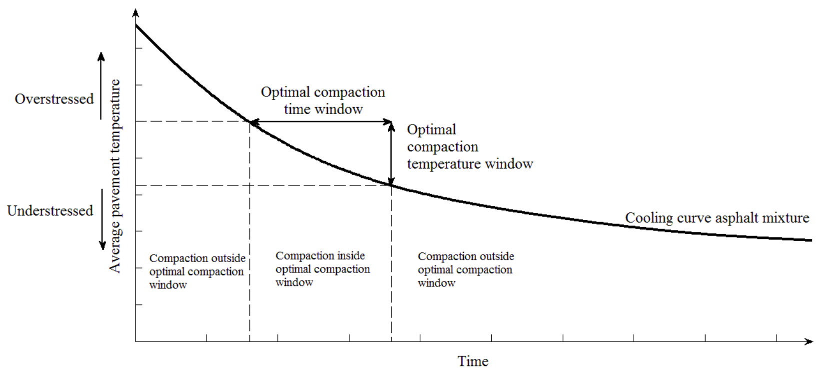

Figure 6.1: Compaction window (based on Timm et al. 2001)

6.4 Materials and compaction procedures

The experiments were conducted using two asphalt mixtures, namely an AC16 base/bind and an SMA 11 surf. These mixtures were chosen since the

AC 16 base/bind is a frequently used asphalt mixture under less than ideal circumstances in the Netherlands and the SMA 11 surf is known to be a critical mixture in terms of compaction. Both mixtures were made without incorporating recycled asphalt (RAP) in order to increase the homogeneity of the mixtures. All the materials were ordered as a single batch to decrease the risk of excessive variability in the raw materials. The compositions of the two asphalt mixtures are shown in Table 6.1. These mixtures were then compacted using two different compaction methods, namely a slab compactor (SC) and small 2.5 ton roller compactor (RC) to create 500mm squared slabs – shown in Figure 6.2.

Table 6.1: Composition asphalt mixtures

Material	AC 16 base/bind	SMA 11 surf
Bestone 4/8	-	30.9 %
Bestone 8/11	-	47.3 %
Granite 2/8	22.7 %	-
Granite 8/16	35.0 %	-
Sand	35.8 %	12.0 %
Wigras 40K (filler)	6.5 %	9.8 %
Bitumen 40/60	4.5 %	-
Bitumen 70/100	-	7.0 %

Figure 6.2: Slab compactor (left) and 2.5ton roller (right)

Three experiments were designed and conducted: (1) varying the temperature window for the AC 16 base/bind mixture using both compaction methods, (2) varying the temperature window for the SMA 11 surf mixture using both compaction methods, and (3) varying the rolling regime for the SMA 11 surf mixture using only the slab compactor. The specified compaction procedures are shown in Table 6.2. In total, 47 slabs were produced in four laboratories from which 776 cores were extracted and analyzed.

The steps (i.e. the procedure) conducted in the experiments were as follows:

1. Mixing the raw materials. This involved heating the bitumen and aggregate to 170 °C. First, the aggregate, sand and filler were put in the mixer, these were mixed for 15 seconds, then the bitumen was added and mixed for 3 minutes.
2. Compacting the asphalt mixture using the slab compactor or the 2.5 ton roller. First, the asphalt mixture was pre-compacted to 90% of the target density (simulating screed compaction). Then the 4-5 rolling phases shown in Table 6.2 were simulated (also based on procedures from Mollenhauer 2009).
    a. To ensure the roller passes were carried out at the intended temperatures, thermocouples were placed in the asphalt mixture at the bottom and middle of the height through the slab. In practice, there was little difference between these two temperatures so the slabs can be considered homogenous in terms of temperature.
    b. The loads applied by the slab compactor were calculated based on the Dutch roller factor, which is calculated by the load of the roller divided by the product of the width and the square of the diameter of the roller. A force of 14 kN was used to simulate a tandem roller, and a force of 25 kN to simulate a three-drum roller.
3. Drilling and removing cores from the slab. Sixteen cores with a diameter 100 mm were extracted from each slab according to a standard drilling scheme.
4. Determining the dimensions and densities of the drilled cores. The dimensions of the cores was measured four times using a digital rod and the density was determined by a procedure based on Archimedes' Law.
5. Polishing the cores: The AC16 base/bind slabs were compacted to a thickness of 80 mm and polished to a depth of 60 mm for testing. The SMA 11 surf slabs were compacted to 60 mm and polished to 50 mm for testing.
6. Determining the dimensions and densities of the polished cores. As in Step 4, the dimensions were measured four times using a digital rod and the density was determined using Archimedes' Law.
7. Conditioning of the polished cores: Eight cores were conditioned in air at 15 °C for 72 hours (further called dry cores) and eight cores were conditioned in a water bath at 5 °C for 72 hours (further called retained cores).

8. Conducting ITS tests: ITS tests were conducted according to EN-12697-23. The ITS tests determine the peak load (P_{max}), the indirect tensile strength (ITS), the work of fracture (W_f), and the fracture energy (G_f). The fracture energy was calculated according to the RILEM TC 50-FMC specification (1985). The work of fracture (W_f) was computed as the area under the load(P) - displacement(u) curve, and the fracture energy (G_f) was calculated by dividing the work of fracture by the ligament area (the product of the diameter (D) and the height (H) of the specimen).

Table 6.2: Design of the compaction procedures

Experiment 1: AC 16 base/bind		
Procedure 1: 10 slabs	Procedure 2: 3 slabs	Procedure 3: 2 slabs
5 tandem passes at 150 °C	5 tandem passes at 120 °C	5 tandem passes at 120 °C
5 tandem passes at 115 °C	5 tandem passes at 100 °C	5 tandem passes at 80 °C
5 tandem passes at 90 °C	5 tandem passes at 80 °C	5 tandem passes at 60 °C
5 tandem passes at 70 °C	5 tandem passes at 60 °C	5 tandem passes at 40 °C
Experiment 2: SMA 11 surf		
Procedure 1: 12 slabs	Procedure 2: 12 slabs	
5 tandem passes at 150 °C	5 tandem passes at 120 °C	
5 tandem passes at 115 °C	5 tandem passes at 100 °C	
5 tandem passes at 90 °C	5 tandem passes at 80 °C	
5 tandem passes at 70 °C	5 tandem passes at 60 °C	
5 tandem passes at 50 °C	5 tandem passes at 40 °C	
Experiment 3: SMA 11 surf		
Procedure 1: 3 slabs	Procedure 2: 3 slabs	Procedure 3: 2 slabs
5 three-drum passes at 150 °C	5 tandem passes at 150 °C	5 tandem passes at 150 °C
5 three-drum passes at 115 °C	5 tandem passes at 115 °C	5 tandem passes at 115 °C
5 three-drum passes at 90 °C	5 tandem passes at 90 °C	5 tandem passes at 90 °C
5 tandem passes at 70 °C	5 three-drum passes at 70 °C	5 tandem passes at 70 °C
5 tandem passes at 50 °C	5 three-drum passes at 50 °C	5 tandem passes at 50 °C

6.5 Experimental results

Three experiments were conducted in four different laboratories. These laboratories are here numbered 1 to 4, and in 1 and 2 the mixtures were compacted using a slab compactor (SC) and in 3 and 4 the mixtures were compacted using a 2.5 ton roller compactor (RC). From each compacted slab, 16 cores were extracted and analyzed. The following aspects were assessed in detail: (1) layer thickness progression during compaction; (2) density before and after polishing; and (3) indirect tensile strength.

Experiment 1: Varying temperature window - AC 16 base/bind

The progression in the layer thickness during compaction is automatically determined when using a slab compactor and determined using a theodolite in the laboratories using a 2.5 ton roller. The progression in layer thickness using the slab compactors (laboratories 1 and 2) showed a consistent trend as shown in Figure 6.3: During pre-compaction, the layer thickness decreased by around 3-4 mm. In the first three roller phases, the layer thickness decreased by 0.1-0.6 mm in each phase. Following this, in the final phase, the layer thickness increased slightly (0.2-0.3 mm). These results are similar to the results of Faheem *et al.* (2007) who also found that density does not always increase as the temperature falls, as we saw in the last compaction phase in our testing. In contrast, the changes in the layer thickness using the 2.5 ton roller (laboratories 3 and 4) were much more variable and no trend could be discerned.

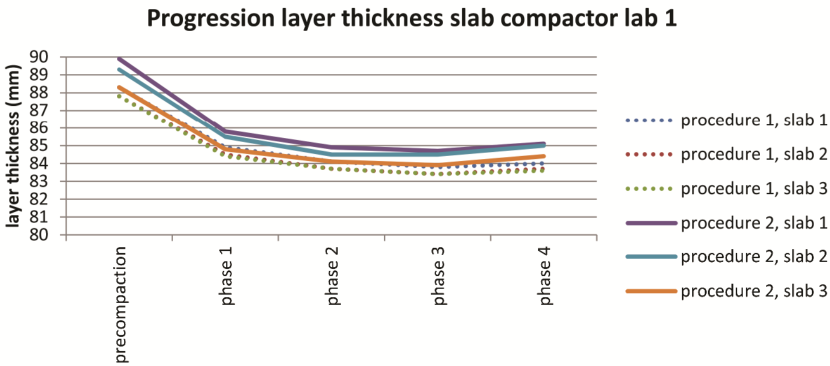

Figure 6.3: Progress in the layer thickness using the slab compactor

Next, the densities of the extracted asphalt cores were determined. With this mixture, no significant differences in density were observed for a given procedure undertaken in different temperature windows. However, differences in density were observed between the two compaction methods and between the laboratories. The average slab density compacted with the slab compactors was 2296 kg/m^3, whereas the average density of slabs compacted with the 2.5 ton roller was 2339 kg/m^3. Also, the average density of slabs compacted with the same roller procedure was 2301 kg/m^3 in one laboratory and 2371 kg/m^3 in the other. The density variability within a slab was also analyzed and the variation within a slab was of a similar order. The average difference between the minimum and maximum densities within a slab was 53 kg/m^3.

Finally, the results of the ITS tests, presented as fracture energy (G_f) values in Figure 6.4, were considered. We concluded that there were large differences between ITS results for slabs compacted using the same procedure - both from slab to slab and from lab to lab. For the dry samples, G_f values ranged from 4.9 to 8.2 Nmm/mm^2. Given this high variability from one slab to another, it was not possible to determine a relationship between the different compaction procedures. Further, it is apparent that the retained ITS values of the slabs compacted in laboratories 2 (SC) and 4 (RC) are relatively low compared to those in the other two laboratories (by 1.97 Nmm/mm^2 on average). As a consequence, the ratio between the dry and retained values (ITSR) are relatively low in laboratories 1 (SC) and 3 (RC), and overall show a wide range (41-91%).

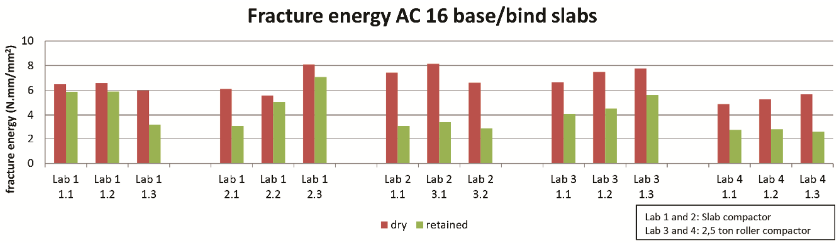

Figure 6.4: Average fracture energy values AC 16 base/bind slabs
** the coding indicates the procedure (1st number) and the slab number (2nd number)*

Experiment 2: Varying temperature window SMA 11

SMA 11 surf slabs were compacted in two different temperature windows, namely at 150-115-90-70-50 °C (Procedure 1), and at 120-100-80-60-40 °C (Procedure 2). Five roller passes with a tandem roller (Hamm DV70) were carried out in each of the five rolling phases.

Again, the progression in layer thickness during compaction was more consistent using the slab compactor than the 2.5 ton roller. Using the slab compactor it was possible to compact slabs with a maximum difference in layer thickness of 2.5 mm (59,7-62,2mm). Using the 2.5 ton roller, the differences in thickness were much more variable (58,9-65,3mm).

From an analysis of the progression in layer thickness, it seems that Procedure 2 was less successful in achieving the desired layer thickness than Procedure 1. This is also reflected in the final densities of the extracted cores. Although all the cores show a compaction degree of 100 to 102%, the densities of the cores compacted using Procedure 2 are approximately 30 kg/m^3 lower than those produced using Procedure 1. As with the AC16 base/bind mixture, the variability in density within a slab was high. Differences between the minimum and maximum densities in a slab were as high as 80 kg/m^3. However, the cores extracted from the central area of the slabs were much more consistent with the maximum difference between the minimum and maximum densities within a slab being 25 kg/m^3.

ITS tests were performed on the extracted and polished cores. Even when the largest differences in density were discounted (by selecting the middle cores of the slabs), there still seems to be a difference in ITS values between the cores compacted using the two procedures. The ITS values from the cores compacted according to Procedure 1 vary from 0.91-1.09 MPa, and using Procedure 2 from 1.01-1.20 MPa. The average ITS of the cores compacted using Procedure 2 was 0.11 MPa (≈ 10%) higher than the ITS of those compacted using Procedure 1. We then looked for a relationship between the density and the ITS of the cores. No relationship was found between the ITS and the density, for the obtained density range (2330 to 2370 kg/m^3).

Experiment 3: Varying roller regime SMA 11

In Experiment 3, SMA 11 surf slabs were compacted following three different roller regimes, namely using a three-drum roller and then a tandem roller (further called D-T), using a tandem roller and then a three-drum roller (further called T-D), and using a tandem roller, followed by a second tandem roller (further called T-T). In all cases, compaction took place in five phases at temperatures of 150-115-90-70-50 °C with five roller passes in each phase.

The successive changes in layer thickness show that the D-T rolling regime results in a much faster reduction in slab thickness than in the slabs compacted using the T-D and the T-T rolling regimes.

Following the procedure, next cores were extracted and analyzed. All the slabs achieved the target density or higher densities. However, the cores compacted using the D-T rolling regime were denser than both the target density and the ones produced using the other rolling regimes. The average density of the cores compacted using the D-T rolling regime were about 30 kg/m^3 higher than those produced in the other regimes (see Figure 6.5). Again, the variability within a slab was high, although the densities in the middle part of a slab were rather constant with the difference between the minimum and maximum densities no more than 25 kg/m^3.

