Shifting paradigms: Process quality as an indicator for asphalt quality.

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Master construction management and engineering

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Hengelo, October 15, 2024

I. Preface

You are about to read the thesis *"Shifting Paradigms: Process Quality as an Indicator for Asphalt Quality."* This thesis represents the completion of my master's degree in "Construction Management & Engineering", with a specialisation in *"Digital Technologies in Construction"*, at the University of Twente. Conducted between February and September 2024, this research focused on asphalt construction and served as the final component of my studies. The research was supervised by the ASPARi research network and hosted by Ballast Nedam, where I was supported as a graduate. I also benefitted from additional supervision from BAM and Dura Vermeer.

This thesis would not have been possible without the guidance and support of several key individuals. I express my sincere gratitude to my supervisors at Ballast Nedam, Radjan Khedoe and Jan van de Water, and my supervisors at BAM, Marco Oosterveld, and at Dura Vermeer, Robbert Naus. Jan generously extended the offer to work under his supervision two years before I began this thesis, a gesture for which I am deeply grateful. This opportunity laid the foundation for pursuing this research, which continuously captured my interest while also challenging me to grow.

I would also like to extend my thanks to Seirgei Miller and João Santos for their invaluable feedback and for serving as members of my graduation committee. Their guidance, full of energy and support, made a significant impact on the direction and quality of this work.

A special thank you goes to my girlfriend Lise, who has been an incredible source of support throughout the entire graduation period. I would also like to thank my friends and family for patiently listening to my endless stories about asphalt. Additionally, I want to acknowledge my friend Hidde, with whom I spent countless days at the University during this phase of my studies. Our discussions, coffee breaks, and shared experiences made the thesis writing process far more enjoyable than it would have been alone.

During my time at Ballast Nedam, I was offered a position by Jan van de Water at *"Nationaal Platform Duurzame Wegverhardingen"*. My role, focused on quality and performance, is perfectly aligned with the themes explored in this thesis. I am excited to bring the knowledge gained through this research into practice.

I hope you enjoy reading my thesis.

October 15, 2024

Bas van der Zande

Image front page: Ballast Nedam ©

Trust the process

II. Summary

In the changing field of asphalt construction, maintaining control over the construction process has gained increasing importance due to the rising expectations from clients. With clients demanding better performance and longer-lasting roads, contractors face the challenge of ensuring high product quality while managing complex construction processes. One of the key aspects of achieving these goals is understanding the influence of construction process quality on the final asphalt quality. Therefore, this thesis explores how monitoring the construction process can be integrated into Quality Control (QC) and Quality Assurance (QA) systems, to ultimately use process quality as an indicator for product quality. To address this, this research synthesises the "Asfalt Impuls" methodologies Hightech = LowCost (HTLC), Functioneel Opleveren (FO), and Kwaliteitsborging (KB), into a framework for systematically verifying product quality through continuous monitoring of key process parameters.

In the first phase of this research, a Delphi study was conducted with a panel of industry experts to identify critical process parameters for asphalt product quality. The experts categorised these parameters into three groups: direct, density, and indirect-related parameters, each linked to different aspects of product quality. In the second phase, these parameters were monitored during a case study of an asphalt construction project using ASPARi's PQi methodology. After the construction process, asphalt cores were drilled at various locations on the project site to assess product quality, focussing on density, stiffness, water sensitivity, fatigue resistance and resistance to permanent deformation.

A correlation analysis between process quality and product quality revealed trends indicating how process quality may influence product quality. Moderate to strong correlations were observed between process parameters and density and mechanical properties. For example, the temperature during the first compaction pass was positively correlated with the resistance to fatigue. Similarly, the number of compaction passes within the temperature compaction window (TCW) demonstrated a strong influence on the final product quality, especially in achieving target density. However, some parameters, such as the time between paving and compaction, showed weaker correlations, suggesting that their impact on product quality may depend on more complex interactions with other variables.

The systematic approach presented in this research, which uses process quality as an indicator of product quality has revealed that process quality is not unsuitable for verifying product quality. While the current methodologies for assessing both process and product quality are still underdeveloped. This approach, if further developed and widely adopted, could shift the industry's reliance on destructive testing toward a more proactive, data-driven QC/QA system. The thesis recommends further development of the PQi and FO methodologies to enhance predictive capabilities, with the potential to set new standards for QC/QA in asphalt construction.

III. Samenvatting

In de voortdurend veranderende wereld van asfaltbouw is het beheersen van het bouwproces steeds crucialer geworden door de toenemende eisen van opdrachtgevers. Aannemers staan voor de uitdaging om hoogwaardige producten te leveren en het complexe asfaltproces beter te beheersen, mede door de vraag naar betere prestaties en duurzamere wegen. Een cruciaal aspect bij het behalen van deze doelen is inzicht verkrijgen in hoe de kwaliteit van het asfalteerproces invloed heeft op de uiteindelijke asfaltkwaliteit. Dit onderzoek kijkt daarom hoe het monitoren van het asfalteerproces geïntegreerd kan worden in systemen voor kwaliteitscontrole (QC) en kwaliteitsborging (QA), zodat proceskwaliteit gebruikt kan worden als indicator voor productkwaliteit.

Om dit te bereiken, combineert dit onderzoek de “Asfalt Impuls”-methodieken: Hightech = LowCost (HTLC), Functioneel Opleveren (FO) en Kwaliteitsborging (KB), in één geïntegreerd raamwerk waarmee de productkwaliteit systematisch gecontroleerd kan worden door continue monitoring van essentiële procesparameters.

In de eerste fase van dit onderzoek is een Delphi-studie uitgevoerd, waarbij een panel van experts uit de industrie werd geraadpleegd om kritische procesparameters te identificeren die van invloed zijn op de asfaltkwaliteit. Deze parameters werden door de experts onderverdeeld in drie categorieën: direct, dichtheid en indirect gerelateerde parameters, die elk gekoppeld zijn aan verschillende aspecten van productkwaliteit. In de tweede fase zijn deze parameters gemonitord tijdens een praktijkstudie van een asfaltproject, waarbij de PQi-methodologie van ASPARi werd gebruikt. Na de uitvoering van het project zijn asfaltkernen geboord op verschillende locaties om de kwaliteit van het asfalt te beoordelen, met de focus op dichtheid, stijfheid, watergevoeligheid, vermoeiingsweerstand en weerstand tegen permanente vervorming.

Uit een correlatieanalyse tussen proces- en productkwaliteit kwamen trends naar voren die aangeven hoe de proceskwaliteit de uiteindelijke productkwaliteit kan beïnvloeden. Er werden matige tot sterke correlaties gevonden tussen procesparameters en dichtheid en mechanische eigenschappen. Zo bleek bijvoorbeeld dat de temperatuur tijdens de eerste verdichtingsronde positief gecorreleerd was met de vermoeiingsweerstand. Het aantal verdichtingsgangen binnen het temperatuurvenster (TCW) bleek ook een sterke invloed te hebben op de uiteindelijke productkwaliteit, vooral als het gaat om het bereiken van de gewenste dichtheid. Sommige parameters, zoals de tijd tussen het asfalteren en het verdichten, vertoonden echter zwakkere correlaties, wat suggereert dat hun effect op de productkwaliteit afhangt van complexere interacties met andere variabelen.

De systematische aanpak die in dit onderzoek wordt gepresenteerd, waarbij proceskwaliteit wordt gebruikt als indicator voor productkwaliteit, heeft aangetoond dat proceskwaliteit niet ongeschikt is om productkwaliteit te verifiëren. Hoewel de huidige methoden voor het beoordelen van zowel proces- als productkwaliteit nog niet volledig ontwikkeld zijn, zou deze benadering, mits verder uitgewerkt en breed toegepast, de afhankelijkheid van de industrie van destructieve boorkernen kunnen verminderen. Dit zou kunnen leiden tot een meer proactief, data gestuurd QC/QA-systeem. Dit onderzoek beveelt aan om de PQi- en FO-methodologieën verder te ontwikkelen om de nauwkeurigheid van voorspellen te verbeteren, met het potentieel om nieuwe normen te stellen voor QC/QA in de asfaltsector.

Acronyms

ASPARi	Asfalt sector professionalisering, research & innovatie
ECR	Effective compaction rate
FO	Functioneel opleveren
HTLC	High tech = Low cost
IC	Intelligent Compaction
ISO	International standardisation organisation
KB	Kwaliteitsborging
PQi	Process Quality Improvement
QC	Quality Control
QA	Quality Assurance
TCW	Temperature compaction window

Glossary

Asphalt construction process The process of constructing asphalt, including paving and compacting operations.

Asphalt cell A cell in a grid-like structure that divides an asphalt layer into smaller sections.

Asphalt layer The physical representation of a single (e.g. surface, bin, base) layer of asphalt.

Asphalt pavement The physical representation of asphalt, including all layers from foundation to surface.

Conforming process quality A construction process executed according to process specification.

Data processing algorithm A systematic, step-by-step computational procedure used to transform raw data into the required dataset.

Intelligent compaction systems Advanced technologies that are used in road construction to enhance efficiency and quality in the compaction process.

Mechanical properties of asphalt The properties t

Fatigue resistance The asphalt's ability to withstand repeated cycles of loading and unloading from traffic without cracking or showing significant distress.

Resistance to permanent deformation (also known as *rutting resistance*) The ability of asphalt to resist long-term deformation under repeated loads.

Stiffness The ability of the asphalt material to resist deformation under load.

Water sensitivity The susceptibility of the asphalt to damage when exposed to moisture.

Non-conforming process quality A construction process executed differently to process specification.

PQi measurement Process Quality Improvement Measurement. A protocol developed by ASPARI to measure a set of important process parameters during asphalt construction.

Process parameter Factors that affect the outcomes of a process. (e.g. roller passes and compaction temperature window).

Process quality The degree to which process parameters match the process specification.

Process specification The set of predefined process parameters to meet the product specification.

Process verification The assessment of process quality against process specification, checking if the process was executed conforming specification.