ITS tests were then performed to complete the experiment. With the largest differences in density being discounted by selecting only the middle cores of the slabs, there seems to be a relationship between ITS and the rolling regime. The ITS of the cores compacted using the D-T rolling regime were about 10% lower than the cores compacted using the other rolling regimes (see Figure 6.6). A possible explanation is that the three-drum roller is too heavy and so creates micro-cracks at the high temperature of 150 °C. However, this hypothesis needs to be confirmed or rejected in other laboratories.

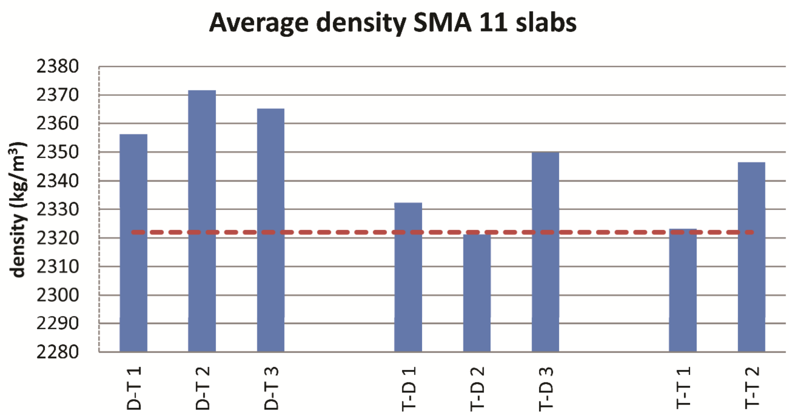

Figure 6.5: Average density SMA 11 slabs
**D and T indicate the roller type (three-drum (D) and tandem (T)) and the numbers correspond to the slab number*

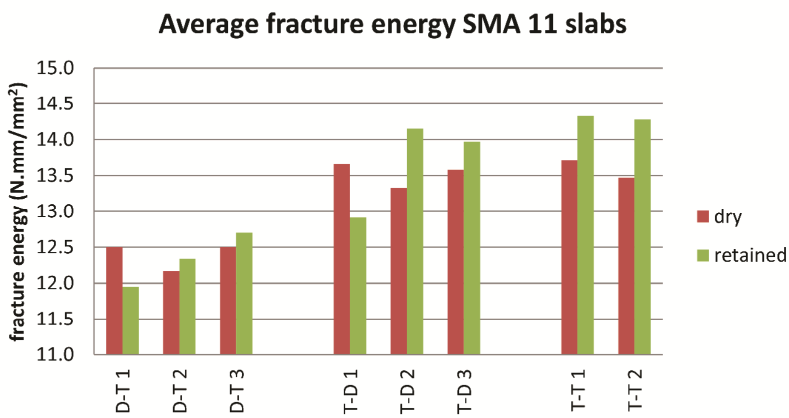

Figure 6.6: Average fracture energy SMA 11 slabs
**D and T indicate the roller type (three-drum (D) and tandem (T)) and the numbers correspond to the slab number*

6.6 Discussion and future research

Although we have succeeded in simulating the asphalt cooling process in laboratory compaction procedures, there are still various points to address. First, we have seen that there is still significant variability in both density and Indirect Tensile Strength (ITS) within the asphalt slabs. As such, the procedures need to be improved to reduce the variability in density. Possibly, this could be achieved by automating the filling of the mold with the asphalt mixture related to the pre-compaction of the paver. Further, the variability in ITS values has a strong influence on the ratio between the dry and retained values (ITSR), and this makes the ITSR an even more unreliable parameter for use in analysis and comparison. A final concern is that the ITS test may not be sufficient to observe differences between slabs that were compacted within different temperature windows. In future research it may therefore be valuable to test cores using other mechanical tests such as the triaxial test or the four-point bending test. Also, additional research could usefully be devoted to further experimenting with different roller regimes, and specifically with more critical mixtures when it comes to compaction, such as thin surfaces. In case of using asphalt mixtures with multiple aggregate sources, it may be better to evaluate the air voids rather than the density. Further, more extreme loads could be tried to determine when micro-cracks due to roller loads may arise. We also plan to explore other variables in the compaction process, such as the timing of the first roller pass and the effect of roller speed, and to determine the effects of additional roller passes once the target density is achieved.

Finally, it is important to validate the experimental results obtained in the laboratory with field experiments. Therefore, further research effort is planned that involves designing a field experiment in which a rolling strategy will be given to roller operators and its implementation monitored using GPS equipment. Following this, the rolling process will be closely simulated in the laboratory and the resulting mechanical properties compared.

6.7 Conclusions

The significance of appropriate rolling and compaction for road quality is widely acknowledged and improved process and quality control are vital. However, procedures to design or specify compaction processes are lacking and thus also methods to provide appropriate instructions for roller operators. Existing laboratory procedures generate a single ‘ideal’ compaction temperature based on the binder viscosity, while in practice roller operators have to select and work within windows based on time and temperature. This paper has described initial work to include asphalt cooling and rolling regimes in laboratory compaction procedures. Typical field compaction processes for an AC 16 base/bind and for an SMA 11 surf were simulated in the laboratory within different temperature windows by applying specified rolling regimes using a slab compactor and a 2.5 ton roller. In this initial stage, we succeeded in imitating, in the laboratory, field compaction processes in terms of temperature windows and rolling regimes. By following a standard procedure, it was possible to conduct roller passes at various temperatures and so compact the asphalt within a specified temperature window.

Using the AC16 base/bind, three temperature compaction windows were experimented with: from 140 down to 70 °C, 120-60 °C, and 120-40 °C. None of these tests suggested a significant and consistent relationship between temperature window and final density and Indirect Tensile Strength. Similarly, two temperature windows were used with the SMA 11 surf mixture, from 150 °C down to 50 °C and 120-40 °C. With this mixture, the slabs compacted in the cooler temperature window were less dense, typically by 30 kg/m^3. When the differences in density were discounted, the slabs compacted in the lower temperature window have Indirect Tensile Strengths (ITS) that are about 10% higher. In a final set of experiments, the rolling regime for the SMA 11 surf was varied. Three regimes were tested: (1) first a three-drum roller and then a tandem roller, (2) first a tandem roller and then a three-drum roller, and finally (3) two successive tandem rollers after each other. The slabs compacted using the first roller regime with a three-drum roller followed by a tandem roller were about 30 kg/m^3 higher in density. However, the ITS of the slabs compacted using this roller regime were about 10% lower.

The results demonstrate that it is certainly important to specify rolling strategies based on temperature windows that depend on the asphalt mixture. If an SMA 11 surf is compacted outside the optimal temperature window, or using a sub-optimal rolling strategy, the density may drop by 30 kg/m^3 and the Indirect Tensile Strength by up to 10%. These experimental results could help in designing appropriate rolling regimes and providing better instructions to roller operators. The results reflect a step forward in diminishing the gap between field and laboratory compaction outcomes. Further research effort will be put into verifying the results under in-situ conditions. Overall, the results are a valuable step in the quest for improved process and quality control.

Acknowledgements

This research would not have been possible without the cooperation provided within the ASPARi network. We would especially like to acknowledge the eleven contractors for the opportunity to conduct research at their construction sites and in their laboratories.

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Chapter 7

Complementary work

In addition to the main research activities that resulted in the papers included in this thesis, complementary research efforts were undertaken that appeared relevant during the research trajectory but that had not directly been considered beforehand.

These research efforts included (1) the filtering of GPS data in monitoring asphalting operations, (2) providing real-time information to operators on-site and (3) explicating process variability associated with Warm Mix Asphalt (WMA) and relating this to the asphalt's quality.

The filtering of GPS data was necessary to obtain accurate information from the GPS sensors placed on the machinery to track machine movements. During the research trajectory, it became apparent that the sensor readings in some projects were very susceptible to noise. Therefore, various complementary research efforts were undertaken to filter the GPS data in order to be able to usefully analyse the GPS data from the machinery.

Further, during the research trajectory, the contractors, including the operators during feedback sessions, pushed for real-time information support rather than the post-processing techniques that were initially the goal. This became increasingly relevant as operators recognised the value of the monitored data and sought real-time information so the process could be adjusted if necessary. Consequently, complementary research efforts were undertaken to provide real-time information to the asphalt operators on-site. Real-time prototypes and visualisations of key parameters were developed to provide decisive information to operators allowing them to adjust their operations.

Finally, during the period of the research trajectory, the use of WMA became increasingly relevant due to a push for sustainability. Therefore, contractors sought deeper insights into on-site operational strategies for constructing WMA and their relationship with the final asphalt quality. Complementary research efforts were put into monitoring on-site process variability and the relation of this with the quality of WMA mixtures.

The next sections provide brief overviews of these complementary research efforts and the main conclusions that were drawn from these efforts.

7.1 Filtering GPS-data in monitoring asphalting operations[6]

The use of global positioning systems (GPS) to analyse the movements of machinery during construction is a growing practice. However, the accuracy of GPS measurements is influenced by a number of factors that lead to noise in the GPS data. Due to this uncertain accuracy in the GPS data, asphalt-paving professionals have problems interpreting and using the data in their operational context. There is a lot to be gained if the noise in the GPS data could be filtered out, enabling the asphalt paving operations to be analysed in greater detail and improved. Filtering however is a difficult task since machinery movements in asphalt paving are very machine-specific and a high level of detail is required to analyse their operations. It is not that easy to decide whether a certain pattern in the GPS data is caused by noise or represents genuine machine-specific movement.

Bijleveld *et al.* (2011) explored and investigated problems with filtering GPS data from actual asphalt paving projects using both post-processing and real-time processing. In particular, two post-processing smoothing techniques (moving average and lowest linear fit) were analysed for GPS data collected on a roller and another real-time processing technique (Kalman filtering) was analysed for GPS data from a paver, all the data being gathered during actual road construction projects.

Implementing these smoothing techniques, while assuming some machine movement limitations, allowed us to apply techniques that are typically used for sophisticated filtering in a clear and self-descriptive way. Simple smoothing would have led to the loss of valuable data, especially at road curves and at the turning points of machines. The applied smoothing techniques improved the accuracy of the GPS path data and, hence, the accuracy of compaction contour plots. To analyse GPS measurements from rollers more accurately and in greater detail it is necessary to detect and isolate noise in the GPS data caused by

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[6] This section is based on the following published papers:

- Bijleveld, F.R., Vasenev, A., Hartmann, T., Dorée, A.G. (2011). Real-time and post processing of GPS data in the field of visualizing asphalt paving operations. In: *European Group for Intelligent Computing in Engineering* (EG-ICE), 5-7 July 2011, Enschede, the Netherlands (pp. 1-8).
- Vasenev, A., Ionita, D., Bijleveld, F.R., Hartmann, T., Doree, A.G. (2013). Information fusion of GNSS sensor readings, field notes, and expert's a priori knowledge. In: *European Group for Intelligent Computing in Engineering*, 1-3 July 2013, Vienna, Austria (pp. 1-10).
- Vasenev, A., Pradhananga, P., Bijleveld, F.R., Ionita, D., Hartmann, T., Teizer, J., Dorée, A.G. (2014). An information fusion approach for filtering GNSS data sets collected during construction operations. *Advanced Engineering Informatics*, http://dx.doi.org/10.1016/j.aei.2014.07.001.

measurement inaccuracies and to discriminate this from the genuine machine-movement patterns.

The initial study by Bijleveld *et al.* (2011) demonstrated that, before GPS measurements in asphalt construction can be meaningfully analysed, the documented movements need to be filtered to exclude outliers. Eliminating outliers manually is a time-demanding process, while automatic filtering can be inaccurate. In particular, path elements may get lost if machine-specific movements are misconceived as noisy data. Therefore, an information fusion approach to filter the paths of construction machines in a semi-automated way was proposed (Vasenev *et al.* 2013). A screenshot of the software is shown in Figure 7.1. This approach allows an expert to relate "hard" sensor data and "soft" field records with knowledge on how machines can realistically move in real construction projects. The proposed approach for filtering the documented paths of machines involved in road construction projects was illustrated in a specially developed open-source software routine. The initial testing of the developed software showed its suitability for filtering outliers in GPS data.

The software assists in data analysis by supporting the task of identifying and eliminating outliers based on expectations of how machines can move during a particular asphalt construction project. Groups of outliers can be selected according to a specific set of search rules or by adjusting the time limits of the identified outlier. The beta-version of the software is freely downloadable at http://asphaltopen.svn.sourceforge.net ("DataImportWizard" project) and has the potential to be useful in analysing the documented paths of construction machines. The developed data-processing techniques and visualisations help operators and decision-makers map, understand and improve their operational strategies and behaviour.

As a final step, this open-source software was applied to filter outliers in sensor readings collected during earthmoving and asphalting projects (Vasenev *et al.* 2014). The software demonstrated its functionality in supporting its users in easily identifying and eliminating outliers based on expectations of how five different types of construction machines could move during asphalting and earthmoving projects. The approach allows users to effectively discriminate and remove outliers in an interactive way with the aim of increasing the accuracy of the GPS-based path trajectories of construction equipment.

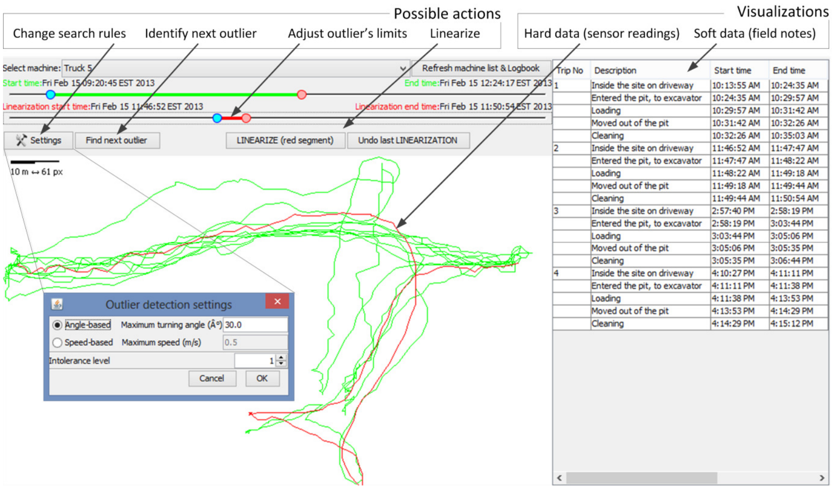

Figure 7.1: Open-source software to filter GPS-paths

7.2 Real-time information on-site[7]

The previously developed and improved Process Quality improvement (PQi) framework uses various technologies to make on-site asphalting operations explicit. However, the data are, in the main, analysed after the monitored process (i.e. post-processing), which makes it impossible to adjust the process. To overcome this limitation, real-time prototypes and visualisations of key indicators, such as the asphalt temperature, were developed to provide key information to asphalt operators to make it possible for them to adjust their on-site operations (Vasenev *et al.* 2011; 2012).