Product specification The required physical and mechanical properties of asphalt layers as set during the design.

Product Quality The degree to which physical and mechanical properties match the product specification.

Product verification The assessment of product quality against product specification, checking if product quality is according to the required specification.

Quality assurance Activities that entail verifying the quality control of the contractor and ensuring that the achieved product quality is adequate to meet specifications. Responsibility of the client.

Quality control Activities that entail exerting control over and testing product quality. Responsibility of the contractor.

Temperature compaction window The range between the upper and lower temperature limits within which an asphalt mat must be compacted.

Typetest the investigation and documentation of a fixed set of physical and mechanical properties in a laboratory to characterise an asphalt mixture.

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1. Introduction

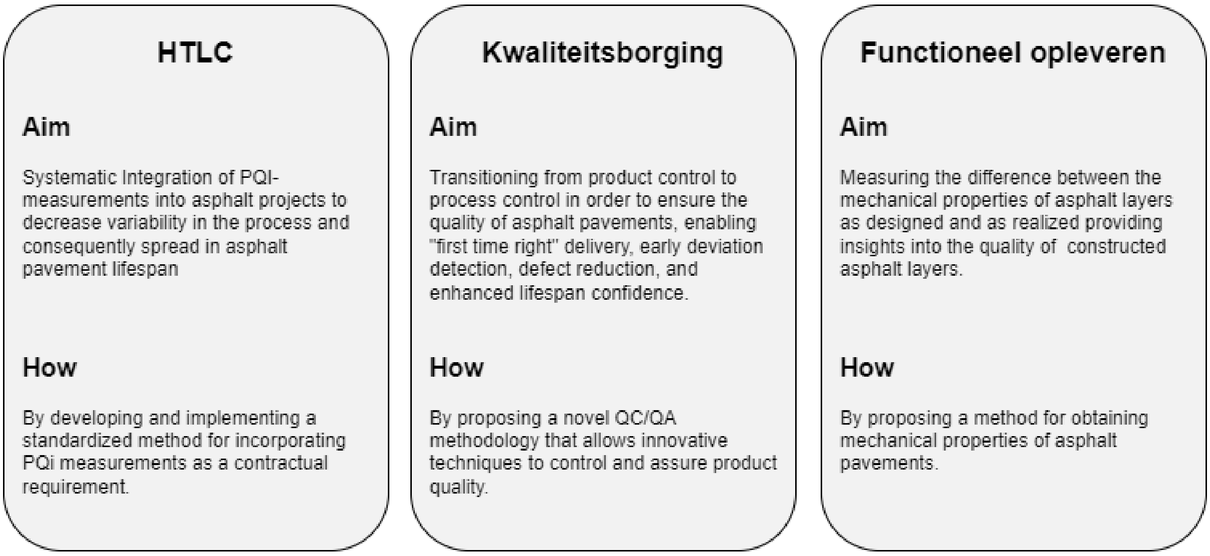
This research seeks to integrate pavement Process Quality Improvement (PQi) metrics into pavement Quality Control/Quality Assurance (QC/QA) practices. The primary objective is to establish a systematic framework in which process quality is used for verification of product quality, thereby developing a comprehensive understanding of the interrelationship between process and product quality.

1.1. Problem context

In the ever-changing field of infrastructure development, ensuring the longevity, reliability, and sustainability of asphalt pavements stands as a crucial challenge for society. This challenge is highlighted by the significant investment of €2 to €3 billion in the Netherlands' highway network in 2022 [1]. In addressing these challenges, clients have turned to performance contracting and extended warranty periods, creating new risks for contractors. Yet, these changes have also presented contractors with opportunities to explore innovative approaches to their work [2]. In the end, this has resulted in asphalt paving companies meeting high product expectations by seeking better control over process and product quality [3].

Simultaneously, the asphalt construction process is inherently complex and relies heavily on the experience of asphalt paving crews and operators. This often leads to significant variations in both paving and compacting operations. While not all process variations have negative repercussions, they are widely recognised as a significant cause of inadequate asphalt pavement quality [4]. Therefore, improving the asphalt construction process itself is key to addressing the issue of suboptimal quality [5]. For example, a consistent temperature distribution behind the paver is known to promote uniform compaction, which ultimately results in better-performing pavements [6]. Moreover, there is currently a lack of a structured approach that can provide contractors with confidence in the effectiveness of their process. This leaves the following question unanswered: "*What should the construction process look like to better control the final asphalt pavement quality?*"

In combination with universities, clients and contractors in the Netherlands are involved in several research initiatives to unify their efforts to ultimately improve the quality of asphalt pavements. One of these initiatives, 'Asfalt Impuls' [7], was started in 2018 and came to an end in 2023. The primary objective of the Asphalt Impulse program was to significantly extend the lifespan of Dutch roads, resulting in lower maintenance costs and less traffic disruption. Within the Asfalt Impuls initiative, eight different projects were managed, from which three are relevant in the context of this study (Figure 1): Hightech = Lowcost (HTLC), Kwaliteitsborging (KB) and Functioneel opleveren (FO).



HTLC

Aim

Systematic Integration of PQI-measurements into asphalt projects to decrease variability in the process and consequently spread in asphalt pavement lifespan

How

By developing and implementing a standardized method for incorporating PQi measurements as a contractual requirement.

Kwaliteitsborging

Aim

Transitioning from product control to process control in order to ensure the quality of asphalt pavements, enabling "first time right" delivery, early deviation detection, defect reduction, and enhanced lifespan confidence.

How

By proposing a novel QC/QA methodology that allows innovative techniques to control and assure product quality.

Functioneel opleveren

Aim

Measuring the difference between the mechanical properties of asphalt layers as designed and as realized providing insights into the quality of constructed asphalt layers.

How

By proposing a method for obtaining mechanical properties of asphalt pavements.

Figure 1: HTLC [8], KB [9], and FO [10] project aims and how.

The HTLC, KB, and FO project groups aim to extend their work beyond the project's end in 2023. The main objective is to ensure the effectiveness of the proposed methodologies and explore the relationships and synergy between them. The ultimate goal is to validate these efforts, potentially establishing them as standard practices and incorporating them into future national guidelines. To achieve this, they are continuing as part of the newly launched 'Deltaplan Asfalt' initiative. This initiative involves potentially carrying out 100 pilot projects to gather essential data in support of their objectives. This research project marks the start of the 100 projects and its outcomes can influence the subsequent 99 projects by providing insights into the adequacy of data collection methods and whether additional or alternative data should be collected.

Initiatives like HTLC, which focus on monitoring the asphalt construction process, are part of a broader movement towards digitalisation within the market. An example is the MIC 4.0 initiative, which aims to develop a uniform, manufacturer-independent digital language for communication with construction equipment [11]. Similar to HTLC, MIC 4.0 seeks to enable the implementation of data-driven processes in construction, with a particular emphasis on standardising and streamlining the exchange of process data.

The thesis is organised as follows: The remainder of the first chapter presents the problem statement and defines the key concepts. Chapter 2 offers a literature review on indicators of product quality and examines the role of the asphalt construction process in QC/QA. Chapter 3 outlines the main hypothesis, research questions, scope and research design. Chapter 4 details the method, results and discussion for the expert panel discussion, while Chapter 5 presents the method results and discussion for the case study. Chapter 6 concludes the research and Chapter 7 provides the recommendations. Finally, Chapter 8 presents a roadmap for using process quality as an indicator of asphalt quality.

1.2. Problem statement

A pavement QC/QA system can help contractors maintain control over their processes [12]. Although the current product-centred approach to QC/QA is crucial in ensuring high-quality pavements [13], it primarily relies on a random, spot-measurement-based approach to test the end product (i.e. one core per 2000m^2). This approach provides limited insight into the overall quality of asphalt pavements, covering less than 0.01% of the surface. Moreover, it provides limited feedback on how quality issues in the construction process affect product quality. In addition, considering the product quality only after construction prevents the possibility of making adjustments to ongoing asphalt construction processes to avoid deviations from expected product quality. As stated by [14], "It is impossible to inspect or test quality into a product".

Therefore, it is crucial for contractors to implement a QC/QA system that incorporates a deeper understanding of how process quality influences product quality. Process quality improvement (PQi)[1] measurements provide a continuous stream of data on the construction process, offering insights across the entire asphalt layer. Incorporating such data into QC/QA practices holds the potential to steer construction processes, granting actual control over the end quality, rather than verifying if quality standards were met. Furthermore, integrating innovative methods such as those presented in the HTLC, KB, and FO projects has the potential to enable real-time monitoring of product quality and provide confidence in product quality based on process quality. Recognising the key role of the asphalt construction process in product quality, the main research question is formulated as follows: "*To what extent can process monitoring during asphalt construction, integrated within QC/QA practices, verify the product quality of asphalt pavements?*

1.3. Key concepts

The first and perhaps the most important key concept is product quality. Quality is broadly defined by the International Standardization Organization (ISO) as "the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs" [15]. In the context of asphalt pavements, this definition translates into specific features and characteristics that ensure the pavement meets long-term performance expectations. Typically, these expectations are ultimately represented by the taxpayer, who demands value for money – specifically, roads that promise durability throughout their intended lifespan [16]. This leads to the following inquiry: "*What are the features and characteristics of asphalt that enable it to last its intended life?"*

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[1] The reader is referred to [3] for info regarding the PQi methodology to make operational behaviour explicit.

For asphalt, physical properties and mechanical properties are extensively studied as influential factors for the pavement life span. In this research, the quality of asphalt layers is defined as product quality and encompasses the set of physical (i.e. density) and mechanical properties (i.e. water sensitivity, stiffness, resistance to fatigue, resistance to permanent deformation) influencing the lifespan of asphalt pavements. In addition, it is essential to ensure that the product quality achieved is in line with pre-defined product specifications in order to maintain the performance of the asphalt layer over time. This process, known as product verification, plays a crucial role in verifying that the product quality meets the required standards, thus assuring the intended life of the pavement.