As a first step towards real-time decision-making support, a workflow process was introduced to deliver information in a meaningful way by providing near real-time and easily understandable visualisations of asphalt temperatures to roller operators (Vasenev *et al.* 2011). Using modern technologies, such as DGPS and temperature linescanners, and with an on-site wireless connection it became possible to deliver visual information on asphalt temperatures that can support the roller operators' decision-making regarding roller regimes. The overall

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[7] This section is based on the following published papers:

- Vasenev, A., Bijleveld, F.R., Hartmann, T., Doree, A.G. (2011). Visualization workflow and its implementation at asphalt paving construction site. In: *CIB W78-W102 2011: International Conference*, Sophia Antipolis, France, 26-28 October.
- Vasenev, A., Bijleveld, F.R., Hartmann, T., Doree, A.G. (2012). A real-time system for prediction cooling within the asphalt layer to support rolling operations. In: 5th *Eurasphalt and Eurobitume Congress*, Istanbul, 13-15 June 2012, Turkey.

workflow process consists of equipment selection, infrastructure organisation, and the data processing and visualisation needed to implement user-oriented visualisations. The feasibility of the workflow process was demonstrated through the implementation of two user-specific visualisations in a real-world asphalt construction project.

Real-time prototypes and visualisations of key indicators were developed to provide key information to asphalt operators (Vasenev *et al.* 2011; 2012). Given that the in-asphalt temperature is not easy to predict and to measure, a reliable real-time information system had to be developed. Therefore, an Automated Temperature Unit (ATU) capable of providing real-time surface and in-asphalt temperature information to roller operators was developed (Vasenev *et al.* 2012) and patented (Vasenev *et al.* 2013). The implemented system displays the measured and predicted asphalt temperature changes as well as the time remaining until the asphalt mixture cools to a specific temperature. This temperature-related information assists machine operators in making decisions when to start, and when to finish, rolling. Analysing the recorded temperature data can help to improve rolling practices and move towards the development of more pro-active rolling regimes based on real-time information.

7.3 Process variability and asphalt quality for WMA[8]

Governments, regulatory bodies and road authorities all push sustainability. Firms respond with strategies to reduce their carbon footprints. Besides optimising their asphalt production and logistics, firms are investing in the development of Warm Mix Asphalt (WMA). WMA is an asphalt mixture produced at lower temperatures, thereby requiring less energy. Essential research effort has been put into developing techniques for adjudicating WMA, optimising their composition and rationalising the design (Jenkins 2000, Prowell and Hurley 2007, Silva *et al.* 2010), with less research effort being put into the operational consequences for asphalt teams. WMA was expected to have workability problems because its lower temperature would lead to higher mixture viscosity and less time to compact. Modifications to the mix have reduced the viscosity and the

[8] This section is based on the following published papers:

- Doree, A.G., Bijleveld, F.R., Miller, S.R. (2012). Paving below zero centigrade - how a project exposed two different approaches to innovation. In: 5th *Eurasphalt and Eurobitume Congress*, 13-15 June 2012, Istanbul, Turkey.
- ter Huerne, H.L., Bijleveld, F.R., Oude Lansink, G.H.M. (2012). Operational behavior ad performance of laboratory and field produced wma asphalt. In: *MAIREPAV7 - 7th International Conference on Maintenance and Rehabilitation of Pavements and Technological Control*, 28-30 August 2012, Auckland, New Zealand (pp. 1 - 11).

mixture is more flexible at lower temperatures enabling the time available for compaction (the compaction window) to be stretched.

The consequences of this strategy of reducing the viscosity for the paving and compaction processes in asphalt construction projects have been described (Dorée and Bijleveld 2012). Here, two WMA projects were analysed with the temperature of the mixture being monitored during the process using linescanners, infrared cameras and thermocouples, and the movements of the machinery observed using GPS sensors. operational handling of WMA was also assessed based on interviews with operators.

The gathered and presented data show considerable variability in important parameters and working methods, for example in the initial surface temperature, compaction procedures, the timing of the first roller pass after the paver and the density progression during the compaction process. However, this variability is not specific to WMA - it is more the consequence of an uncoordinated approach. Nevertheless, from the gathered data, the conclusion was drawn that WMA seems more vulnerable to variability in operational parameters than Hot Mix Asphalt (HMA). Should the resulting asphalt construction be of poor quality, the shortened lifespan will undo the sustainability advantages of WMA. With less time available for the paving and compaction processes, intensive monitoring and quality control become increasingly important.

The implication for decision-makers is that the planning and organisation of a project requires more attention if WMA is to be used, and a continuous process should be pursued. For planners, this means that the logistics are more critical and the delivery of a continuous stream of asphalt to the paver is essential. Also, project managers need to be aware that WMA is more vulnerable to loss of quality and therefore the paving and compaction processes require more comprehensive preparation. In addition, road agencies should be aware of this vulnerability to variability in on-site operational strategies, and this should be taken into account in the decision-making process regarding the use of WMA in a project.

Following these results, the consequences in terms of operational behaviour and performance of the addition of a Zeolite (Advera) to the WMA mixture were evaluated (ter Huerne *et al.* 2012). To investigate changes in behaviour and performance, (1) laboratory experiments were conducted to evaluate performance in the laboratory, (2) the effects of the timing of adding the additive to the mixture were determined during a field study, and (3) the resulting mechanical properties in a field study were analysed. The results of the laboratory experiments and the field studies show that the performance of this WMA with an added Zeolite can be comparable with that of an HMA. However, the results in terms of resistance to rutting (f_c) show considerable variability. Additionally, the operational performance when using the WMA with the Zeolite shows a lot of variability that seems related to the variability in mixture temperature and compaction operations. That is, WMA seems more vulnerable to the variability in operational behaviour than HMA, especially in terms of resistance to rutting. From a production perspective, it seems feasible to include the additive in the production phase and, since the final product seems to be fairly insensitive to the timing of the addition, the process seems quite robust. These results could help designers, planners and project managers make better-informed decisions about the use of WMA under specific project conditions.

7.4 Conclusion complementary work

The complementary research efforts achieved the following:

1. Filtering GPS data in monitoring asphalting operations: this resulted in open-source software that can be used to filter outliers in GPS data. This was tested in earthmoving and asphalting projects which provided insights into the effects of various filtering techniques and demonstrated the relevance of combining 'hard' sensor data, 'soft' field data and expert knowledge.
2. Providing real-time information to support operators on-site: this resulted in an Automated Temperature Unit (ATU) that can provide real-time information to operators about the surface and in-asphalt temperatures, and the rate of asphalt cooling. A workflow process was also developed to deliver meaningful real-time visualisations to operators. This also provides insights into the technical possibilities in providing real-time information during on-site operations as well as the relevance of real-time information support.
3. Explicating WMA process variability and relating this to the asphalt quality: this resulted in an overview of the process variability when using WMA and empirically tested the relationships between the timing of dosing the Zeolite additive and both the density and rutting resistance of the asphalt layer. This provides insights into the consequences of using WMA, and additives, from production and process perspectives.

The next chapter provides an overview of the outcomes from the five papers, included as Chapters 2 to 6, and the complementary work outlined in the present Chapter. The key outcomes are then aggregated to summarise the findings of the entire research trajectory and answers are provided to the research questions. The scientific and practical relevance of these findings are discussed in Chapter 9.

Chapter 8

Key findings and conclusions

The previous chapters provide frameworks, models and empirical data related to deeper insights into the asphalt construction process and improving the operational strategies of asphalt teams. This is achieved by enhancing technology adoption in the asphalt construction process, by methods and data to analyse the on-site operational strategies and their effects on asphalt quality, and by enhancing reflective and method-based construction practices. In this chapter, the key findings of this research are discussed and conclusions drawn regarding the initial research questions. First, an overview of the research activities and outcomes is given, after which the key findings and conclusions are described. Chapter 9 positions these findings in the ongoing scientific and societal debates.

8.1 Overview research activities and outcomes

This section provides an overview of the key research activities and outcomes. Table 8.1 shows, for each chapter, the main research activities and the resultant research outcomes. The next section describes the key findings and conclusions in more detail using this overview and provides answers to the corresponding research questions.

Table 8.1: Overview of research activities and outcomes, and their relationship to the research questions

Chapter	Research activities	Research outcomes	Research questions
2	• Further developing and formalising the PQi framework • Implementing the PQi framework and technologies in the Dutch road construction industry • Applying the PQi framework in 30 asphalt road construction projects	• Improved PQi framework and technologies implemented in practice • An extensive dataset with on-site process data: 30 projects, 250 hr machinery-movements, 250 hr lay-down temperatures, 120 cooling and density curves • An overview of the variability in key on-site parameters and activities • Pointers to reducing process variability • Lessons to encourage technology adoption	1, 2
3	• Determining process variability from 30 monitored projects • Determining, from 30 monitored projects, common operational strategies used by asphalt teams	• An overview of variability in compaction operations • An overview of common compaction strategies • Pointers to reducing variability in compaction • A method to extract common operational strategies from a structured dataset	1, 2
4	• Developing and applying a method-based learning model for asphalt construction • Enhancing learning and reflection competencies in practice	• A method-based learning model • A demonstration of the learning model for highway construction • Insights into the differences between planned strategies and those actually conducted	3
5	• Implementing the asphalt temperature in laboratory compaction procedures • Empirically testing the effects of the compaction temperature on the asphalt quality in the laboratory (based on 18 slabs and 162 cores)	• Empirically tested relationship between the compaction temperature and the density, fracture energy and cumulative axial strain • Pointers to aligning laboratory and field compaction in terms of asphalt temperature	4, 5

Chapter	Research activities	Research outcomes	Research questions
6	• Implementing asphalt cooling and rolling regimes in laboratory compaction procedures • Empirically testing the effects of asphalt cooling and rolling regimes on the asphalt quality in the laboratory (based on 47 slabs and 776 cores)	• Empirically tested relationship between the cooling process and the asphalt's density and fracture energy • Empirically tested relationship between rolling regimes and the asphalt's density and fracture energy • An overview of the variability in test results between various laboratories and compaction methods • Pointers to aligning laboratory and field compaction in terms of asphalt cooling and rolling regimes	4, 5
7	• Developing and applying different filter mechanisms for filtering GPS data • Developing and applying semi-automatic filtering techniques • Developing software to filter outliers in GPS data • Developing and applying real-time information and visualisation techniques for operators • Monitoring and mapping WMA projects • Empirically testing the impact of process variability on asphalt quality	• Insights into the effects of various filtering techniques on GPS data • Information fusion approach to semi-automatic filtering machinery paths • Open-source software to filter GPS outliers • A workflow process to deliver meaningful visualisations to operators in real-time • An Automated Temperature Unit to provide real-time surface and in-asphalt temperatures • An overview of process variability in using WMA • Empirically tested relationship between dosing WMA with an additive, and its density and rutting resistance	-

8.2 Key findings and conclusions

At the start of this dissertation, it was stressed that current market conditions in the road construction industry encourage improved on-site operational strategies while there is limited understanding about current on-site construction processes. The literature stresses that the on-site asphalt construction process is relevant for road quality, but that only limited solutions for monitoring and improving the on-site construction process, in rather fragmented areas, are available. Therefore, the aim of this research was to develop deeper insights into the on-site asphalt construction process and their relationships with the asphalt quality in order to provide a basis for improving on-site operational strategies.

The premise guiding this research was that improving current on-site operational strategies in the asphalt road construction industry requires: an explicit and controllable on-site construction process; a reduction in process variability and thus a consistent on-site construction process; method-based working practices rather than the current ad-hoc experience-based practices; an understanding of the influence that variability in on-site operational strategies has on the asphalt quality; and an alignment of operational strategies with laboratory design procedures.

This guiding premise led to five research questions. Research activities were accordingly undertaken to answer these research questions. The next sections describe the key findings and conclusions of this research structured to answer the initial research questions.

Encouraging technology adoption to make on-site operational strategies explicit

There are rapid technology developments to make operational strategies of asphalt teams explicit. However, although these technologies are becoming widely available, their adoption in practice has been slow. As it stands, on-site operational asphalting strategies are generally not systematically monitored and mapped. This makes it challenging to improve on the current operational strategies. Encouraging technology adoption and continually assessing how new technologies can help the on-site process is vital to improve on-site operational strategies.

The key findings regarding encouraging technology adoption to make on-site operational strategies explicit are:

- The PQi framework, initially developed by Miller (2010) and further advanced in this research, to make on-site operations and key parameters explicit encourages the use of D-GPS, temperature linescanners, infrared cameras, thermocouples and a weather station. This framework was further developed by formalising the procedures, shortening the feedback loop and adding questionnaires to the framework for determining the operators' planned process (appendices 1 and 2, Chapter 4). The improved framework is being widely implemented in Dutch construction practice and contractors are now able to organise and execute the monitoring of their own construction projects by themselves.

- The implementation of this framework demonstrates the value of the technologies in making the on-site construction process explicit. The introduction of our approach, including the use of new technologies, helps to break through the vicious 'no understanding – no adoption' circle in which the failure to adopt technologies can be attributed to insufficient understanding of operational strategies while there is insufficient understanding because the technologies are not adopted. Having data gathered in a structured and systematic way, and then synthesised to meet the needs of practitioners, proved relevant in creating an improved appreciation of the value of the technologies. The seven feedback sessions with asphalt teams from six different contractors were also helpful in developing this improved appreciation.
- The research demonstrates the value of a participatory action research approach in developing practical solutions and facilitating adoption by industry. Support from research organisations and individuals, both technically and financially, was vital for the successful adoption and implementation of the framework and the technologies. Our research approach, which introduced and evaluated the technologies gradually so as to align them with the operator's needs, helped in gaining this support from contractors. The ASPARi network became a testing ground for new technologies, enabling to receive feedback from potential users. This network is essential for machine and technology manufacturers to test and evaluate their prototypes and enhance the adoption process.
- The adopted and implemented framework for explicating on-site processes was shown to be relevant, applicable and useful in asphalt construction. From a contractor's perspective, the framework was useful in that it helped to create a better understanding of the on-site construction operations, whereby it leads to improvements in the quality of these processes in practice. For example, to reduce temperature differentials and make the compaction process more consistent, asphalt road construction companies should adopt and implement technologies such as D-GPS, temperature linescanners and infrared cameras in their daily practice to make operational behaviour explicit and improve process control further. Implementing the framework in construction practice leads to a data-rich understanding of the process.

By aggregating these findings, research question 1 can be answered:

“How can available technologies be implemented and used in current practice in order to develop an extensive dataset with explicitly monitored on-site operational strategies?”