Besides product quality, the proposed research also focused on the concept of process quality. Following the same definition provided by the ISO[15], it is important to note that the need for process quality can be found in the need for product quality. In this context, process quality is defined as the set of process parameters that affect product quality.

This creates a clear distinction between conforming process quality, where the process aligns with specifications, and non-conforming process quality, where deviations from specifications have occurred. Additionally, process verification refers to the assessment of the alignment of process quality with the process specification. In manufacturing industries, evaluating and controlling processes to ensure they meet specifications is a well-established practice. For example, the lean manufacturing approach emphasizes enhancing process control to closely adhere to specifications, thereby producing products that consistently meet the desired criteria [17]. This underscores the importance of tightly controlling the construction processes to constantly create a product with the desired quality.

However, achieving similar control in the asphalt construction process presents unique challenges. Unlike manufacturing processes, which typically take place in controlled environments with consistent product quality, asphalt construction is carried out under variable conditions, making it difficult to maintain the same level of control. These challenges underscore the complexity of ensuring process quality in asphalt construction, where external factors can significantly impact the ability to conform to specifications.

While the term QC/QA is commonplace in the road construction industry, the specific activities it encapsulates vary widely. Nevertheless, there is a commonly accepted division of responsibilities within any QC/QA framework: the contractor is responsible for QC, while the client oversees QA [12], [18], [19], [20]. However, the interpretation of QC activities differs among researchers. According to [18], they include the planning, execution, and reporting of product quality testing and sampling. In contrast, others take a more operational perspective and define QC as the control over quality during construction [6] [21]. QA involves the owner's verification of the contractor's testing and sampling of product quality [18], [19], and ensuring that the achieved product quality meets specifications [12]. KB takes a similar approach to QC/QA framework, with the contractor responsible for QC and the client for QA, verifying QC practices from the contractor. Additionally, this approach emphasises the benefits of ongoing collaboration between the contractor and client throughout the project lifecycle, aiming to address potential issues before construction works are finished [22]. This research views QC as the contractor demonstrating control over product quality, either by showing the process was in control or through test results of product quality. QA, in line with KB, verifies the validity of the QC.

2. Literature Review

This literature review summarises, compares, and discusses relevant research works on the topic under investigation. This is followed by the identification of the research gap and the positioning of this research.

2.1. Indicators of product quality

To understand how product quality in asphalt construction is assessed, it is essential to examine the key indicators used in the industry. Dobrowolski and Bressette [18] concluded in their study that effective QC/QA practices in asphalt construction projects typically yield superior product quality. Their research particularly emphasises the importance of compaction as a critical indicator, suggesting that the degree of compaction is a primary determinant of pavement quality. However, while compaction is commonly highlighted in the literature, it may not fully capture the complexity of asphalt quality.

Lin et al. [13], for example, argue that mechanical properties are more sensitive to variation in quality compared to the degree of compaction. They suggest that mechanical properties (e.g. stiffness), provide a more realistic indicator of product quality. This perspective is supported by the Federal Highway Administration [23], which also identifies mechanical properties as relevant indicators of pavement quality. However, their approach still relies on density as a predictor of mechanical properties, rather than on direct measurements of the mechanical properties.

The use of density as a representative of mechanical properties raises critical questions about the validity of using density alone. Bijleveld [24], [25] found that even when target density may have been reached for an asphalt layer, the mechanical properties can vary significantly. These findings challenge the validity of using density as the only indicator of asphalt quality.

2.2. Process-based QC/QA in asphalt construction

QC/QA frameworks in asphalt construction have historically been oriented towards the final product, with the objective of verifying its conformity to the specified requirements. However, as research in this field has advanced, there has been a growing emphasis on the process that leads to the final product. This shift in focus reflects the recognition that controlling process parameters is crucial for achieving consistent and high-quality outcomes. Nearly 15 years ago, Miller [3] highlighted the inexistence of research on the asphalt construction process, and its significant variability. Since then, substantial progress has been made with numerous studies examining different aspects of asphalt construction quality. Miller [3] contributed to the field with the initial development of the PQi framework, which aims to make operational behaviour explicit by monitoring machine movement, tracking temperature homogeneity and density progression, and storing relevant process parameters that influence product quality.

Although the PQi methodology stands out as the most comprehensive real-time descriptive process control system, alternative methodologies exist. For example, Kassem et al. [26] developed a system for monitoring the asphalt compaction process, but with a focus on improving uniformity in density rather than reducing process variability as emphasised by the PQi framework. This reflects a more traditional QC approach where the emphasis is on controlling specific product quality outcomes.

Similarly, Xu and Chang [27] and Yoon et al. [20] investigated methods to improve the uniformity of asphalt density in a single layer by using Intelligent Compaction (IC) systems to predict density in real time during construction. However, despite their promise, the consistency of density predictions provided by IC systems remains uncertain, as noted by the USA Federal Highway Administration [23]. This uncertainty underscores the ongoing challenges in achieving reliable real-time control over the asphalt construction process within the QC/QA framework.

The demand for real-time density insights during asphalt construction makes explicitly the necessity for contractors to exert greater control over their processes, aligning with the trend towards continuous monitoring as highlighted by the US Federal Highway Administration [23]. Building on the PQi methodology, Makarov et al. [28] introduced real-time data collection capabilities, facilitating instant access to process measurements. Subsequently, Makarov et al. [29] utilised real-time PQi measurements to guide roller operations and introduced the Effective Compaction Rate (ECR) as a novel indicator of compaction quality, a unique approach that evaluates the adherence to a predefined process specification (i.e. process verification) rather than attempting to monitor product quality throughout the process.

While the ECR holds significant potential by enabling real-time process verification, its application is limited to the compaction aspect of asphalt construction. Moreover, it solely emphasises achieving minimal compaction, overlooking potentially crucial compaction parameters such as over-compaction or compacting at sub-optimal temperatures. Shen [30] attempted to use the ECR as a process indicator to predict product quality (i.e. degree of compaction, IRI, and pavement lifespan). Although promising results were found for the long-term performance indicators (i.e. IRI and pavement lifespan), using the ECR as a predictor of density did not show the desired predictive performance.

The combined work of Makarov et al. [28], [29] and Shen [30] has demonstrated the potential of process parameters as indicators of product quality. However, the ECR might be too narrow as a quality indicator for the entire asphalt construction process. Thus, to fully integrate process control into QC/QA practices, a more comprehensive set of indicators is needed that quantify the full range of process variables affecting asphalt quality.

2.3. Research gap

The literature reveals a significant reliance on compaction and density as primary indicators of asphalt quality, as highlighted by several studies, including those of Dobrowolski and Bressete [18] and Lin et al. [13]. However, the limitations of using density as a sole predictor of mechanical properties, as noted by Bijleveld [24], [25], suggests that this approach may be insufficient. Recent studies have begun to explore process-based indicators, such as the ERC introduced by Makarov et al.[28]. While these methodologies enhance real-time process control, they often have a narrow focus on specific aspects like compaction, thereby failing to account for the full range of variables that inherently belong to the complexity of asphalt construction. Ultimately, research on the relationship between process quality and product quality remains scarce.

This research addresses the existing gap by examining the relationship between process and product quality and providing a systematic approach to using process quality as an indicator of product quality. By adopting a broader approach to process quality, this study seeks to enhance the integration of process control within QC/QA practices, and thus overcoming the limitations of current methodologies. In particular, it focuses on the mechanical properties of asphalt after construction, which play a crucial role in pavement design, investigating how process quality impacts whether what is built aligns with what was designed.

3. Research objectives, questions and scope

The proposed research aims to enhance the understanding of the relationship between process and product quality in asphalt construction. Specifically, it seeks to establish a systematic approach where process quality is an indicator of product quality, enabling a more comprehensive assessment of product quality. Consequently, this approach has the potential to facilitate an improved control of the construction process. Within this broader aim, the research objective can be stated as:

1. Synthesise HTLC, KB, and FO methodologies into a systematic approach to assessing process quality and product quality.
2. Investigate the relationship between process quality and product quality to determine the predictive capability of process quality as an indicator of product quality.

3.1. Main hypothesis

This research work relies on the main hypothesis that integrating PQi measurements with the evaluation of physical and mechanical properties provides valuable insights into how the quality of the construction process affects the quality of asphalt layers. This integration allows process quality to serve as an indicator of product quality. Consequently, it enables steering the asphalt construction process towards achieving the desired product quality.

3.2. Research questions

To fulfil the research objective, the following main question and sub-questions need to be answered:

"To what extent can process monitoring during asphalt construction, integrated within QC/QA practices, verify the product quality of asphalt layers?"

A set of sub-questions are formulated to support the main research question. The first sub-question is motivated by the knowledge gap about how different actions in the asphalt construction process influence the product quality of the constructed layer. Thus, it is included to understand how process quality may influence product quality in construction projects. This sub-question is formulated as follows:

1. *How does the asphalt construction process influence the quality of asphalt layers?*

Furthermore, the different process parameters can affect the product quality of asphalt layers in different ways. Investigating the predictive capabilities of the individual process parameters on the different product quality aspects provides insight into which process parameters are more important compared to others. The second sub-question is formulated as follows:

2. *To what extent can the asphalt construction process be used as a predictor of product quality?*
    a. *Does a process parameter of conforming quality result in a product of the specified quality?*
    b. *Is there a correlation between process quality and product quality?*

3.3. Scope and limitations

The proposed research is limited to examining the effect of process quality on product quality. Specifically, it aims to understand how quality issues identified during the construction process align with issues in the final product quality. This research primarily examines the impact of process-related parameters on the physical (density) and mechanical (moisture sensitivity, stiffness, resistance to fatigue, resistance to permanent deformation) properties of asphalt as indicators of product quality. The scope encompasses the integration of existing tools and methodologies for assessing process quality and product quality such as PQi measurements. Additionally, the research explores the feasibility of process quality as a predictor of product quality within QC/QA practices. This research has the following limitations:

1. The research is limited to studying the influence of process quality on product quality and does not address the effects of different asphalt mixture compositions (e.g., % binder content) on the final product. Therefore, the research focuses only on a single asphalt mixture, and a single project to reduce the variability in asphalt mixture composition to a minimum, and supports the assumption of a constant asphalt mixture quality.
2. The research focuses specifically on individual bind or base asphalt layers. Currently, surface layers do not have the required thickness for extracting mechanical properties, and are therefore not included in the analysis. Additionally, the assessment of the combined product quality of multiple asphalt layers within an asphalt pavement is beyond the scope of this research.
3. The dimensions of each sample taken for collecting data on the product quality are adjusted to ensure uniformity. Therefore, the physical property (layer thickness) of the asphalt layer under investigation is constant and beyond the scope of this research.
4. While the study focuses on the physical and mechanical properties of asphalt layers as indicators of product quality, other aspects such as long-term durability are beyond the scope of this research.
5. This research is specifically focused on utilising the PQi methodology developed by ASPARi for collecting process data during asphalt construction. The study does not extend to the

evaluation or comparison of other systems, including commercial alternatives that may offer different levels of accuracy or data filtering capabilities. Additionally, the research does not aim to enhance or modify the existing PQi methodology; rather, it seeks to assess the applicability and effectiveness of the current PQi system in its present form.

3.4. Proposed framework and research design

3.4.1. Proposed framework

In the context of this research, a comprehensive framework is crucial for understanding the interactions between various aspects of the construction process and how they contribute to achieving the desired product quality. For this research, a framework is proposed that addresses this need, bridging the methodologies from the HTLC and FO projects and integrating them into the KB methodology.

The framework, outlined in Figure 2, begins in the pre-construction phase, where the mixture is designed and selected. This phase provides product specifications and ideally process specifications as part of HTLC. By combining mix design, product, and process specifications (i.e., desired processes with acceptable quality boundaries), expectations for process and product quality are established.

During construction, ASPARi's PQi methodology is employed to monitor the construction process in real time. Following construction, process verification is conducted to ensure that the executed construction process adheres to the specifications set during the pre-production phase. However, certain critical process parameters, such as compaction temperature ranges and the number of compaction passes, are often not predetermined, leading to uncertainty about whether the specified process will result in the desired product quality.

This uncertainty makes product verification, as part of the FO methodology, essential. Thorough testing is required to confirm that the final product, constructed according to the specified process, meets the product quality specification. This process of using product verification to ensure that the process quality leads to the desired product quality is known as process validation.

During process validation, the outcomes are analysed and used to refine the process specifications. The goal is to adapt the process until it consistently produces the desired quality. Once a validated process is established, the need for extensive product verification becomes obsolete. Instead, verifying that the construction process adheres to the validated process specifications should be sufficient to ensure confidence in the resulting product quality.

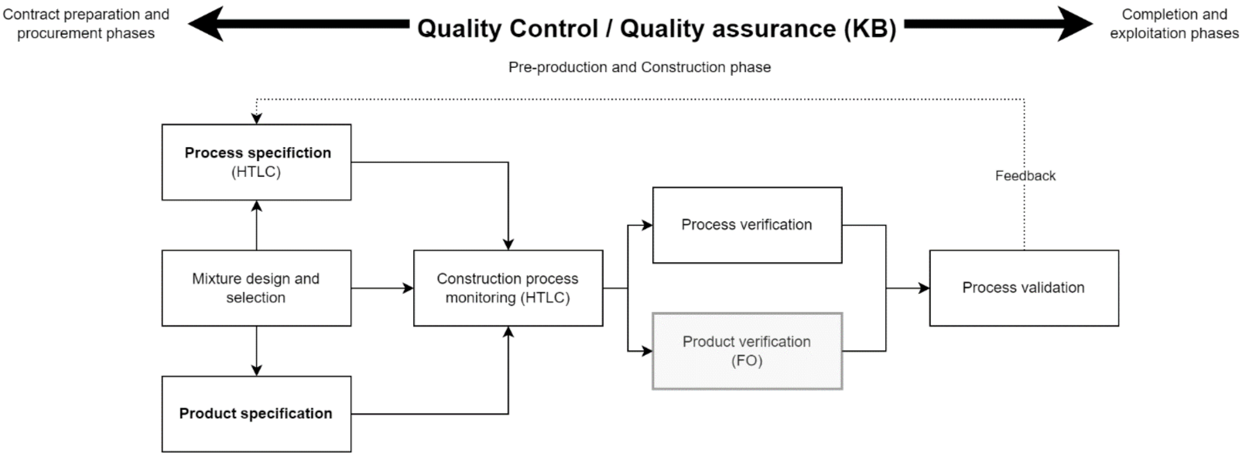

Figure 2: Proposed framework for integrating HTLC with FO in KB

3.4.2. Research design

This research employs a multi-phased approach to investigate the relationship between process and product quality by integrating HTLC with FO in KB using the proposed framework. This is achieved by integrating expert knowledge with empirical data and statistical analysis (Figure 3).

In the first phase, a Delphi study is conducted with a panel of experts to address the first research sub-question. This phase aims to identify a set of process parameters that are likely to significantly influence the product quality of asphalt layers. The Delphi method allows for a systematic and iterative gathering of expert opinions, leading to a consensus on the most critical process parameters.

The second phase involves an empirical case study in which the identified process parameters from the Delphi study are investigated. The construction process is monitored using the PQi methodology, focussing on the key parameters identified in the first phase. Following the construction process, both process quality and product quality are rigorously assessed and, where possible, verified against the established process and product specifications. This assessment forms the basis for a correlation analysis, which seeks to empirically explore the relationship between the monitored process parameters and the resulting product quality. By comparing process quality with the corresponding product quality, the process specification can be validated, ensuring that conforming process quality consistently results in conforming product quality.

The outcomes of the case study will directly inform the second research sub-question, providing empirical evidence to support or refine the initial insights gained from the expert panel.

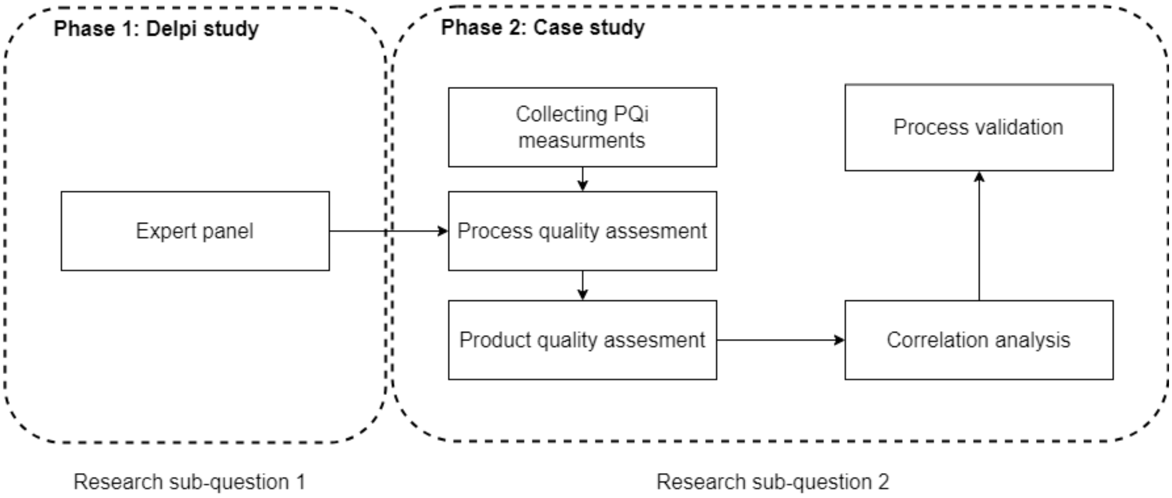

Figure 3: Research design

4. Delphi study on key process parameters

The primary objective of this first phase was to gain a basic understanding of how process quality is expected to impact product quality, by identifying which process parameters are expected to influence the physical[2] and mechanical[3] properties of asphalt layers. The Delphi method allows the collection of expert opinions through multiple iterative rounds of questionnaires, with the ultimate goal of developing a consensus on the critical process parameters. The insights gathered in this phase lay the foundation for the empirical case study that followed.

4.1. Delphi study methodology

4.1.1. Rationale for Delphi methodology

Although a traditional survey could have been used to gather input from experts, the Delphi method was selected due to its rigorous approach to querying experts [31]. Specifically, the reasons for selecting the Delphi method are as follows:

1. Investigating the influence of process parameters on product quality in asphalt construction is a complex issue that requires insights from experts who understand the various technical, environmental, and procedural factors involved. The Delphi method effectively addresses the study questions by leveraging the specialised knowledge of the experts.

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[2] Density

[3] Water sensitivity, Stiffness, Fatigue resistance, Deformation resistance

2. The research questions are best answered by a consensus among experts rather than individual responses. The asphalt construction process is complex and sharing the responses between rounds can potentially bring the experts additional ideas that would result in a more complete list of process parameters. Furthermore, the Delphi method does not require the experts to physically meet, making it suitable for a study that has a limited time frame.
3. While there may be a limited number of experts with the necessary knowledge, the Delphi method accommodates smaller sample sizes effectively. For this study, engaging 10 individual experts is practical and sufficient to achieve reliable results.
4. The Delphi method follows a structured procedure, such as the one outlined by Schmidt [31] , which helps prevent the collection of responses that are not related to the research topic.

In conclusion, the Delphi method is well-suited for this study due to its ability to handle complex issues, facilitate group consensus, work with a limited number of experts, and follow a structured procedure for obtaining results.

4.1.2. Procedure for selecting experts

The ASPARi network was employed to identify a set of experts who, based on their experience in process and product quality, would be appropriate to integrate the expert panel. To create a versatile list, all ASPARi founders received an open invitation via email. This email described the research and requested the participation of experts with experience in both the asphalt construction process and the physical and mechanical properties of asphalt. The email invitation can be found in Appendix A1: Invitation for participation in expert panel. This inquiry of the ASPARi network has resulted in a set of experts from eight different contractors, a client and a consultancy firm that participated in the expert panel. In general, the experts fulfil advisory roles within their field of work.