Available technologies to make on-site operational strategies explicit are implemented and used in current construction practice by: (1) adopting the PQi framework, in which technologies are used to make operational strategies explicit and feedback provided by potential users (the asphalt team); (2) using the organisational, operational and managerial insights, as discussed in Chapter 2, gained from contractors who had implemented the PQi framework; (3) breaking through the ‘no-introduction - no adoption’ cycle by gradually introducing technologies and demonstrating their relevance in improving current practices; and (4) using a participatory action research strategy to develop practical solutions and facilitate technology adoption in the industry. By implementing the PQi framework and the available technologies, an extensive dataset was built that included the explicitly monitored operational strategies of asphalt teams relevant and practical for researchers to boost research into the on-site construction process.

Process variability and common operational strategies

In order to design a consistent on-site construction process, it is vital to understand current on-site process variability and the common on-site operational practices. Explicating and understanding these make it possible to reduce variability in the process and to work towards a more consistent on-site construction process.

The further developed PQi framework to make on-site processes and key parameters more explicit was used in 30 asphalting projects including seven feedback sessions with asphalt teams creating an extensive dataset to allow an analysis of the extent of process variability and common on-site operational strategies.

The extensive data-resource includes: 30 projects, approximately 250 hours of movements of all on-site machinery with a X-Y-Z location every second (so about 900.000 locations for every on-site machine), about 250 hours of lay-down temperatures behind the paver with 20 temperatures over the width of the road every second, and more than 120 asphalt cooling and density progression curves.

The key findings regarding process variability and common on-site operational strategies based on the gathered dataset are:

- The PQi framework and the associated technologies are helpful in explicating the on-site construction processes, and make process variability and the common practices explicit. The framework allows a rigorous, structured and systematic data-collection process, and this is essential to determining the extent of process variability and the common on-site operational strategies.
- Considerable variability was found in the initial asphalt surface temperature behind the screed, the cooling rate of the asphalt mixture, the compaction process and density progression, and the on-site movements of the machinery. Further, within the compaction process, on-site conducted by rollers, a substantial degree of variability became apparent from the monitored and analysed projects. The compaction process is very often executed using different sets of rollers. Further, the number of roller passes and the time and temperature windows in which these roller passes are conducted vary considerably.
- Due to the large variability, only one common compaction practice could be extracted from the 30 monitored projects. This was for one asphalt mixture, an Asphalt Concrete (AC) Surf 8 of 30-35 mm, but it still is unclear whether this identified strategy amounts to best practice. The fact that only one common practice was found further emphasises the large variability in on-site key activities and parameters.
- The variability explicitly established from the monitoring creates pointers as to where variability should be reduced to establish a more consistent asphalting process. Process variability can firstly be reduced by better specifying and improving forecasting of the key process parameters; secondly by monitoring (direct observation) and analysing the key process variables; and thirdly by providing real-time information support during the construction process.
    - Specifying 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 help in developing 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 practices. The use of a Material Transfer Vehicle, to reduce temperature differentials and enable a continuous process, is recommended.
- Tools and equipment to support on-site roller operators with real-time information, such as asphalt temperatures and the number of roller passes made, allows operators to adapt the process when deviations occur.

- The feedback sessions and the explicit data generated enables asphalt operators and teams to verbalise their tacit knowledge and to make their own processes and choices transparent. This further promotes reflection and learning processes in the on-site construction process.
- With the opportunity to make on-site activities and parameters explicit, and to monitor process variability, it also becomes possible to (1) overlay on-site construction data with later inspection data during service life and then draw conclusions on the impacts of on-site construction on durability and serviceability of the road, and (2) better align laboratory tests with the on-site construction process and to relate on-site parameters to the mechanical properties of the asphalt layer. This is an essential step to relate the on-site process to the asphalt quality.

By aggregating these findings, research question 2 can be answered:

"What is the extent of on-site process variability and what are the common on-site operational strategies in the gathered dataset?"

Considerable variability was found in:

- The initial asphalt surface temperature behind the screed of the paver. In total, 140 paver stops were observed in the 30 projects and the temperature differentials varied from 20 °C to 100 °C.
- The cooling of the asphalt mixture. The cooling rates depend on the asphalt mixture, the thickness of the layer and the weather conditions. In terms of the weather, the cooling times depend on the wind speed and the solar radiation. With a wind speed above 5 m/s, cooling rates drop by between approximately 10% and 50%, and with a solar radiation above 100 W/m^2 cooling rates are approximately 10% to 50% longer. The cooling curves derived from PaveCool and CalCool

predictions correspond well with the measured on-site cooling curves with the exception of open-graded mixtures.

- The compaction process and density progression. Firstly, it is observed that a compaction process is very often executed using a sequence of different type of rollers. In 29 projects and five asphalt mixture categories, 17 different roller type combinations are monitored. Secondly, the number of roller passes and the time and temperature windows in which these roller passes are conducted vary considerably. Roller passes varying between 10 and 20 roller passes are not exceptional. Also, the compaction time can vary between 50 and 90 minutes, and the temperature during this compaction window varies, for instance, between 145-100 °C and 120-65 °C.
- On-site and laboratory measured densities. The relationship between the densities measured on-site and the core density determined in the laboratory is weak (R^2=0.69). Differences are found from +137 to -213 kg/m^3. The available on-site measurement devices seem useful in determining whether the desired density progression has been achieved. However, the current devices are imprecise in determining the absolute density. The results show considerable variability and, therefore, are difficult to use to predict the absolute density. This suggests a need to re-evaluate on-site density measurements and possibly search for alternatives. The debate continues as to whether the estimations made by these systems are sufficiently accurate for on-site process control.
- On-site machinery movements. There is considerable variability in the number of roller passes that are conducted and the paver speed during the laying process. The process animations developed, the Compaction Contour Plots and the graphs of paver speed were helpful in analysing the entire process, the teamwork involved, and the causes and consequences of discontinuities in the process.

Given the extraction of only one common compaction practice from the monitored projects, the large variability in key on-site activities and parameters is emphasised. As a first step in better informing and guiding on-site roller operators, this common practice is analysed in more detail. Once more projects have been monitored, and more data gathered, the method can be used to extract additional common operational strategies applied under varying conditions.

The common practice identified concerns compacting a 30-35 mm AC Surf 8 mixture. First a three-drum roller completes between 4 and 8 roller passes within 10-20 minutes, starting the compaction process when the mixture is at approximately 130-160 °C and finishes around 90-100 °C. Next, a tandem roller conducts between 6 and 8 roller passes, starting the compaction process when the mixture is around 80-110 °C and finishes around 50-60 °C. This identified common practice in compacting an AC Surf 8 of 30-35 mm is visualised in Figure 8.1 and is useful to better inform and guide on-site roller operators. However, it is unclear whether this identified strategy amounts to best practice because the relationship with the resulting asphalt quality is unclear.

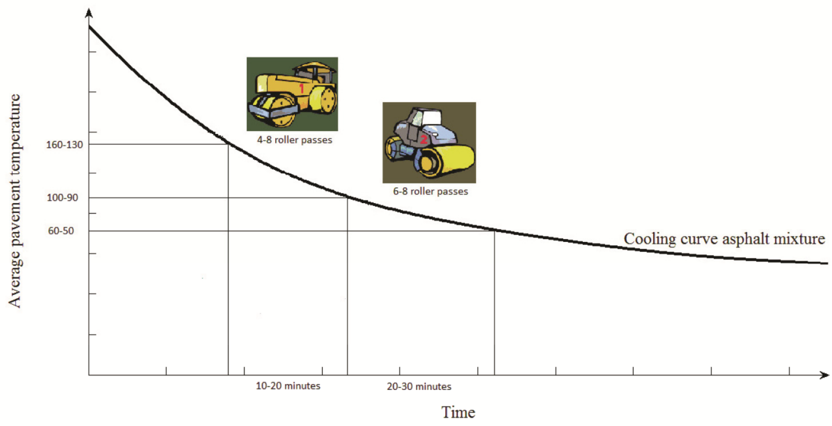

Figure 8.1: Sketch common compaction practice AC Surf 8 (30-35 mm)

The explicitly monitored process variability suggests that there are virtually no common operational strategies nationally available. The monitored variability shows that every contractor and asphalt team selects their own operational strategies. Given that long term studies are costly and time consuming and procedures in the laboratory to experiment with different strategies are lacking, it remains largely unclear whether a selected strategy amounts to good or poor operational practice. Therefore, in this research, efforts are undertaken to align laboratory and field practices in order to distinguish between good and poor operational strategies.

A model to enhance method-based learning

Current construction processes rely heavily on the skills and on-site experience of operators. This essentially results in individual implicit learning and lengthy learning cycles. Given these aspects, it is essential to move away from the current implicit individual and lengthy learning towards explicit and method-based learning practices.

The key findings regarding the transition from experience-based learning towards method-based learning are:

- In order to encourage a change towards method-based learning, the learning model of Kolb (1984) was adopted, with 'monitoring the process' (explicating) added as an additional step in this learning cycle. Using various technologies, such as GPS, laser and infrared measuring devices, it became possible to monitor key parameters and operations in the construction process and to explicitly map them. The introduction of Kolb's learning cycle fused with on-site data collection was critical in explicating the tacit knowledge and implicit processes.
- In addition to the framework proposed by Miller (2010) to monitor the on-site processes using various technologies, questionnaire surveys were introduced to determine the process as planned by the operators. This helps in analysing differences between what the operators initially planned and what they actually did on-site and provides contractors understanding how well asphalt teams and individual operators can predict their operations. The technologies and the questionnaire surveys were invaluable tools in enriching the data and opening communication channels to facilitate a transition towards method-based learning based on an explicit process.
- The action research strategy with alternate steps of technology introduction, explicating operational strategies, and undertaking feedback with operators, shows that this strategy is effective in the quest for improved method-based learning approaches and competencies in practice. It helps uncovering and verbalising the tacit knowledge and experience present within the operators.
- The explicit method-based learning framework leads to improved awareness of the quality and value of communications with and within the asphalt team. It responds to the current lack of explicit learning and reflection in the construction industry. The model is useful in developing the method-based learning and reflective competencies of both individuals and teams. By explicating the 'as constructed' process, it becomes possible to have meaningful discussions with the team's operators in a feedback session, where the explicated process helps to unravel the intentions and reasoning of the chosen strategies. Transparency in the process and operational choices were created using these technologies and the well-designed visuals help individual operators and the asphalt team in their sensemaking about the construction processes and their interdependencies.

By aggregating these findings, research question 3 can be answered:

"How can the current experience-based operational construction practices be changed to more method-based practices?"

In response to the current lack of explicit learning and reflection in the construction industry, a transition from experience-based construction practices to explicit, method-based, practices is initiated and then advanced by: (1) applying the learning model of Kolb and including the additional step of monitoring the process (explicating); (2) using the PQi framework to monitor the on-site construction process and questionnaire surveys to uncover the process planned by the operators; and (3) using an action research strategy where operators, researchers and technologies drive the research process based on methods and explicit data.

Influence of operational strategies on asphalt quality

After explicating the on-site construction process and demonstrating the substantial variability within the process, it was vital to relate the monitored on-site operational strategies to the asphalt quality in order to determine the significance of the on-site process variability and enabling to distinguish between good and poor operational practices.

Therefore, experiments were conducted to imitate various compaction strategies, as observed on construction sites, under controlled laboratory conditions and to determine their influence on asphalt quality. Based on the monitored operational strategies, the research question was narrowed down to: (1) the influence of the compaction temperature during the on-site construction process on the density and the cracking toughness of the final asphalt layer for an AC 16 base/bind; (2) the influence of the cooling times on the density and the cracking toughness of an AC 16 base/bind and of an SMA (Stone Mastic Asphalt) 11 Surf; and (3) the influence of the rolling regime on the density and the Indirect Tensile Strength of an SMA 11 Surf.

The key findings regarding the influence of on-site operational strategies on asphalt quality characteristics are:

- From the experiments, it is clear that the compaction temperature clearly has an impact on the final quality of the asphalt layer in terms of fracture energy. The results show that the compaction process should ideally start within a certain temperature window. The compaction process when using an AC 16 Base with conventional bitumen (40/60 pen) should ideally start when its temperature is in the range of 135-155 °C. If the compaction process starts outside this temperature window, it is still possible to achieve the target density, but the mechanical properties will be inferior. Compacting outside the optimal compaction window decreases the fracture energy of a representative base layer by as much as 30%. So, the experiments demonstrate, based on 18 slabs and 162 tested cores, that the asphalt temperature when the compaction process starts does influence the asphalt quality.

- The laboratory experiments that varied cooling times during the compaction process produced less clear conclusions. Using the AC 16 base/bind, the tests failed to identify a significant consistent relationship between temperature window and the final density and Indirect Tensile Strength. Using the SMA 11 Surf, the slabs compacted in the cooler temperature window were less dense, typically by 30 kg/m^3, but their Indirect Tensile Strengths (ITS) about 10% higher. So, the experiments demonstrate, based on 15 AC 16 base/bind slabs and 24 SMA slabs and 648 tested cores, that the temperature window in which the compaction process takes place does influence the asphalt quality.
- The laboratory experiments that varied the rolling regime for the SMA 11 Surf indicate that the rolling regime does influence both density and Indirect Tensile Strength. Three different rolling regimes were tested: (1) a three-drum roller followed by a tandem roller, (2) a tandem roller followed by a three-drum roller, and finally (3) two successive tandem rollers. The slabs compacted using the first of these roller regimes, a three-drum roller followed by a tandem roller, were about 30 kg/m^3 higher in density. However, the ITS of the slabs produced under this regime was about 10% lower. So, the experiments demonstrate, based on 8 slabs and 128 tested cores, that the roller regime does influence the asphalt quality.
- The results of the laboratory experiments demonstrate, based on 65 asphalt slabs compacted using different asphalt cooling rates and rolling regimes and 938 tested cores, that the operational strategies of asphalt teams do influence final asphalt quality. Dependant on the asphalt mixture and the temperature windows used for compaction, the mechanical properties vary by 10-30%. This exposes a contractor to the risks associated with a shorter pavement lifespan and possible liability for extra maintenance costs. The risk for clients (agencies), if they use density as their prime acceptance criterion, is that they accept substandard work that does not fulfil all their quality goals.

By aggregating these findings, research question 4 can be answered:

"What is the influence of variability in on-site operational strategies on the asphalt quality?"

The experimental results show that the on-site operational strategies chosen by asphalt teams influence the asphalt quality:

- Compacting during sub-optimum temperature windows decreases the fracture energy by up to 30% for a representative base layer.
- Compacting during sub-optimal cooling windows varies the density by 30 kg/m^3 and the Indirect Tensile Strength (ITS) by about 10% for a representative SMA layer.
- Compacting using sub-optimal rolling regimes varies the density by 30 kg/m^3 and the Indirect Tensile Strength (ITS) by about 10% for a representative SMA layer.