4.1.3. Data collection

4.1.3.1. Mechanisms for administering the questionnaires

The questionnaires were distributed via email. The advantage of this method is that it allows the researcher to create personalised emails, which can encourage experts to become more involved in the study and therefore more actively participate in the research process. This is particularly important in the multi-round questionnaire approach in Delphi studies, as non-response and drop-out can potentially harm the reliability of the findings.

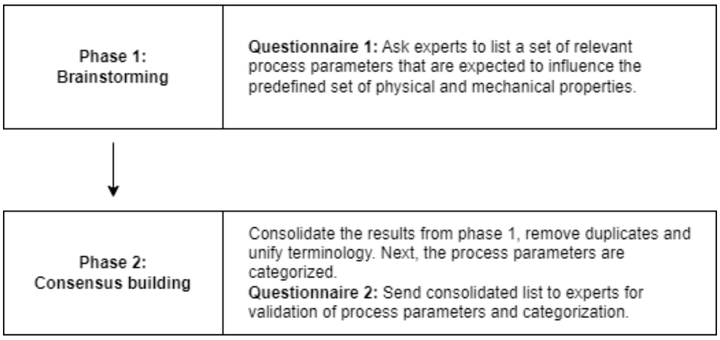
4.1.3.2. General questionnaire design issues

The Delphi study has multiple rounds, which is known to be more time-consuming for participants in comparison to a single questionnaire approach. Therefore, the objective was to keep the required time for completing each questionnaire as low as possible.

Additionally, this research is exploratory. Therefore, the questionnaire was designed to provide sufficient freedom in answering, while providing a structured format that would reduce the likelihood of off-topic answers or complex answers that go beyond the scope of this research.

4.1.3.3. Administration procedure

The procedure for administration of the questionnaires follows a classical Delphi procedure as outlined by Dalkey and Helmer [32]: (1) Initial collection of factors (Brainstorming), (2) validation of categorised list of factors and consensus building. This procedure can be found in Figure 4.



Questionnaire 1: Ask experts to list a set of relevant process parameters that are expected to influence the predefined set of physical and mechanical properties.

Consolidate the results from phase 1, remove duplicates and unify terminology. Next, the process parameters are categorized.
Questionnaire 2: Send consolidated list to experts for validation of process parameters and categorization.

Figure 4: Administration procedure of the Delphi study

In the first round, the experts completed a questionnaire aimed at gathering their insights on which and how process parameters influence asphalt properties. They were given a set of assumptions on a project (e.g. mixture and equipment type) to prevent getting a list of conditional clauses applying to the vast amount of different project characteristics. Additionally, each of the experts was explicitly instructed to not only provide process parameters where the relation with product quality was supported by facts but also indicate parameters where a relation was expected based on their personal experience and knowledge. The full questionnaire for round one can be found in Appendix A2: Questionnaire 1.

Before the next round, the responses were consolidated, and irrelevant information was removed. Next, the input was analysed and a categorisation for the process parameters was developed. The results of the first round were subsequently shared with the experts as a list of categorised process parameters (Appendix A3: Summary of results questionnaire 1). The expert panel was then asked to review the consolidated list, verify whether their initial responses were accurately reflected, and indicate whether they agreed with each process parameter on the list. In cases of disagreement, experts were asked to provide explanations. Finally, the experts were also asked whether they agreed with the categorisation.

4.1.4. Assessing the level of consensus

Consensus among the participants was assessed based on the level of agreement across the 10 responses. The scale for assessing the degree of consensus can be found in Table 1.

Table 1: Consensus scores

Score	Degree of consensus
Absolute	10 out of 10 participants agree
Strong	9 out of 10 participants agree
Moderate	7 – 8 out of 10 participants agree
Weak	6 or less participants agree

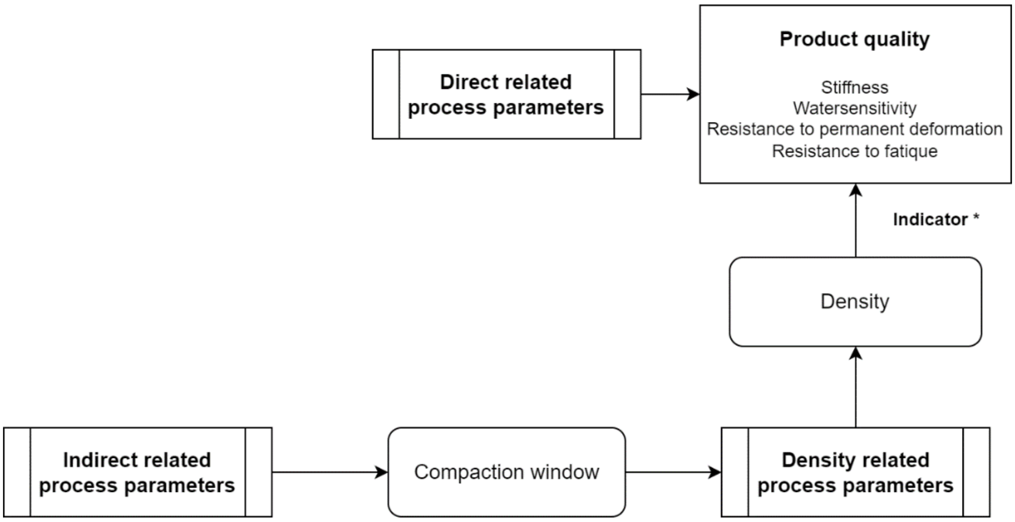
4.2. Results

The findings from the Delphi study conducted with experts in the field of asphalt construction are presented here.

4.2.1. Categorisation of process parameters

Based on the responses from the expert panel, three distinct categories of process parameters were identified. These categories are based on the type of relation to the mechanical property aspect of product quality. The relation between each category and product quality is visualised in Figure 5. The first category comprises the directly related process parameters, i.e. the parameters that have a direct impact on the mechanical properties of constructed asphalt layers. This is independent of any changes in the density, which are known to also influence mechanical properties. For example, compacting at a very low temperature is expected to impact the stiffness of the asphalt layer, but in this case, this impact is not related to a change in density. Mechanical properties that are affected by process parameters through a difference in density are a separate category, and therefore called density related process parameters. An example of a density related process parameter is the number of compaction passes within the temperature compaction window (TCW). The last category of process parameters are the indirectly related process parameters. These are process parameters that influence the time available for compacting within the TCW. For example, a low sub-base temperature can increase the cooling rate of paved asphalt, reducing the time available for compacting within the TCW. As compacting within the TCW is a density related process parameter, indirect related process parameters are related to the mechanical properties through density.

This categorisation of the process parameters was corroborated by the expert panel.



** In the traditional QC/QA density is used as an indicator for the mechanical properties of constructed asphalt*

Figure 5: Relations between process parameter categorisation and product quality

4.2.2. Categorised process parameters

In total, the expert panel listed 22 process parameters that are expected to influence the product quality of asphalt layers.

The results for the process parameters categorised as directly related process parameters are presented in Table 2. These are the parameters that experts identified as having a direct impact on the mechanical properties of asphalt layers, independent of the effect on density.

A moderate to strong consensus was observed regarding the impact of excessively high production temperatures on the mechanical properties of asphalt layers, with a strong consensus for stiffness and fatigue resistance, and a moderate consensus for water sensitivity. Furthermore, there was a strong consensus on the adverse effects of a long period between asphalt mixture production and paving, in particular on stiffness and fatigue resistance. Moreover, a strong to full consensus was reached on the negative effects of a temperature during compaction that is too low.

Despite the moderate to strong consensus on almost all directly related process parameters, a weak consensus was reached on the negative effects of a too-high temperature during compaction and water sensitivity. Furthermore, moderate consensus was reached on the impact of tamper speed[4] and screed temperature on water sensitivity and fatigue resistance.

Additionally, some experts provided specific insights into the influence of certain process parameters. For instance, a handful of experts noted that the scale of the impact could vary depending on the asphalt mixture. Furthermore, one of the experts suggested that microcracks are likely to occur

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[4] In Dutch “Snelheid stampmessen”

primarily at the surface and therefore only have a limited effect on the overall product quality of the asphalt layer. Another expert indicated that the time between asphalt mixture production and paving might not necessarily age the binder, but could make the binder stiffer, making it difficult to reach target density with the compaction effort, thus suggesting that this parameter might also relate to density effects

Table 2: Responses categorised as direct related process parameters

Process parameter	**Impact description**	**Mechanical property**	**Degree of consensus**
Production temperature *(Too high)*	Accelerates binder ageing, reducing flexibility	Water Sensitivity	**Moderate** (8/10)
		Stiffness	**Strong** (9/10)
		Fatigue resistance	**Strong** (9/10)
Time between asphalt mixture production and paving *(Too long)*	Accelerates binder ageing, reducing flexibility	Stiffness	**Strong** (9/10)
		Fatigue resistance	**Strong** (9/10)
Tamper speed (Too high)	Causes texture issues (micro-cracks)	Water Sensitivity	**Moderate** (7/10)
Screed temperature (Too cold)	Causes texture issues (micro-cracks)	Water Sensitivity	**Moderate** (8/10)
		Fatigue resistance	**Moderate** (7/10)
Compaction temperature *(Too low)*	Causes damage to adhesive bridges.	Water Sensitivity	**Absolute** (10/10)
	Causes micro-cracks, reducing cohesion	Stiffness	**Strong** (9/10)
		Fatigue Resistance	**Absolute** (10/10)
Compaction Temperature *(Too High)*	Displacement of binder, reducing adhesive bridges	Water Sensitivity	**Weak** (5/10)
	Causes texture issues (micro-cracks)	Fatigue Resistance	**Moderate** (8/10)
Roller characteristics (Too heavy)	Causes texture issues (micro-cracks)	Stiffness	**Moderate** (8/10)
		Fatigue resistance	**Moderate** (/8/10)

The results for density related process parameters are summarised in Table 3. These are parameters that the members of the expert panel have indicated to impact the degree of compaction of the constructed asphalt layer.