In conclusion, the compaction temperature, the cooling window and the rolling regime influence the mechanical properties of the finished asphalt layer by up to 30%.

Alignment of laboratory and field compaction

After making process variability explicit and determining the significance of variability in operational strategies for asphalt quality, the importance of better aligning laboratory design procedures with on-site asphalting processes became apparent. This process has focussed on the rolling regimes and the asphalt temperature during compaction.

Laboratory procedures to design or specify on-site compaction processes are lacking in the Netherlands as are methods to provide appropriate guidelines for roller operators. Further, the laboratory approach is quite dissimilar to the on-site field compaction process. The traditional laboratory approach to determining the compaction temperature is selecting the binder viscosity and then use binder viscosity - compaction temperature charts to read off the corresponding single temperature for compaction. The asphalt mixture is compacted at this temperature using a standard procedure to determine the target density. The mechanical properties of the mixture are then determined at this target density by carrying out several functional and mechanical tests. This laboratory simulation is different from the compaction process in practice, where successive roller passes are undertaken as the asphalt cools, until the target density is reached. Non-destructive density measurements and operator observations are used in deciding when the target density has been reached, and the rolling process is complete, or whether further roller passes are required. Thus, whereas the existing laboratory approach uses the binder viscosity to provide a single optimum compaction temperature, the roller operator on the construction site has to determine a temperature window in which to compact as the asphalt mixture will be cooling during the rolling process. In addition, the laboratory approach uses a fixed level of compaction energy to determine the target density, while the compaction energy in practice varies due to the use of different roller types and number of roller passes.

This research moved forward in the following directions to better align laboratory and field compaction procedures:

- Important steps were taken to include asphalt cooling and rolling regimes in laboratory compaction procedures using Roller Sector Compactors and 2.5 tonne rollers. In this initial stage, the field compaction processes were successfully imitated in terms of temperature windows and rolling regimes. By following a standardised procedure, it was possible to conduct roller passes at various temperatures and so compact the asphalt within a specified temperature window. However, there are still various points to address. First, significant variability was found in both the density and the Indirect Tensile Strength (ITS) within the asphalt test slabs. Consequently, the procedures need to be improved to reduce the variability in density, for example by standardising the asphalt mixing process. A further concern is that the ITS test may not be sufficient to identify all the differences between slabs compacted within different temperature windows. To address this latter point, future research should test cores using other mechanical tests such as the triaxial test or the four-point bending test.
- The experimental results, and the laboratory procedures developed, help in specifying appropriate rolling regimes and providing better guidelines to roller operators. Based on the findings, the researcher proposes defining roller compaction windows based on a temperature range and the resulting mechanical properties, rather than on bitumen viscosity at a single compaction temperature and final density. This reflects a step forward in closing the gap between field and laboratory compaction practices.

Aggregating these findings, research question 5 can be answered:

"How can laboratory design procedures be better aligned with the on-site operational strategies?"

There is a need to align field and laboratory practices in order to distinguish between good and poor operational strategies and provide better instructions to asphalt teams and operators on-site. Therefore, the following aspects should be included in the laboratory compaction procedures: (1) asphalt temperature, (2) asphalt cooling, and (3) rolling regimes, including roller types and the number of roller passes.

8.3 Strategy for progressively improving on-site operational strategies

The overall challenges addressed in this research have been: that on-site operational strategies are not systematically monitored, captured and made explicit; that technology adoption and process improvements are slow in practice; that current practices are mainly based on experience and craftsmanship resulting in long individual learning cycles; that the influence on asphalt quality of the operational strategies chosen by asphalt teams is unclear; and that laboratory procedures are only limited aligned with on-site reality. All these factors make it challenging to improve the on-site operational strategies of asphalt teams.

Given these challenges, the aim of this research was to improve operational strategies by developing deeper insights into the on-site activities and key parameters and their relationships with the asphalt quality. To achieve this aim, on-site asphalt construction projects were monitored using various technologies and laboratory experiments were conducted with the aim of aligning laboratory processes with on-site construction and to determine relationships between the on-site process and the asphalt quality. This has led to frameworks, models and empirical data that lead to a deeper understanding of the on-site asphalt construction process and its relationship with asphalt quality.

By aggregating the key findings of the entire research, a strategy is proposed for progressively improving on-site operational strategies, and the main research question can be answered:

"What is a comprehensive strategy for progressively improving on-site operational strategies?"

On-site operational strategies can progressively be improved using a cyclical iterative strategy that includes: (1) technology enhancements in the on-site construction process; (2) using more consistent and method-based on-site operational strategies, including feedback sessions with operators; and (3) adopting laboratory procedures that better relate on-site operational strategies to the laboratory design.

The improved and implemented monitoring PQi framework, that includes various technologies, the method-based learning model and the empirical data are all essential in this strategy towards an explicit, consistent and method-based asphalt construction process. A vital component of this strategy is its cyclic and iterative character that results in progressively improving on-site operational strategies. It is essential to gradually move forward in all three components rather than addressing them individually. For example, only advancing technology enhancements in the on-site construction process soon stagnates because it not directly improve the operational strategies and so the relationship with asphalt quality remain uncertain. Similarly, experimentation in the laboratory becomes unfocussed if on-site strategies are not explicitly monitored using the technology enhancements. So, professionalising the approach in all three directions becomes mutually reinforcing in advancing towards a more professional asphalting practice.

This strategy for progressively improving on-site operational strategies provides a distinctive form of triangulation to create deeper insights into the asphalt construction process. Using this triangulation approach, the on-site construction process is analysed from (1) a technological perspective, (2) a human (operator) perspective and (3) a laboratory design perspective, as shown in Figure 8.2. Triangulation is not new, and is already widely used in social sciences. Triangulation is expected to facilitate the validation of data through cross-verification from two or more perspectives (Van de Ven 2007). For research in the asphalt construction domain, these perspectives and research methods are a valuable and distinctive combination to boost progressively improving on-site operational strategies.

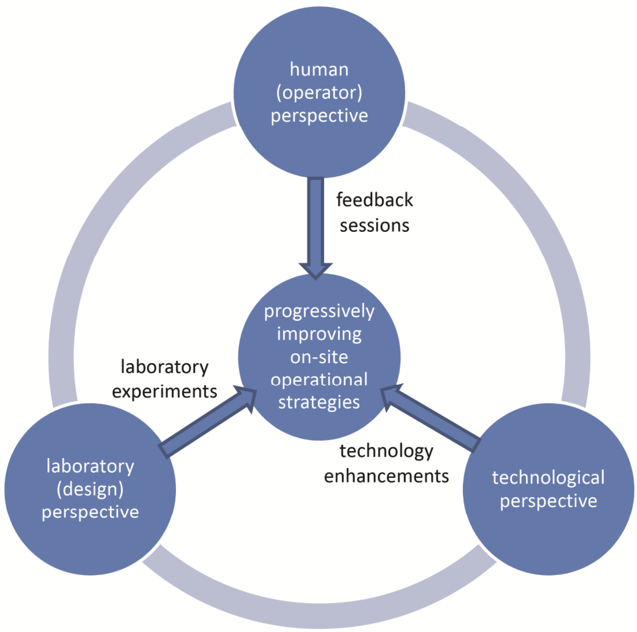

Figure 8.2: Triangulation approach to improve on-site operational strategies

In conclusion, the key outcomes of this research are:

- Improved PQi framework and the accompanying technologies implemented in practice to monitor the on-site asphalt construction process and breaking down barriers to technology adoption;
- Thirty asphalt road construction projects are systematically monitored and mapped including seven feedback session with asphalt teams creating an extensive dataset with on-site monitored process data;
- The extensive data-resource includes: 30 projects, approximately 250 hours of movements of all on-site machinery with a X-Y-Z location every second, about 250 hours of lay-down temperatures behind the paver with 20 temperatures over the width of the road every second, and more than 120 asphalt cooling and density progression curves;
- From the dataset the operational strategies of asphalt teams are made explicit and process variability is demonstrated in terms of the initial asphalt surface temperature behind the screed of the paver, the cooling rate of the asphalt mixture, the compaction process and density progression, and the on-site movements of the machinery;
- A model to enhance method-based learning practices based on explicitly monitored data is developed and applied to an asphalt construction project;
- Empirically tested relationships between the compaction temperature, the asphalt cooling process, the rolling regimes and the density, the fracture energy and the cumulative axial strain;
- An overview of the variability in test results between four laboratories and two compaction methods;
- Laboratory design procedures aligned with the on-site construction process in terms of asphalt compaction temperature, asphalt cooling and rolling regimes;
- A distinctive triangulation research approach to progressively create deeper insights into the asphalt construction process and to improve on-site operational strategies from a technological perspective, a human (operator) perspective and a laboratory design perspective.

Together, the outcomes of this research lead to a deeper understanding of the asphalt road construction process and enables to progressively improve operational strategies of asphalt teams. The outcomes contribute to various ongoing scientific debates and provide practical contributions for contractors, agencies, and technology and machine manufacturers. The next chapter describes the scientific and practical contributions of the outcomes of this research.

Chapter 9

Discussion and reflection

The scientific community and roads industry aim for higher quality asphalt roads. The findings of this research demonstrate that the operational strategies of asphalt construction teams substantially impact on asphalt quality. Given that current on-site operational strategies are not routinely monitored and mapped and heavily lean on tacit knowledge of operators and teams, improving the operational strategies of asphalt teams requires: adoption and implementation of technologies in the asphalt construction process, explicit data about the on-site activities and key parameters, method-based learning competencies, and aligning laboratory procedures and the on-site construction process.

For achieving higher quality asphalt roads, the on-site operational strategies need to be improved. Therefore, other decisions are taken and need to be made by researchers, contractors, agencies and manufacturers in terms of research efforts, the role of technology in the asphalt construction process, and regarding laboratory testing procedures. This research provides frameworks, models and empirical data for researchers and practitioners to boost technology adoption, to analyse on-site operational strategies and their effects on asphalt quality, to enhance reflection and method-based learning competencies, and to align laboratory procedures and the asphalt construction process to better inform and guide asphalt teams on-site. This research is an important step that leads to improvements in the on-site construction process, informed asphalt teams and operators based on a laboratory designed process, and consistent and method-based asphalting quality. Together this results in an improved construction process towards higher quality asphalt roads.

In this final chapter, the scientific and methodological implications as well as the relevance of the findings for agencies, for contractors and for machine and technology manufacturers will be discussed. Following this, a methodological reflection on the chosen research approach is given, followed by the limitations of this research and an agenda for future research. The chapter concludes by closing the loop back to the initial aim of this research and the continuing road towards a professionalised asphalt construction process.

9.1 Scientific relevance

Given the distinctive strategy for progressively improving on-site operational strategies from a technological, a human (operator) and a laboratory perspective, this research contributes to three ongoing scientific debates: (1) the need to create deeper insights into the asphalt construction process for improving operational strategies of asphalt construction teams, (2) the complexity of technology adoption and implementation in the traditional experience-driven construction practice, and (3) the relevance to connect laboratory design procedures and the on-site asphalt construction process.

Deeper insights into the asphalt construction process for improving operational strategies of asphalt construction teams

Whereas the quality of the asphalt layer is generally well defined through various functional and mechanical properties, such as stiffness, resistance to fatigue, rutting, stripping, the quality of the on-site construction process is largely unknown. Most of the asphalt-related literature deals with the characteristics of materials, with only a limited focus on systematically mapping and analysing the effects of construction processes on the final quality of the constructed layer (El-Halim *et al.* 1993, Fitts 2001, Dorée and ter Huerne 2005, Miller 2010). Therefore, the key characteristics of the construction process are not monitored and systematically mapped and their variability remain unidentified. Although the impact and importance of the on-site construction process to the final quality of the asphalt layer is recognised in the scientific community, knowledge of the on-site construction process and its effects on the final quality of the construction is still in its academic infancy. Consequently, the focus of this research was on the asphalt construction process and expanded knowledge and understanding about this topic. This resulted in methods for analysing and improving on-site operational strategies of asphalt construction teams.

This research contributes to deeper insights into the asphalt construction process for improving on-site operational strategies in the following ways:

- ***A structured and systematic data-collection is vital to improve the on-site construction process.*** The adoption of technologies is essential to make the on-site construction process explicit, and the structured and systematic approach is crucial to meaningfully analyse the on-site construction process. In the current research, the structured and systematic PQi framework developed by Miller (2010) was further developed. For example by formalising the procedures, shortening the feedback loop to asphalt teams, and questionnaire surveys were added to the framework in order to search the process planned by the operators. The improved PQi framework has proven to be applicable and useful, and has been widely adopted by the Dutch asphalt road construction industry. The broad adoption of the improved PQi framework shows that the organisation and execution of monitoring construction projects can be carried out by contractors themselves, which is a ground-breaking step to systematically collect data about the on-site construction process. It became easier and less time consuming for researchers to collect data about the on-site construction process spurring this field of research. This is relevant and practical for researchers in further analysing and promoting research into the on-site construction process.

- ***The extensive dataset is relevant to create deeper insights into the on-site asphalt construction process.*** By widely implementing the improved PQi framework in the Dutch asphalt construction industry and monitoring approximately 30 projects, an extensive dataset became available on asphalting processes. The dataset includes approximately 250 hours of movements of all on-site machinery, about 250 hours of lay-down asphalt temperatures, and more than 120 asphalt cooling and density progression curves. The dataset responds to the lack of explicitly monitored and mapped on-site construction data. When starting this research, there was little systematically gathered data available about on-site construction processes (Dorée and ter Huerne 2005, Miller 2010, Akhavian and Behzadan 2013, Cho *et al.* 2013). The dataset was used, in Chapter 2 and 3, to demonstrate the extent of process variability and common operational practices. This provides deeper insights regarding the extent of variability in lay-down temperatures, asphalt cooling, number of roller passes, density progression, compaction windows and paver speeds. From these insights, the conclusion drawn was that there are hardly any common operational strategies available nationally. A combination of operators working based on experience and craftsmanship and the absence of common operational practices triggers to determine the influence of operational strategies on asphalt quality. This research validates the research work of Miller (2010) regarding the framework, that proved relevant for making the on-site process explicit and monitoring process variability, and regarding the process variability, that was demonstrated for a broad spectrum of asphalt projects. The collected data and the insights form a foundation on which to build a consistent asphalting process. Having this amount of empirical data of on-site activities and process parameters available is a huge step for researchers wanting to conduct further research into the on-site asphalt construction process. The data was already used for further experimenting with the effects of on-site operational strategies on asphalt quality in the laboratory. The dataset can further be used for the future monitoring of pavement distress and premature failure, and for Pavement Management Systems (PMS). A challenge for future research will be to handle such big datasets and use them for improved instructions to operators and to make informed decisions around future maintenance.