A strong to absolute consensus was reached on both insufficient and excessive number of roller passes, causing under and over-compaction, respectively. Furthermore, there was a moderate consensus on the impact of waiting too long between the moment of paving and the first compaction pass. Conversely, there was a weak consensus on the effects of the screed's condition or pre-compaction force, as well as the impact of tamper speed. The experts also did not agree on the influence of processing speed (speed of the paver). These process parameters with weak consensus are generally associated with the risk of under-compaction due to insufficient pre-compaction. The primary reason for the weak consensus can be found in differing views among the experts in the panel. Some experts indicated that insufficient pre-compaction does not necessarily lead to under-compaction, as it can be compensated by increasing the number of roller passes. However, if pre-compaction is not monitored, the construction team may not be aware that additional compensation is needed, leading to potential issues in achieving the desired compaction. Conversely, the other experts did indicate the relation to under-compaction, on the basis that the compaction process was not adapted to the lower pre-compaction.

Table 3: Responses categorised as density related process parameters

Process parameter	Impact description	Degree of Consensus
Number of roller passes within temperature/compaction window (Insufficient)	Under-compaction	**Absolute** (10/10)
Number of roller passes temperature/compaction window (Excessive)	Over-compaction	**Strong** (9/10)
Time between paving and first compaction pass (Too Long)	Under-compaction	**Moderate** (7/10)
Condition of the Screed (Worn)	Under-compaction due to insufficient pre-compaction	**Weak** (6/10)
Condition of the Screed (Too cold)		**Weak** (5/10)
Pre-compaction force of the Screed (Insufficient)		**Weak** (6/10)
Speed of Tampers (Too Low)		**Weak** (6/10)
Processing Speed (Too High)		**Weak** (6/10)

Finally, the results for indirectly related process parameters are summarised in Table 4. These parameters were identified as impacting the time available for compacting within the TCW.

A strong to absolute consensus was reached for all process parameters within this category. All process parameters ultimately affect the extent to which sufficient compaction capacity is available to perform sufficient compaction passes in the TCW. Although these parameters affect the required compaction passes, insufficient compaction capacity only occurs when there are neither enough rollers available on the construction site, nor sufficient space on the asphalt layer for an additional roller. Furthermore, a stopping point does lead locally to a temperature drop that makes it more difficult or even impossible to compact within the TCW. However, a stoppage point creates a possibility for rollers to catch up on the rest of the paved area when behind in the compaction process.

Table 4: Responses categorised as indirect related process parameters

Process parameter	**Impact description**	**Degree of consensus**
Temperature behind the screed (Too Low)	Reduces the available time in the temperature-compaction window, leads to insufficient compaction capacity	**Absolute** (10/10)
Processing speed (Too High)	Increases the area to be paved in the temperature-compaction window which leads to insufficient compaction capacity	**Absolute** (10/10)
Stopping Points (Presence)	Localised reduction in the temperature, reducing the available time in the temperature-compaction window	**Absolute** (10/10)
Substrate Temperature (Too cold)	Accelerates cooling of the asphalt layer, reducing the available time for compacting in the temperature-compaction window	**Absolute** (10/10)
Weather conditions (Too cold)		**Strong** (9/10)
Weather Conditions (Too much wind)		**Strong** (9/10)
Weather conditions (Too much rain)		**Absolute** (10/10)

4.3. Discussion

The expert panel has provided valuable insight into the relation between process quality and product quality. Furthermore, the categorisation of process quality in direct, density and indirect related process parameters helps in understanding how the different process parameters affect product quality.

The results of the first phase are used to answer the first research sub-question:

How does the asphalt construction process influence the quality of asphalt layers?

The expert panel indicated a set of 22 process parameters and described how process quality is affected. These parameters were then categorised based on their influence on product quality. Among these, the seven indirect related process parameters impact product quality by affecting density related process parameters. Although these parameters are important, the indirect relationship is accounted for within the density-related process parameters. For example, a too-low temperature behind the screed may lead to insufficient compaction passes within the TCW. Since the number of compaction passes in the TCW is already a density-related parameter, monitoring these indirect parameters does not add value in establishing the relationship between process quality and product quality.

However, despite some variations in the strength of consensus regarding specific process-product quality relationships, at least 50% of the expert panel acknowledged the relevance of each identified process parameter. This underscores the importance of investigating the direct and density related process parameters, not only to highlight their significance but also to support future research. Ultimately leading to a set of process parameters that are unanimously agreed upon to be critical to product quality.

Furthermore, the majority of the process parameters indicated by the expert panel are impossible to monitor without the use of equipment. This underscores the need for the PQi methodology or any similar approach to be integrated into every construction project. Without making the construction process explicit, the construction team lacks the essential information needed to optimize the process, leading to (excessive) reliance on guesswork and intuition. A view that is shared by the work of Miller [3] and Bijleveld [24]. Additionally, failure to monitor the process makes it impossible to trace product quality issues back to process-related causes, leaving the origins of many quality issues unresolved.

Finally, the expert panel has brought up the underlying discussion about density as an indicator of product quality, which was also highlighted in the literature review of this research. Some experts argue that when the density meets the specification, the mechanical properties are inherently according to the specification. They suggest that any deviations in mechanical properties are primarily attributed to issues related to density. This view is challenged by other experts, who explicitly indicate that despite the correct density, mechanical properties may not be conform specification. This perspective disputes the absolute relation between density and mechanical properties.

Given this division in experts' opinions, the second phase of this research will also include an investigation of the relationship between density and mechanical properties. Understanding this relationship is crucial, as density-related process parameters are only meaningful if density reliably reflects product quality. By examining this relationship, the research aims to clarify whether density can be considered a robust indicator of mechanical properties, thereby informing future QC/QA practices in asphalt construction.

Although the Delphi study contained a wide variety of experts, it is possible that the limited number of experts, with potentially limited knowledge, did not capture all relevant process parameters. Additionally, the relatively novel topic of relating process quality to product quality could have further extended this effect, which may have led to a list of process parameters that do not cover all relevant process parameters. Furthermore, the Delphi method, while valuable for reaching consensus, is inherently iterative and time-consuming. The limited time for this study has limited the number of iterative rounds conducted, potentially affecting the level of consensus reached on certain parameters.

The findings from this first phase are generally consistent with previous research on the relationship between process and product quality, though some differences are present. For instance, the work of Ter Heurne [33], which focused exclusively on compaction, also emphasised the importance of pre-compaction, the first roller pass, compaction temperature, and the number of roller passes. However, Unlike this research, Ter Heurne's study did not explore the impact of process parameters on the mechanical properties of asphalt layers. For example, only linking compacting below the TCW to not being able to reach target density instead of also indicating the adverse effects on the mechanical properties of asphalt as highlighted by the experts in this study. In contrast, the work of Bijleveld [25] emphasises that compacting below the lower limit of the TCW has adverse effects on the mechanical properties of asphalt layers, regardless of density, thereby supporting the experts' insights in this study.

In alignment with this research, Meerkerk's work [34] also addressed additional aspects of the process, including production, logistics, and paving operations. His study highlighted the potential influence of factors such as paver speed, temperature during compaction, and the time interval between production and paving. However, unlike the views of the expert panel, Meerkerk argued that the interval between production and paving negatively affected material segregation, while the expert panel suggested that it contributed to the excessive aging of the binder material. Meerkerk's findings further support the categorisation of process parameters as outlined in this research. He identified that while some process parameters may not directly impact product quality, they can affect other parameters that do. Moreover, this research reinforces the classification of certain parameters as indirect process parameters, which indirectly influence product quality.

Finally, the results from the first phase challenge the use of the ECR, developed by Makarov et al. [28], as an indicator of process quality. The findings suggest that the ECR is only valid when specific boundary conditions (i.e. temperature during each compaction pass and pre-compaction effort) remain consistent with those under which the required number of compaction passes in the TCW were originally determined. Consequently, the ECR appears overly simplistic and is based on assumptions that may not hold true in real-world conditions.

Instead, process quality depends on the interaction of many and distinct process parameters. The results suggest that there is not a one-size-fits-all approach to assessing the asphalt construction process. However, boundary conditions exist (e.g. minimum temperature during compaction) that must be met to avoid negatively impacting the quality of the asphalt product. This emphasises the importance of including such boundary conditions in process specifications, a practice that is currently not standardised, unlike the way boundary conditions are specified for product quality.

5. Case study linking process to product quality

Following the initial expert panel inquiry in Phase 1, where critical process parameters (potentially) influencing process quality were identified and categorised through their input, phase 2 focused on an empirical case study. The purpose of this phase was to assess the extent to which the theoretical insights obtained from expert opinions are supported by real-world data, thus providing a comprehensive understanding of how process quality impacts product quality in an actual construction project.

This phase involved a detailed examination of an ongoing asphalt construction project. The primary objectives were to monitor, document and analyse the specified process parameters during construction, and to quantitatively assess the resulting product quality in terms of physical (density) and mechanical properties (moisture sensitivity, stiffness, fatigue resistance and deformation resistance). The collected data were then used to investigate the correlation between process quality and product quality, and reflect on whether a process conform quality leads to a product conform quality.

5.1. Construction project description

5.1.1. Background information

This case study examines the construction of a temporary road, selected as the most feasible option given the extensive number of destructive tests required. The construction project was located in the city of Cruquius, province of North Holland. This temporary road is an integral part of the Wickevoort Estate development, a new neighbourhood project, and spans approximately 550 metres.

This site was particularly suitable for this research due to the ability to drill a large number of cores within a relatively small distance (53 in 550m, approximately one core every 30m^2), as opposed to the regular sampling frequency of one core every 2000m^2. An overview of the constructed road can be found in Figure 6. A detailed summary of the project characteristics is provided in Table 5.

The construction activities took place on May 28, 2024, during which various measurements were conducted to monitor and document the construction process. Additional measurements to assess product quality were carried out on the next day, May 29, 2024. Due to the lack of quality of the initial data[5], a subsequent visit was made on June 14, 2024, to perform new measurements and ensure an accurate assessment of product quality.

Figure 6: Wickevoort estate[6] project overview (constructed road in orange)

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[5] The GPS locations of the drilled cores were measured with an accuracy of +-50cm, remeasuring resulted in an accuracy of +-2cm

[6] Picture: https://venhoevencs.nl/projects/wickevoort-estate/

Table 5: Case study project characteristics

Project characteristic	Description
Project name	WE Cruquius – ontsluiting zuidelijke Laan van Wickevoort
Date of Construction	28-05-2024
Layer type	Base layer
Mixture Id	17770202
Mixture description	AC22 base 30/45 70%PR ECO
Asphalt plant	Asfalt Productie Amsterdam (APA)
Layer thickness	60 mm
Estimated Volume	485 ton
Transport distance	22km (25 min)
Construction period	07:30 – 13:00

5.1.2. Mixture design and layers composition

The mixture used in the project is the AC22 base 30/45 70%PR ECO with the code 17770202. The mixture is an asphalt concrete layer with a maximum nominal grain size of 22mm, typically used as a base layer, and the combination of old and new binder in the mixture is 30/45. Additionally, 70% of the aggregate volume in the mixture is made of recycled material, whereas the remaining aggregates are cleaned aggregates (e.g. cleaned from tar contamination).

Unlike most asphalt construction projects that consist of multiple asphalt layers, the temporary nature of this road allowed for a design consisting only of a single 60mm bin/base layer that serves both as a bin/base as well as a surface layer. The single asphalt layer was constructed on top of a 350mm thick layer of rubble and a 500mm thick sand bed layer (Figure 7). The 60mm thick bin/base layer complies with the requirement for this research for a bin/base layer of at least 50mm.

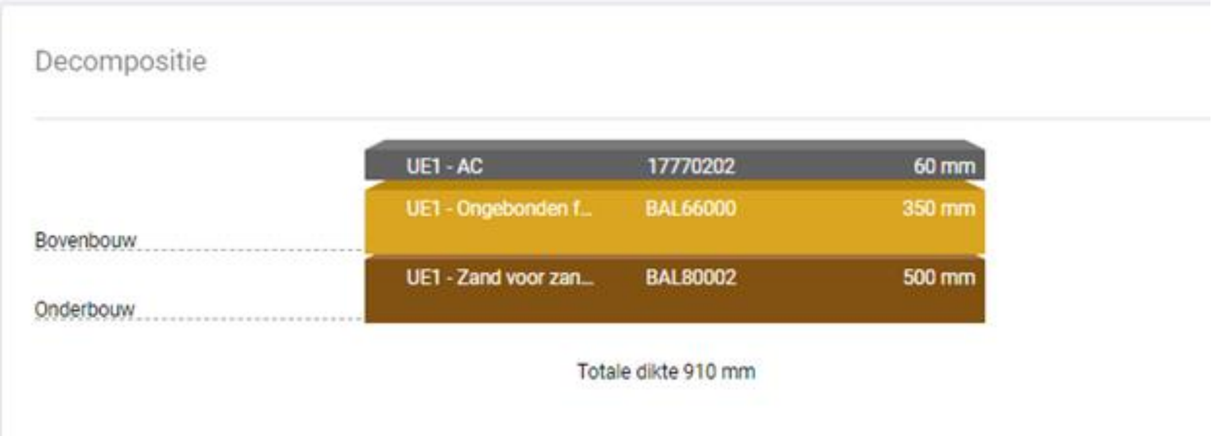

Figure 7: Pavement structure

5.2. Case study methodology

The methodology of the case study follows the steps proposed in the framework for integrating HTLC with FO in KB (Figure 2). Given the exploratory nature of this research, additional analyses were conducted beyond the core elements of the framework. These include a correlation assessment between the physical and mechanical properties of asphalt to investigate the suitability of density as an indicator of product quality. Similarly, a correlation analysis between individual process parameters and product quality was also performed to investigate the relevance and importance of the process parameters that resulted from the first phase of this research.

5.2.1. Product specification and verification

Based on the mixture used in the design of the temporary road, there is a specification of the desired product quality. For the applied mixture, the product quality is specified by the typetest[7]. In current QC/QA practices, the typetest provides a certain target density. When this target density is obtained in a construction project with this mixture, this indicates that the mechanical properties may be comparable to those found in the typetest. In short, the constructed asphalt layer has the potential to provide the properties as specified by the typetest when the target density is reached within a margin of error. The product specification, as determined through the typetest belonging to the mixture used in the case study, can be found in Table 6. Besides a single value, each of the specified properties also contains a set of limits indicating a conform specification state. Therefore, this specification can be used for assessing the product quality of the asphalt layer constructed in the case study. It is important to note that the product specification, as determined by the typetest is in practice not valid for drilled cores. A valid product specification for drilled cores does not yet exist, the absence is also part of the initiation of the FO project in “Asfalt Impuls”. Therefore, the interpretation of whether product quality is conform specification should be done with caution.

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[7] The investigation and documentation of a fixed set of physical and mechanical properties in a laboratory to characterize an asphalt mixture.

Table 6: Product specification for AC22 base 30/45 70%PR ECO

Product characteristic	Value	Unit	Conform specification Limit
Target density	2370	kg/m^3	2298 - 2441
Mixture density	2491	Kg/m^3	-
Voids	4.9	%(V/V)	3.0 – 6.0%
Binder content	4.3	%(m/m)	> 4.2
Water sensitivity	79	%	> 70
Stiffness	10104 *(11923*)*	MPa	7000-14000 *(8260 - 16520)**
Deformation resistance	0,11	µm/m/n	0 - 0.4
Fatigue resistance	(110)	µm/m	> 90

** The Stiffness measured using the testing method on cores is typically 18% higher than measured in the typetest* [35]*, therefore the specification limit has also been set 18% higher.*

5.2.2. Process specifications and verification

Besides a product specification, the selected mixture should be accompanied by a process specification as indicated in the proposed framework (Figure 2). Although most contractors do provide construction advice for the different mixtures they construct, in most cases they do not provide a specification for all the process parameters that have been considered critical in the first phase of this research. Ballast Nedam, the contractor in the case study, also provides construction advice (Appendix B3: Construction advice AC 16 bin/base ECO). However, this construction advice does not mention all the process parameters from the first phase of this research. Therefore, an expert at Ballast Nedam has been consulted to fill the gaps between the construction advice and the process specification. The process specification limits as determined by the construction advice and the expert from Ballast Nedam can be found in Table 7.

After completion of the asphalt construction process in the case study, the specified process quality can be compared with the observed process quality to verify the process quality. It is important to understand that the proposed framework has an iterative step from process validation back to process specification. This means that this first process specification does not have to be perfect and can be refined based on the process validation step. Also, this procedure is likely to be repeated in a number of future projects using this mixture.

Table 7: Process specification

Process parameter	**Source**	**Unit**	**Min**	**Max**
Production temperature	Construction advice	[°C]	155	195
Paver speed	Construction advice	[m/min]	0	6
Paving temperature	Construction advice	[°C]	150	195
Time between production and construction	Construction advice	[Hours]	0	8
Temperature compaction window	Construction advice	[°C]	80	140
Number of compaction passes in TCW	Expert	[-]	9	--
Time between paving and first compaction pass	Expert	[min]	0	5

Excluded from the process specification are: tamper speed, screed temperature, roller weight, conditions of the screed, and pre-compaction force of the screed. The current PQi methodology does not account for measuring these parameters.

The construction team has not been informed prior to the project about the process assessment based on the specification on the basis that this mimics the real-world scenario. However, the construction advice from the contractor is available to the construction team and therefore should have already been known to the construction team.

5.2.3. Collecting process quality data

Process data is collected and processed using the PQi methodology initially proposed by Miller [3] and further developed by ASPARi [36]. Included in the PQi measurements and considered in this research are:

- Temperature homogeneity – asphalt surface temperature behind the paver using infrared cameras and GPS
- Compaction consistency – number of roller passes, roller speed trajectory using GPS
- Cooling rate - Asphalt surface and core temperatures using infrared cameras and thermocouples
- Asphalt batch information – Production time and temperature, and loading and unloading times.

The collection of the data can be divided into 3 nodes in the data collection network: Paver node, Roller node and Asphalt node (Figure 8). Each of the nodes consists of a configuration of sensors to capture the required information for that node.

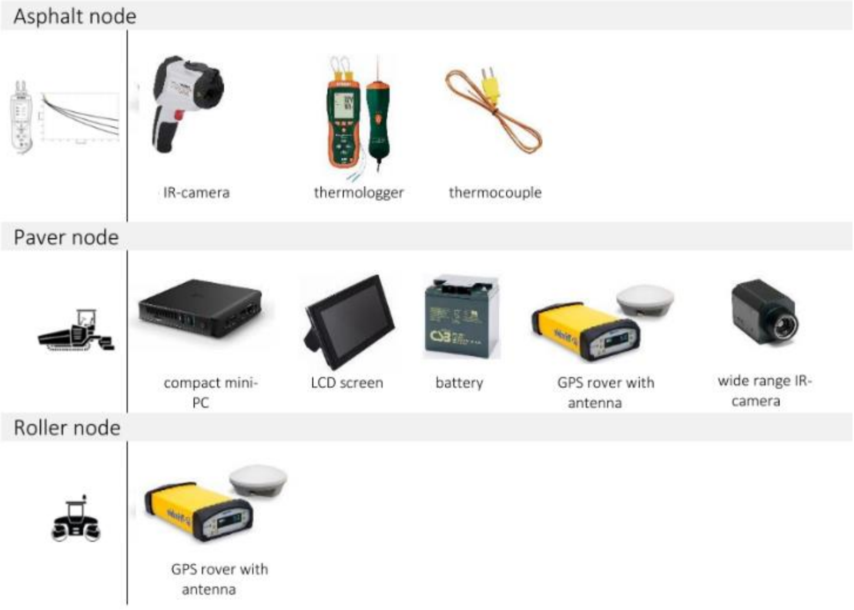


Figure 8: Different data collection nodes (adaptation of [37])

Although the PQi methodology has been widely used in academic research [3], [4], [28], [29], [30], [37], [38], as well as practical applications in case studies [8]. To the best of the authors' knowledge, a comprehensive and standardised protocol for setting up the monitoring equipment, including positioning of the equipment, does not yet exist. Therefore, a full overview of the case study setup and configuration of the nodes in this research can be found in Appendix B1: Data collection.