- ***A method-based learning approach leads to improved process and quality awareness and to improved communications with and within the asphalt team.*** The method-based learning model, as described in Chapter 4, responds to the lack of reflection and learning competencies in the asphalt construction industry as well as to the challenges to verbalise tacit knowledge of asphalt teams and operators (Orange *et al.* 2005, Miller 2010, Bakker *et al.* 2011). Having made it possible to make on-site construction operations and key parameters explicit, a model to enhance method-based learning and improving in the construction industry was developed. This model was demonstrated in a specific real-life case in the asphalt road construction industry. The model enables learning and improving on-site operational strategies based on explicit data. Feedback sessions with asphalt teams and operators, as described in Chapter 2 and 4, are essential in this learning process. Applying this framework leads to improved awareness of the quality and value of communications with and within the asphalt team. For example, as demonstrated in Chapter 4, the operators had improved their predictions of lay-down temperatures, asphalt cooling and number of roller passes. The explicated process helps to verbalise and unravel the intentions and reasoning for the chosen strategies during feedback sessions. It is a method to enhance method-based learning and reflective competencies of both individuals and teams. This model can also be relevant for other experience-driven domains in the construction industry, such as in the laying of pipes, cables and sewers in the sub-surface domain, for enhancing learning and reflection competencies.

Understanding the technology adoption and implementation process in the traditional experience-driven construction industry

Many technological solutions are becoming available to monitor and map the asphalt construction process. Several studies show that technologies help contractors to make their processes explicit, learn explicitly what they do and, hence, gain greater understanding of their own processes in order to meet the need for improved on-site operations by asphalt teams (Navon and Shpatnitsky 2005, Miller 2010, Commuri *et al.* 2011, Gallivan *et* *al.* 2011, Beainy *et al.* 2012, Cho *et al.* 2013). However, although some technologies were developed into industrial applications, their adoption in practice is slow and very few have become widely accepted 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 due to being built on an insufficient understanding of the current experience-driven operational strategies, which are not explicit. As a result, the technologies lack evidence of added value for the asphalt quality. A vicious circle prevails in which technologies are hardly adopted because of the lack of evidence of added value, whilst evidence of added value is lacking because the technologies are rarely adopted. Technology adoption may also be hindered by the scepticism and reluctance of operators. They can feel that their workmanship is being devalued or that management could use the technology punitively (Miller 2010). Progress in adopting and fully integrating new technologies into current experience-driven operational strategies will only come about 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.

The findings of this research demonstrate the value of integrating new technologies into current experience-driven construction practice and provide the following lessons to enhance technology adoption and implementation:

- ***Demonstrating the added value of using technologies in the on-site construction process breaks down barriers to technology adoption.*** By implementing technologies in practice, the added value of the use of technologies is widely demonstrated. Previous research efforts show that the new technology must provide a clear advantage to current practices (El-Halim and Haas 2004, Caerteling 2008, Gallivan *et al.* 2011). In this research, the essential data was collected that provide evidence of the importance and added value of using these new technologies. For example, the added value of the use of GPS and temperature scanners is widely demonstrated in the Netherlands and is now nationally recognised. Demonstrating this added value breaks through the vicious circle of no technology adoption leading to no evidence of the importance of new technologies leading to no adoption. In doing so, barriers to technologies adoption were broken down promoting the technology adoption and implementation process.
- ***A research network provides opportunities to test prototypes, synthesise them with practitioners' needs, reconfigure and improve the solutions.*** This assists technology adoption and implementation in

practice. During the research trajectory, the ASPARi network evolved to a test-bed for new technologies. Manufacturers of rollers, of GPS equipment and of density measurement systems approached the network themselves, provided the technologies to be tested, and received feedback on how the technologies need to be improved to better meet the requirements of the final users. As indicated by El-Halim and Haas (2004), the opinions and constructive criticism of researchers, practitioners and users are a vital step for successful development and implementation of technologies. The research network provides these opinions and criticism, and strengthens the link between, researchers, contractors and manufacturers. This supports the successful development and implementation of technologies that are synthesised with the needs of practitioners.

- ***Researchers adopting a mediating role is relevant for enhancing technology adoption and implementation.*** The researcher is an essential link in connecting people within asphalt construction companies, between different contractors, and between contractors and other stakeholders, such as machine and technology manufacturers. In this research, the researcher adopted the position of a mediator, and the explicit data facilitated in communicating and mediating between stakeholders about technology enhancements. By adopting a mediating role, the researcher is able to inspire practitioners for testing and adopting technologies and to encourage the further adoption and implementation of technologies in the on-site asphalt construction process.

Enhanced understanding of the relevance of connecting laboratory procedures with the on-site construction process

With the on-site construction process becoming increasingly explicit, there is a need for enhanced understanding of the relevance to connect laboratory procedures with the on-site construction process. In order to evaluate the influence of employed on-site operational strategies on asphalt quality and to design operational strategies in the laboratory before actual construction, field and laboratory procedures need to be connected.

Various laboratory tests have been developed and accepted for determining certain asphalt characteristics, such as the Indirect Tensile Strength test, the triaxial test and the four-point-bending test. However, there is limited agreement throughout scientific community and industry with regard to the test procedures required to predict asphalt mixture performance and how this relates to field construction and performance (ter Huerne 2004, de Visscher 2006, Schmitt *et al.* 2009, Plati *et al.* 2014). Little research effort has gone into aligning laboratory procedures with the actual on-site construction process or into the sensitivity of asphalt quality characteristics to changes in on-site construction process. The existing laboratory procedures barely take process parameters and activities into account to reflect the field construction process. Clearly, this has traditionally been near impossible given the largely implicit on-site processes. Only when the on-site process is systematically monitored and mapped, it does become possible to connect laboratory design procedures with realistic on-site operational strategies.

This research developed a basis to connect laboratory design procedures and the on-site construction process which is important in two ways. First, the framework enables the evaluation the influence of employed on-site operational strategies on asphalt quality in the laboratory. This is relevant to distinguish between good and poor operational strategies, but also, for example, to guide the coring and testing process, more specifically determine the places where to drill and extract cores based on an explicitly monitored construction process. Second, the framework enables to design operational strategies in the laboratory in order to better guide the on-site construction process. This is a crucial step for laboratory testing, whereas not only the asphalt mixture, composition and potential asphalt quality characteristics will be designed, but also the on-site construction process, possibly for various conditions per asphalt mixture.

This research contributes to an enhanced understanding of the relevance for better connecting laboratory procedures and the on-site construction process in the following ways:

- ***To evaluate the impact of the on-site process on asphalt quality and to design the on-site process, it is vital to align laboratory and field procedures based on explicitly monitored data on-site.*** This research shows that there is a disconnect between field practices and laboratory procedures, in terms of compaction temperature, asphalt cooling and roller regimes. If laboratory design procedures are not aligned with the on-site process, it is very inefficient design the on-site construction process and to distinguish between good and poor operational strategies, for example by trial-and-error on-site leading to long learning cycles or by constructing various, costly, test sections. The compaction procedures generally used in the laboratory aim to achieve a certain density and based on that density determine the potential mechanical and functional characteristics of the compacted material (Muniandy *et al.* 2007, Mollenhauer and Wistuba 2013, Airey and Collop 2014, Plati *et al.* 2014). However, these procedures make little attempt to simulate the real field compaction process. This research took important steps by aligning laboratory and field compaction procedures in terms of initial compaction temperature (Chapter 5), asphalt cooling and rolling regimes (Chapter 6). The developed procedures respond to the need for better aligning laboratory and field compaction. It enables the evaluation of the effects of employed compaction strategies on asphalt quality and the design of compaction strategies in the laboratory to provide improved guidelines to operators on-site.

- ***On-site process parameters and activities substantially influence asphalt quality characteristics.*** This responds to the lack of empirical data between on-site process parameters and asphalt quality characteristics as well as to the ongoing debate to align laboratory and field procedures. The empirically tested relationships between the on-site process and asphalt quality demonstrate that it is relevant to align laboratory and field procedures. This is an essential departure to design the on-site construction process in the laboratory and to evaluate employed operational strategies. The following empirically tested relationships demonstrate that it is relevant to align laboratory and field compaction procedures:
    - The temperature of the asphalt mixture and the cooling process is barely taken into account in current laboratory compaction procedures. Only a starting temperature based on the bitumen grade and the viscosity is defined and reported. The current laboratory methods specify to compact within a small temperature range (typically 5-20 °C) whereas the field compaction process takes place over a much larger temperature range (from maybe 160 °C down to 60 °C). This research has developed laboratory compaction procedures that take this range of compaction temperatures into account as well as the cooling of the mixture during the compaction process. The experiments with different compaction temperature ranges show that ***compacting during sub-optimum temperature windows can decrease the relevant mechanical properties by up to 30% for a representative base layer and by at least 10% for a representative surface (Stone Mastic Asphalt) layer.***
    - The current laboratory compaction procedures often fail to make a distinction between the on-site pre-compaction by the paver and the final rolling compaction process, on-site conducted by different type of rollers. Some studies based on rolling compaction in the laboratory use an unrealistically high number of roller passes (60-75 passes) in comparison to field compaction (Muniandy *et al.* 2007), maybe on the premise that density is all that matters. This research initiated laboratory compaction procedures that were based on actual monitored roller regimes with the aim of bringing on-site and laboratory compaction closer

together. The experiments with different roller regimes show that ***compacting using sub-optimal roller regimes can vary the relevant mechanical properties by at least 10% for a representative surface (SMA) layer.***

The outputs from this research are relevant for the Civil Engineering domain because they provide: an improved understanding of the asphalt construction process to improve on-site operational strategies; ways to break down barriers to technology adoption; methods to make the tacit knowledge of asphalt operators and teams explicit; a basis to align laboratory procedures and the on-site construction process to evaluate the impact of the employed operational strategies on asphalt quality and to design the on-site construction process before actual construction.

Together, this research is an essential step that provides methods for researchers and practitioners to implement technologies, analyse operational strategies of asphalt teams and their effects on asphalt quality, design the asphalt construction process and enhance reflective and method-based construction practices.

9.2 Practical relevance

Apart from the theoretical implications, the findings of this research also have practical relevance for contractors, agencies and machine and technology manufacturers in improving the asphalt construction process.

Relevance for contractors

<u>Operational level</u>

- ***The improved PQi framework and the method-based learning model stimulate meaningful discussions with the team's operators in working towards process improvements.*** The implementation of the improved PQi framework, as discussed in Chapter 2, and the method-based learning model, as described in Chapter 4, enable asphalt teams and operators to gain deeper insights into their own operational strategies. For example, the feedback sessions with operators open up a communication channel between operators, field engineers, and managers in addressing process improvements, as demonstrated in Chapter 4 (Table 4.4). The technologies used and the data gathered helps practitioners to unravel the logic and reasoning behind the chosen strategies and triggers operators to verbalise their tacit, implicit knowledge. The explicit data and operators’ knowledge assist in employing construction process improvements.

- ***The gathered dataset creates opportunities to actively test solutions for reducing process variability.*** The systematically collected on-site data provide operators and asphalt teams with deeper insights into both the variability in their own processes and the process variability of other teams. The data offer pointers as to where action can be taken to reduce process variability and improve both current and future operational strategies. For example, evaluating the use of a Material Transfer Vehicle (MTV) on its merits to reduce temperature differentials by analysing the lay-down temperatures behind the paver measured by the linescanner, as described in Chapter 2.

<u>Project management level</u>

- ***The explicit data allow project managers to improve the organisation and allocation of their equipment, operators and monitoring technologies.*** The explicit data on the on-site construction process enable project managers to link other phases of the construction process, such as work preparation and asphalt design, to the on-site construction process. For example, by determining the number of asphalt trucks required for transportation based on the speed of the paver and the roller set.
- ***The on-site construction data and laboratory procedures help project managers to better inform and guide asphalt operators on-site.*** The explicit on-site construction data provide the opportunity to relate on-site operational strategies to asphalt quality using laboratory-based procedures. The procedures developed in Chapter 5 and 6 for compacting asphalt in the laboratory are a stepping-stone in enabling project managers to better specify the field compaction process. For example, the laboratory experiments show that compacting SMA with first a three-drum roller and then a tandem roller results in 10% lower Indirect Tensile Strength compared to other roller regimes. Given some caution of variability in laboratory test results and varying circumstance in practice, this information is valuable to provide better guidance to roller operators. By further aligning laboratory procedures, project managers can grasp the sensitivity of asphalt mixtures to variability in the on-site construction process before actual construction. This will help project managers to better inform and guide asphalt operators on-site.

<u>Organisational level</u>

- ***The implementation of the improved PQi framework boosts contactors to take responsibility for the data-collection and analysis of***

their own on-site construction process. Rather than researchers collecting and analysing the data, contractors in this research were trained to take responsibility for the entire data collection process. Whilst researchers took responsibility for the ongoing process of data filtering and the transformation of raw data into visualisations, contractors also took responsibility for the post-construction analysis of their construction process. This is a huge departure and shows that contractors are now able to organize and execute the monitoring and analysis of construction projects themselves. Asphalt construction companies are encouraged to further test and adopt technologies, for example to monitor the layer thickness and paver settings, in their daily practice to systematically explicate and improve their operational strategies.

- ***The developed learning model facilitates contractors to have shorter, collaborative and method-based learning cycles.*** The on-site construction data enable the transition from an implicit to an explicit construction process, the feedback sessions enable the transition from individual to collaborative learning and together the developed method-based learning model enables the transition from experience-based to method-based learning. This forms a basis for improving and learning on various levels within their companies. As part of this process, the model developed for method-based learning is valuable in creating a learning environment within the organisation. For example by adopting feedback sessions with operators in their process. The procedure for enhancing method-based learning creates process and quality awareness and improves communication across various levels of the company. Both an explicit process and an opportunity to discuss the process during feedback sessions are essential in creating shorter, collaborative and method-based learning cycles and enhance a learning organisation.
- ***The laboratory procedures and the empirical data are a stepping-stone for contractors to evaluate the employed operational strategies and to design their strategies in the laboratory.*** Contractors should use and further enhance the developed laboratory procedures to ascertain the effects of different compaction strategies on the asphalt quality for various asphalt mixtures and conditions before actual construction. This will help contractors to distinguish between good and poor operational strategies, to design the on-site operational strategies in the laboratory before construction and to provide better guidelines to asphalt teams and operators on-site.
- ***The implementation of the improved PQi framework stimulates contractors with further training and education opportunities within their company.*** An example of this educational opportunity is

provided by the several contractors, who have already used the monitored projects in presentations during their annual 'asphalt days' that are organised during winter-time to inform and educate people involved in asphalt projects. To further train and educate operators, steps are currently being undertaken to develop a virtual construction site in which scenarios from actual monitored projects can be played back, and alternative operational strategies discussed, to boost quality awareness and diminish process variability in future projects (Vasenev *et al.* 2013).

- ***Overall, contractors are enriched with a competitive advantage.*** A better understanding of their own construction processes for on-site construction improvements, the use of additional technologies for improved process and quality control, and a method-based learning environment provide contractors with a competitive advantage. By reshaping and improving their operational strategies based on explicit data a higher asphalting quality can be achieved.

Relevance for agencies

- ***The improved PQi framework enables agencies to reduce their risks and fits in the current contracting philosophy.*** Dutch road agencies nowadays use system-oriented contract control (Dutch: Systeemgerichte contractbeheersing), in which contractors are responsible for their own quality assurance and quality control, and road agencies check the contractors' systems using system, product and process checks. Within this context, agencies can challenge contractors in a contractual manner to perform a system-check or process-check on the construction process, i.e. systematically monitor the on-site construction process and map this process data for quality assurance and control. The improved PQi framework provides methods and technologies to systematically monitor and map the on-site construction process. Such additional contractual requirements reduce the risk for agencies of accepting a poorly constructed deliverable. This fits in the Dutch contracting philosophy, in which contractors are responsible for the quality assurance and control, and road agencies check and control the contractors.
- ***The implemented technologies create opportunities for agencies to encourage the use of technologies for improved process and quality control.*** Agencies can support the use of available monitoring 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. Whilst it is demonstrated that the compaction

temperature, asphalt cooling and rolling regimes are relevant, agencies can, for example, stipulate that the contractor must monitor and map these relevant key parameters and operations. During the research trajectory, several agencies were already starting to include some requirements in their contracts, such as the prescription 'to monitor lay-down temperatures behind the paver' and some agencies penalises 'stopping places of the paver' to encourage a continuous process. Although some of these requirements are not yet functionally described in contracts, the innovative power of contractors is being challenged to integrate technologies in the on-site construction process towards improved process and quality control.

- ***This research observed variability in test results between different laboratories and contribute to a ground for agencies to compare test results.*** Since 2008, the Dutch asphalt construction industry has chosen to work with functional and mechanical properties of asphalt (CE-marking), in which a reliable relationship between the characteristics tested in the laboratory and the performance in the field is essential. Although it was already known that different laboratories and compaction methods result in asphalt samples with different mechanical properties (Mollenhauer and Wistuba 2013, Airey and Collop 2014, Plati *et al.* 2014), this research observed that these differences can vary up to 40%. The experimental results described in Chapter 6 demonstrate maybe no more than the tip of the iceberg in variability between laboratory test results. These results stimulate agencies to further standardise test procedures and create a ground such that the test results of different contractors can be meaningfully compared. Therefore, the research programme initiated to determine relationships between various laboratory tests and field performance (NL-LAB) is strongly encouraged.
- ***Overall, this research assists agencies in the design and construction of long-lasting roads.*** In essence, road agencies are responsible for providing a sustainable, durable and safe road. The deeper understanding of the on-site construction process supports the design of a process that minimises the hindrance of road users, for example by enabling better-informed decisions regarding the timing and duration of road closures.

Relevance for machine and technology manufacturers

- ***The implementation of the improved PQi framework and accompanying technologies in practice boosts the adoption and implementation process of technologies developed by manufacturers.***

By testing and implementing various technologies in the asphalt construction process, the adoption process of technologies, such as GPS and temperature scanners, is further enhanced. For example, the added value of the use of GPS and temperature scanners is now nationally recognised. An improved understanding of the on-site construction process is relevant for machine manufacturers in helping them to break down barriers to technology adoption and implementation. The explicit data on on-site construction processes are relevant to placing manufacturers' equipment and technologies in the context of the entire asphalt construction process.

- ***The on-site construction data and feedback sessions allow manufacturers to better align their machines and technologies with the operators' needs.*** The explicit on-site construction data and feedback sessions provide information about the operators' needs. It is increasingly important for manufacturers to design their machines not only from a mechanical perspective, but also from the practical on-site asphalting perspective. For example, by providing more detailed information about the temperature of the asphalt mixture, about the cooling of the asphalt mixture and possibly about the density progression during the compaction process. The data collected on the on-site operational strategies of asphalt teams help machine manufacturers to design their machines based on the operators' needs.
- ***The research network (ASPARi) allows manufacturers to test their prototypes with the potential users and improve their solutions.*** The ASPARi research network is a unique testing ground for providing manufacturers with feedback from potential users, such as operators, asphalt teams and technicians, on their products. Machine manufacturers are challenged to use the opportunities provided in research networks, such as ASPARi, to test prototypes in order to improve their offered solutions.

To conclude, this research makes the following practical contributions: for contractors to improve their on-site operational strategies of asphalt teams and by providing pointers to reduce process variability; for agencies to reduce their risks and to encourage improved process and quality control; and for machine and technology manufacturers to enhance technology adoption and implementation in practice. Together, this research is an important step that leads to construction process improvements, more consistent asphalt quality, and more professional operators and asphalt construction companies.

9.3 Recommendations

The research outcomes emphasise that the on-site construction process substantially influences asphalt quality. Therefore, further attention must be given, in science and practice, to the asphalt construction process and its effects on the final quality rather than focussing mainly on advanced construction materials and production techniques. Both science and practice are recommended to continue research from technological, human (operator) and laboratory perspectives, given that these perspectives mutually reinforce each other to enhance the quality of the asphalt construction process.

Researchers are recommended to:

- Further test technologies for their potential relevance in the on-site construction process. For example, technologies to monitor and map the paver settings and the layer thicknesses during the construction process.
- Advance laboratory design procedures and further align them with the on-site construction process. For example by better simulating compaction of the paver and the pneumatic tired roller in the laboratory. It is further recommended to reduce variability in laboratory testing, for example by automating the mixing process. To test various asphalt quality characteristics, such as particle orientation (X-ray topography) and fatigue (4point-bending test), it is recommended to search for further collaboration with universities that are specialised in asphalt materials and testing techniques.
- Put further research efforts into investigating the effects of additional feedback and learning loops with asphalt teams and operators on process quality. For example, by further developing the questionnaires used in this research and discussing the results during feedback sessions, possibly during long-term studies with asphalt teams.

Contractors are recommended to:

- Integrate technologies in the asphalt construction process, such as GPS, laserlinescanners and infrared cameras, to make key activities and parameters explicit, especially in performance contracts with lengthy guarantee or maintenance periods.
- Further align laboratory procedures with the on-site construction process. In doing so, attention should be given to the variability in test results and between laboratories. Contractors are advised to

take part in the initiated programme to determine relationships between laboratory test results and field performance (NL-Lab).

- Include additional opportunities for feedback and reflection with asphalt teams into their process. This helps to verbalise the current experience and craftsmanship and to better align the on-site construction process with other phases of the supply chain, such design and work preparation.

Agencies are recommended to:

- Include system and process checks into their system-oriented contract control (Dutch: Systeemgerichte contractbeheersing) regarding the on-site construction process. In doing so, agencies further stimulate the innovative power of contractors for further quality assurance.
- Encourage the use of new sensors and technologies to make the on-site construction process explicit by including (functional) requirements into their contracts. This challenges contractors to integrate technologies into their process for improved process and quality control.
- Empower innovation and test projects in which contractors are challenged for a professionalised asphalt construction process. Examples of previous challenging projects are 'More silent, cleaner and more homogenous asphalt' (Dutch: Stiller, schoner en homogener asfalt) and 'Paving below zero centigrade' (Dutch: Asfalteren onder het vriespunt).

Machine and technology manufacturers are recommended to:

- Align their machines and technologies with the asphalt operators' needs by testing and evaluating their prototypes with asphalt operators in practice.
- Use networks, such as ASPARi, to design their machines and technologies from an operational asphalting perspective and to test their prototypes in order to improve the offered solutions.
- Integrate the collaboration with research networks, universities and researchers into their technological agenda and roadmaps in order to tap into the knowledge base and the ideas for machine and technology development.

9.4 Impacts on the ASPARi network

Besides the practical implications for contractors, agencies and manufacturers, this research has also impacted on the established ASPARi network. Contractors work together with the university on technology development and on professionalising the on-site construction process. The relevance of this research for the ASPARi network is:

- The network and members actively involved in the research projects have expanded considerably. During the research trajectory, new contractors joined the network, additional manufacturers were linked to the network as well as educational institutes. Further, a working group consisting of laboratory technicians from each founding member was established.
- The responsibility to organise and execute the monitoring of asphalt construction projects has moved from the university to the contractors. Whilst researchers still take responsibility for data processing and the development of visualisations, contractors currently take responsibility for the data collection and post-construction analysis of their construction process. This is an important step and shows that contractors are now capable of measuring and analysing their own construction processes. They increasingly recognise that it is vital to systematically monitor certain parameters rather than conducting ad-hoc measurements.
- Contractors also went through a behavioural change in terms of the use of new technologies in the on-site construction process. Initially, contractors were reluctant to use new technologies in their processes. Today, contractors take the initiative to search for and integrate additional technologies in their construction processes in a systematic manner.
- Finally, the work of the ASPARi network is increasingly recognised in both national and international platforms. Nationally, the network has gained broad recognition in the industry, with researchers being invited to make presentations during national asphalt days. Internationally, at various conferences and in several scientific journals, the work of ASPARi has been visible. This recognition not only increases the status of the ASPARi network, but also the status of the contractors involved.

In conclusion, this research impacts the ASPARi network positively in terms of active involvement in the research topic, contractors taking the responsibility of monitoring on-site construction processes, the positive stance of contractors on additional technologies in the process, and finally the recognition and status of the research network.

9.5 Contributions to closely related research

This research is in many ways close to the work of Miller (2010) and has built upon his results. As such, it is relevant to emphasise the contribution of this research to the work of Miller (2010) and to explain where it differs from previous work. First, the main contributions by Miller (2010) are summarised, and then the contributions of this research, in terms of the work of Miller, are explained.

Miller (2010) conducted research that explored key parameters of the asphalt construction process by making operational behaviour explicit using a combination of technologies, models and visualisations. The aim was to enrich understanding of the asphalt construction process and to work towards consistently reducing the variability inherent in the process. Miller (2010) conducted ground-breaking work by testing various technologies in the asphalt construction process and making several key parameters and operations explicit. Tools and visualisation techniques were developed to create deeper insights into the on-site asphalt construction process.

So, several technologies were tested and introduced into the asphalting process, and their relevance in making on-site activities and key parameters explicit was demonstrated. Further, a network (ASPARi) was established in which practitioners and researchers work together on introducing technology along with the professionalisation of the on-site construction process.

The current research has continued this direction and has made the following contributions to the work of Miller (2010):

- The PQi framework has been enhanced for implementation in the industry by improving and formalising the process, by reducing the cycle time in analysing the data and by shortening the feedback cycle to the asphalt team and operators.
- The framework has been gradually implemented in construction practice by educating the contractors so that they are able to conduct the measurements on their own, and then to analyse and reflect on the gathered data. PQi and laboratory working groups were established within the ASPARi network to discuss experiences and results.
- The number of measurements are scaled up in order to create an extensive dataset of on-site monitored data. Thirty projects were monitored, analysed and made explicit. From this dataset, conclusions were drawn regarding process variability and common operational practices. The established dataset is relevant and

practical for researchers in further analysing and promoting research into the on-site construction process.

- This research has pushed on towards more explicit and method-based learning practices. Miller (2010) had already introduced a feedback step into the PQi framework. This research adopted the learning model of Kolb (1984) and added 'monitoring the process' (explicating) to this learning model. The resulting method-based learning model was tested in practice and was shown to be useful in improving awareness of the process quality.
- This research advanced by relating the monitored on-site strategies of asphalt teams to the asphalt quality in terms of mechanical properties determined in the laboratory. Initial steps were taken to align laboratory compaction procedures with field compaction practices in order to evaluate the employed compaction process and to design the on-site compaction process in the laboratory.

The current research is also closely related to the research of Vasenev (2011, 2012, 2013, 2014). First, the research work of Vasenev is briefly explained and then the contributions of this research, as they relate to the work of Vasenev, are explained.

Vasenev conducts vital research work in (1) combining various 'hard' sensor data with 'soft' operator data and translating this into understandable visualisations, (2) developing prototypes to provide real-time information to on-site operators about key parameters and activities, and (3) developing a virtual construction site, where operators are trained and educated and gain a deeper understanding of the on-site asphalt construction process. The work of Vasenev provides practitioners with the opportunity to verbalise their tacit knowledge and make that knowledge explicit, and to experiment with and evaluate alternative working strategies, both individually and as a team.

This research and the work of Vasenev strengthen each other in contributing to the professionalisation of the on-site asphalt construction process. This research complements Vasenev's work and has made the following distinct contributions to that work:

- The expanded ASPARi network is essential for testing and evaluating, with practitioners, the visualisations and prototypes developed by Vasenev. The network provides opportunities to implement research findings in practice.
- The developed visualisations, as well as the systems developed to provide real-time information support to operators on-site, by Vasenev, were used in this research. The feedback sessions in this

research facilitated opportunities to evaluate and provide feedback on the developed visualisations and prototypes.

- The construction projects monitored in this research form essential input for the virtual construction site. In turn, the developed virtual construction site is valuable in feedback sessions by explicating tacit knowledge, opening up an additional communication channel and enhancing the learning and reflection competencies of asphalt teams.

Further, this research is not directly connected to the research work of Caerteling (2008) and Caerteling *et al.* (2013), who studied the roles of government in technology development for the road construction industry, but various phenomena are observed that are relevant for this line of research.

Caerteling found that government championing behaviour is key in the success of technology development projects, and exceeds both public procurement and government assistance. Further, Caerteling shows that defensiveness and proactiveness of firms should not be seen as opposites but complementary in achieving high performance. The research empirically demonstrates that government roles extend beyond regulations and funding. Government as a buyer and champion is a significant factor in the success of technology development projects and thus championing behaviour is an important instrument in technology development and commercialisation.

During this research trajectory, examples of technology push, demand pull and governmental championing behaviour are observed, partially driven by the results obtained in the ASPARi network. The relevant phenomena observed for this line of research are:

- Road agencies apply forms of championing behaviour to advance technology development in road construction. An example is that road agencies sometimes prescribe the use of a Material Transfer Vehicle (such as Shuttle Buggy's) in order to reduce temperature differentials during the lay-down phase. Another example is that road agencies sometimes put penalties on stopping places of the paver in order to push for a continuous asphalt construction process. Further, the road agencies sometimes reward additional process and quality control in performance contracts and at times specifically support the use of the PQi framework and accompanying technologies, and thus actively promotes the technology's advantages. Altogether, this shows that several agencies adopt championing characteristics, which according to Caerteling (2008) is an important positive factor for technology development and commercialisation.

- Contractors, nowadays, adopt and push the PQi framework and technologies to show agencies the opportunities and added value of additional process and quality control. Further, the strategic behaviour of contractors is changing from largely defensiveness to more proactiveness. Several contractors were initially reluctant to use new technologies in their processes, while now contractors take the initiative to search for and use additional technologies in their construction processes.

To sum up, this research observed, in line with the research efforts of Caerteling, championing behaviour of road agencies and increasingly proactive behaviour of contractors. This research is complementary to the research of Vasenev by providing data for a virtual construction site and using the developed visualisations during feedback sessions with asphalt teams in this research. Further, this research has built upon the results of Miller and further advances in this direction by implementing the PQi framework and technologies in practice creating an extensive dataset with on-site monitored process data and relates laboratory design procedures to the on-site asphalt construction process.

9.6 Methodological contribution and reflection

An action research strategy was adopted and applied in this research. This strategy involved alternating steps of: (1) technology introduction and implementation in practice; (2) systematically monitoring and mapping field construction projects including feedback sessions with operators; and (3) experimenting with the effects of process variability on asphalt quality under controlled laboratory conditions. This was not a sequential process but enacted as a cyclic iterative process. The intention was to gradually implement technologies, improve on-site operational strategies and then create deeper understanding of the on-site asphalt construction process. The researcher worked closely with construction companies in the Netherlands, in both on-site construction projects and in laboratory research projects, in order to improve the on-site operational strategies of asphalt teams. This is a distinctive action research strategy for the asphalt construction domain. Using this engaged action research approach, in which the researcher is directly involved in the projects in practice, enables the following methodological contributions:

- This research validates and demonstrates that participatory action research is appropriate and useful for the asphalt construction industry. The developed triangulation approach leads to progressively improving on-site operational strategies from (1) a technological perspective, (2) a human (operator) perspective and (3) a laboratory design perspective. It helps to better align technology development, on-site construction processes, and laboratory design. These perspectives mutually reinforce each other to gradually create deeper insights into on-site operational strategies and to progressively improve them. For the asphalt construction industry, this is a distinctive combination of perspectives and research methods, and has proved valuable in progressively improving on-site operational strategies.

- The process and operational perspectives are often neglected in research on asphalt road construction. The adopted action research strategy provides deeper insights into the on-site asphalting process. The active involvement of the industry in this research offers opportunities to conduct research from an operational perspective. The willingness of the asphalt teams and operators to cooperate and their openness, are vital to the success of this research.
- The action research approach, in which theories on asphalt construction are developed and further tested in parallel with considering the implementation of the theories in practical settings, helps to embed the research findings in practice. For example, technologies were tested and evaluated in collaboration with practitioners. Then, a framework was developed to systematically monitor the on-site construction process, leading to procedures for monitoring and analysing, which were then formalised and standardised. These were finally transferred to the industry by providing courses to educate the contractors and enable them to monitor their own on-site construction processes. The collaboration between practitioners and researchers is vital in providing deeper insights into on-site operational asphalting strategies.
- The engaged research approach, in which the researcher was working in a practical setting, was essential in understanding the complexities of the asphalt road construction process. The process can only be captured by describing what really happens when asphalt teams are doing their job, incorporating the context in which they operate, as well as their frame of reference.
- The adopted research strategy was shown to be relevant for both introducing and developing new technologies in the construction industry that fulfil the on-site needs of operators and for making the on-site construction processes explicit using these technologies. By organising feedback sessions with the operators, it became possible to start a discussion on current operational strategies and improving current practices.

The chosen action research strategy had various advantages when it came to the implementation and evaluation of technologies and in providing insights into the on-site construction process from an operational perspective. However, the chosen strategy and methodology also raises some difficulties and challenges:

- Carrying out research in a network of eleven contractors is valuable because of the amount of data that can be generated, communicating with and organising working groups of the various contractors is time consuming. So, researchers who opt for this strategy should take into account that 'managing' the contractors and people involved is time consuming.
- Starting up working groups, such as the PQi and laboratory working groups within the ASPARi network, takes time. While this led to a dataset addressing the similarities and differences between companies, it made it more complex to determine relationships between operational strategies and pavement quality because different laboratories can produce conflicting results.
- Formalising data collection and analysis in a structured way is important for ensuring broad implementation of the technologies and methods in the industry. The sooner that procedures and manuals are formalised, the more time that becomes available for analysing the data and introducing new technologies.
- Maintaining a long-term relationship with contractors is important in this kind of research, and support is required from various levels within the companies. Support from operational-level asphalt teams is essential to implement technologies and understand the strategies chosen on the construction site. Support from project managers, R&D departments and directors on the tactical and strategic levels is important in ensuring the continuation of research projects and demonstrating the relevance of the research within the company.
- Finally, this research strategy was chosen and conducted with a pragmatic research philosophy in mind. For researchers with a more positivist philosophy, the chosen action research strategy may prove challenging because many of the insights were not provided by inductively generalising from data, but rather from reflecting on conceptually organised data from various viewpoints.

In conclusion, the research strategy had various advantages as well as some difficulties. However, the chosen research strategy has proven to be relevant, especially in this phase of the professionalisation trajectory where contractors had to be included in the monitoring of asphalt construction projects.

9.7 Limitations

This research provides interesting scientific, methodological and practical contributions. However, it should also be acknowledged that much is still unknown and uncertain about asphalt construction processes and their relationship with the asphalt quality:

- To date, approximately 30 paving projects have been systematically monitored and mapped using the PQi framework. Although this might seem a lot, many parameters vary, such as the asphalt mixture, weather conditions and several key project conditions. Therefore, it is still difficult to extract statistically meaningful relationships. To extract statistical relationships, more projects have to be monitored. If more projects are monitored, Structural Equation Modelling (SEM) could assist to statistically determine relationships between key parameters, operational strategies and asphalt quality parameters.
- In this research, a first step has been made in bringing laboratory compaction closer to field compaction. However, when attempting to simulate field compaction in the laboratory, several issues remain unclear, such as the effect of the speed of the roller and the influence of further compacting once the desired density is reached, i.e. when compaction becomes critical and when it is still acceptable. Also, the conclusion was drawn that the variability between test results of various laboratories is rather high and needs to be reduced.
- All the monitored construction projects took place in the Netherlands. The likely generalisability of the results to other countries can be evaluated by studying if the observed operational strategies and process variability are similar in other countries using the improved PQi framework as well as by studying whether the method-based learning approach including feedback sessions with operators can be used in other countries.

The limitations of this research can be overcome by further research. The next section describes an agenda for future research.

9.8 Agenda for future research

Although this research involved relevant work regarding the professionalisation of asphalt construction processes, the industry is still changing and new trends are visible. In the near future, a greater focus on the on-site construction process and on quality control as a contractual requirement is expected, and more technologies will be introduced to the market, creating new challenges and opportunities. Given the findings of this research, the following directions for future research are recommended:

- Monitoring asphalt construction projects is the backbone of the professionalisation of the on-site construction process. It is therefore vital to continue monitoring projects and increasingly gather data about the on-site construction process. From the monitored projects, process variability becomes increasingly visible, creating new research questions on how this variability influences asphalt quality and how it can be reduced. In future research, the monitoring should be more focussed on specific asphalt mixtures and conditions in order to be able to extract statistical relationships. The data collected during on-site monitoring are the basis for connecting the on-site construction process with other parts of the supply chain, such as the laboratory design and project preparation stages. The data can also be used for georeferencing of roads, in which on-site construction data can be related to other georeferenced datasets, for example inspection data of a road. Initial steps have been taken by Sluer *et al.* (2014) to overlay these datasets but it is too early to observe significant damage.
- While a basis is laid to connect laboratory procedures and the on-site construction process, further steps are required in order to really design the on-site construction process and provide improved guidelines to operators and teams on-site. Besides monitoring on-site construction projects, more research effort needs to be put into simulating on-site construction processes in the laboratory and determining their effects on asphalt quality. Along this direction, it is recommended to search for further collaboration with other universities, for example to test various asphalt characteristics, such as particle orientation (X-ray topography) and fatigue (4point-bending test). When it becomes possible to accurately imitate the on-site construction processes in the laboratory, the observed variability in on-site processes and its link to the final asphalt quality will be able to be investigated under controlled circumstances. This will create opportunities to investigate various potential on-site processes in the laboratory and determine optimum conditions. This will reduce the number of test sections that have to be constructed for new mixtures or when asphalt mixtures have to be constructed under critical circumstances, for instance in sub-zero ambient temperatures. This is a vital step along the road towards method-based asphalting practices and provide improved guidelines to operators as part of the further professionalisation of the asphalt construction process.
- An important trend that needs to be recognised is the aging population and the shortage of educated people in the construction industry in general, and specifically in the asphalt paving industry. Anecdotal evidence shows that in the last couple of years in the

Netherlands, only three to five people have been educated annually as paver/roller operators, whereas at least double that number have retired. It is therefore important to develop and start educational programmes at various levels (technical craftsman schools, and higher and scientific education) regarding on-site asphalt construction and operational strategies to overcome the expected shortage of educated personnel.

- Another inevitable trend is the increasing technocratic nature of society. Increasingly, technologies will be introduced in the construction industry. For many of the new technologies it will initially be unclear how good they are and what kind of useful information they provide. Therefore, it will be important to have a network that evaluates and tests the new technologies coming on to the market.
- In future research, it will be essential to take the step to using real-time information on-site. By providing real-time information on-site, it becomes possible to evaluate what is being constructed in real-time and then possibly adjust the process if necessary. A challenge will be to combine all the data (data fusion) and handle those big datasets in such a way that it becomes comprehensible to operators and provides the information needed to adjust and improve the process where necessary.

Some future research initiatives are included in the ongoing road to professionalising the asphalt construction process in the ASPARi network. The next section will close the loop in terms of the initial aim set in this research, after which a sketch will be projected about the ongoing professionalising trajectory for the ASPARi network.

9.9 Closing Remarks

At the start of this dissertation, the following aim was set for this research: *"To improve on-site operational strategies by developing deeper insights into the on-site activities and key parameters and their relationships with the asphalt quality."* Given the main findings and implications of this research, the researcher is confident that this research contributes to a deeper understanding of the on-site asphalt road construction process and its impact on asphalt quality. The current on-site operational strategies can progressively be improved by a combination of: (1) explicating on-site operational strategies; (2) making process variability explicit as a step towards more consistent operational strategies; (3) using more method-based operational working practices; (4) understanding the influence of variability in on-site operational strategies on asphalt quality; and (5) aligning on-site operational strategies and laboratory procedures. The findings are a vital step in providing opportunities to improve on-site operational strategies for contractors, agencies and machine manufacturers. Given the wider discussion on the role of technology enhancements, and of consistent and method-based working practices, in the construction industry, this research remains relevant and offers practical tools to improve on-site operational strategies. The research approach, the monitoring framework, the method-based learning model and the empirical data all offer opportunities to professionalise the traditional, experience-driven construction industry such that it better fits with current and future policies and practices in the asphalt road construction industry.

9.10 The ongoing road to professionalising the asphalt construction process

This research should be seen as a step towards the professionalisation of the asphalt construction process. It was not the first step and it will not be the last. About ten years ago, the Dutch asphalt road construction industry changed dramatically. In 2005, the ASPARi network was initiated and the University of Twente and several contractors bundled their professionalisation activities together in research projects and technology developments to improve the performance of the asphalt road construction industry.

In the period from 2006 to 2010, Miller (2010) conducted ground-breaking work by implementing various technologies into the asphalt construction process and making several key parameters and operations explicit. Tools and visualisation techniques were developed to create deeper insights into the on-site asphalt construction process.

The research reported in this thesis has continued in this direction and implemented the developed monitoring framework into construction practice to make process variability and common operational strategies explicit. Further, the research has made advances towards more consistent and method-based working practices and by relating the now explicit on-site operational strategies to laboratory design procedures. This is relevant in order to evaluate the employed on-site construction process and to design the on-site process before actual construction.

The growing focus on long-term guarantee periods, effectively transferring risks from agencies to contractors, is continuing to increase the pressure on the on-site asphalt construction process. In response, the professionalisation of the asphalt construction process within the ASPARi network will continue. Professionalisation in the next few years should focus on providing real-time information support to operators on-site, further aligning laboratory and on-site procedures including a thorough evaluation and redesign of the on-site construction process based on realistic laboratory tests, and the development of a broad educational programme in the Netherlands to support asphalt construction. Together, these actions should lead to a more professional asphalt construction process and better constructed asphalt roads.

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About the author

Frank Bijleveld was born in 1986 in Zwolle, the Netherlands. In June 2007, he received his Bachelor of Built Environment (BBE) at the University of Applied Sciences in Leeuwarden. In February 2010, he finished his Master of Science (MSc) in Civil Engineering and Management at the University of Twente. Frank previously worked for two civil engineering contractors, BAM Wegen bv and Ooms Nederland Holding bv, where he was involved in asphalt construction projects. Also, he worked for KOAC-NPC, a commercial services provider in road construction, covering consultancy, research, road monitoring, laboratory research, and quality supervision.

In October 2010, he started as a PhD researcher in the Department of Construction Management and Engineering. This research is about 'Professionalising the asphalt construction process'. He has published about his research in various journals, national and international conferences and in professional magazines. He has given various presentations about his research for national and international asphalt-related communities. During his research he worked closely together with eleven Dutch contractors within the ASPARi (Asphalt Paving Research and innovation) network that gives him a unique background and set of skills in asphalt road construction.

This research addresses the need to professionalise the asphalt construction process. A distinctive action research strategy is designed and carried out to progressively improve operational strategies of asphalt teams from technological, human (operator) and laboratory perspectives. Using information technologies, such as GPS, a laser-linescanner, and infrared cameras, the on-site construction process is made explicit. More than thirty asphalt construction projects are systematically monitored and mapped demonstrating the extent of process variability. By organising feedback sessions with asphalt teams, the tacit operators' knowledge is extracted. In the laboratory, the monitored process is simulated and compaction procedures are developed to evaluate and design the process. This research provides methods for researchers and practitioners to implement technologies, analyse operational strategies of asphalt teams and their effects on asphalt quality, design the asphalt construction process and enhance reflective and method-based practices. This is an important step that leads to construction process improvements, more consistent asphalt quality, and more professional operators and companies. Together, this research contributes to a professional asphalt construction process and to better constructed asphalt roads.

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