Furthermore, creating a complete process quality dataset requires the collected raw data to be processed into a structured dataset. However, a detailed description of the data processing steps required by the PQi methodology is, to the author's best knowledge, not available. Therefore, this section of the methodology explains the data processing steps adopted in this research. While these steps are aligned with the approaches used in the studies by Makarov [37] and Shen [30], there are distinct variations in the methods applied. In this section, both the data processing algorithm and output dataset are explained.

The data processing algorithm begins by taking raw data from sensors and performing specific processing steps based on the data type and intended use, ultimately producing a dataset that helps assess the construction process and understand the relationship between process quality and product quality. A visual representation of this algorithm is shown in Figure 9. Initially, the raw data is converted into standardised formats for each data type: GPS, IR temperatures, and batch information. For GPS data, a Kalman filter is applied to reduce measurement noise, thus enhancing data quality. The GPS coordinates are then used to determine speed, direction, and distance travelled, effectively mapping the equipment trajectories. In contrast to the GPS data, the IR temperature and batch information do not require any post-processing of the data.

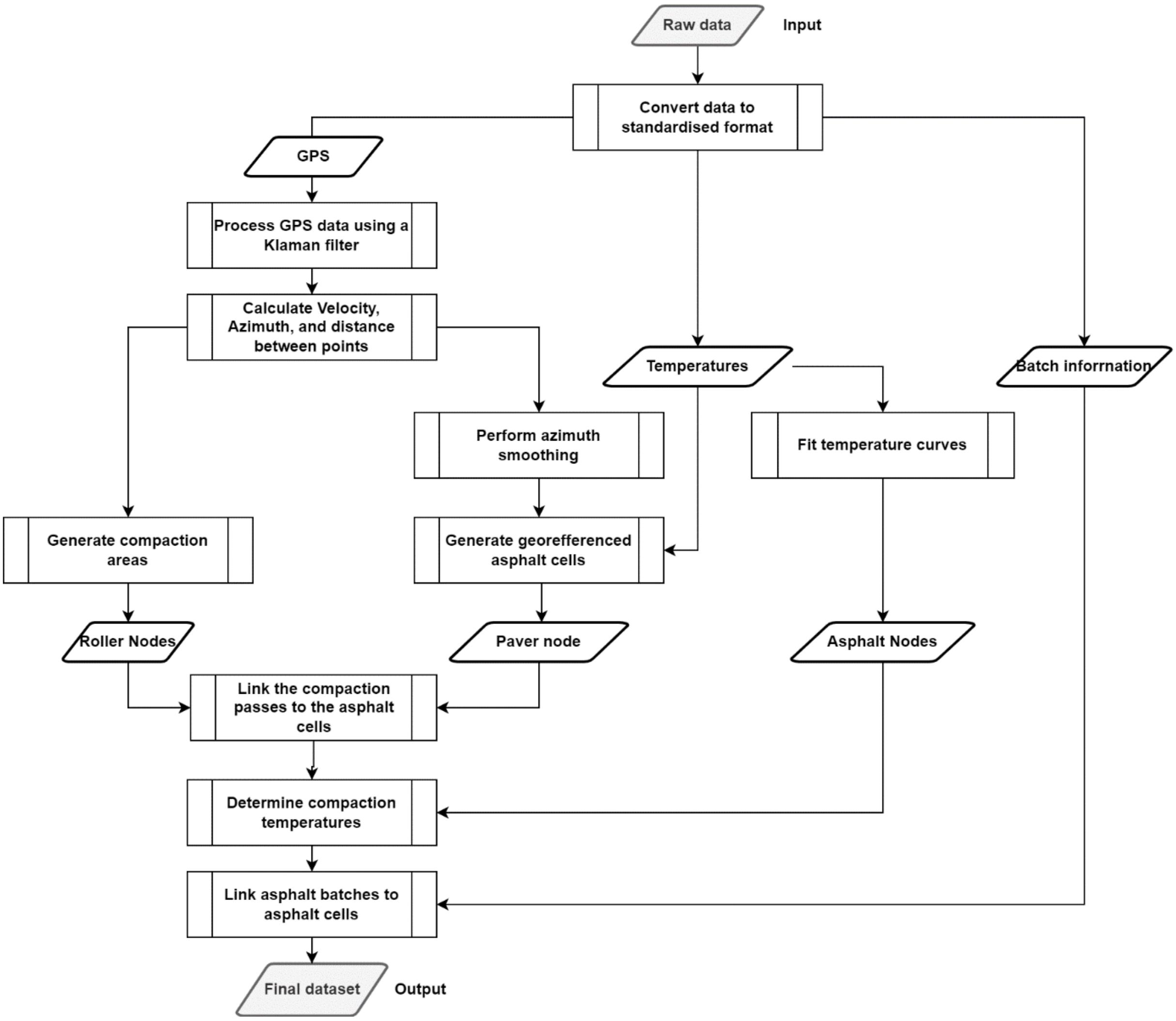


Figure 9: Simplified visual representation of the data processing algorithm

Subsequently, the GPS data from the rollers is used to determine the compacted area for each roller pass, taking into account the geometry of the different rollers. In contrast, the GPS data from the paver receives a second filtering step to further reduce noise by smoothing the direction based on multiple GPS coordinates. These refined GPS coordinates are then used to create asphalt cells, incorporating the paver's speed, direction, and temperature readings across the road width. For the asphalt node, the recorded temperatures are analysed to fit a double exponential decay curve, representing the cooling behaviour of the asphalt for both surface and core temperatures.

Finally, the Roller Paver nodes are combined by matching the compaction passes with the asphalt cells. The cooling curves based on the asphalt nodes are then used to determine the temperature during each compaction pass, after which the batch information is linked to each of the asphalt cells. Each of the data processing steps and a rationale for applying the step is described in more detail in Appendix B2: Data processing. The output of the data processing algorithm is a comprehensive dataset crafted around the asphalt cells (Figure 10). This means that for every asphalt cell, information can be retrieved about the asphalt batch, paving, rollers and finally the compaction process.

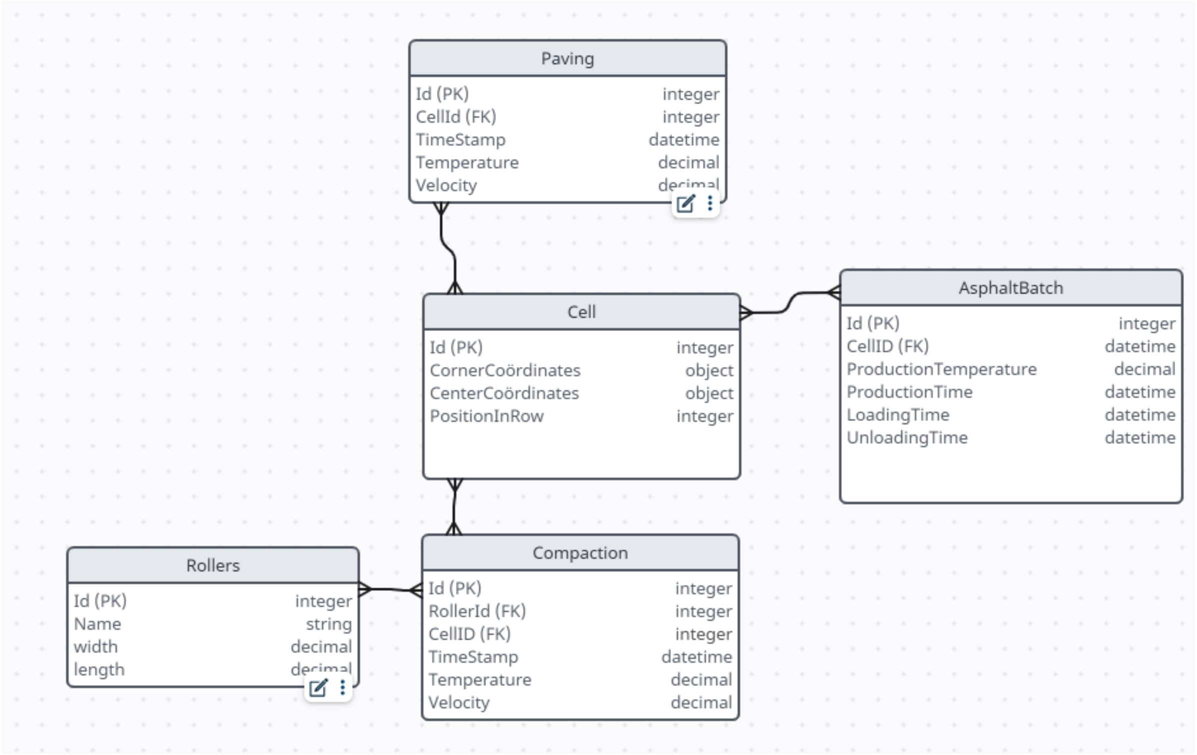


Figure 10: Database Scheme

5.2.3.1. Validation

The dataset that results from the processing does not hold any value for the verification of product quality if the dataset is not validated. Therefore, a validation step has been performed to provide insights into the accuracy of the methodology in capturing the asphalt construction process.

To validate the compaction passes in the process quality dataset, manual observations were conducted at three pre-selected locations throughout the case study project. At each location, the following details were recorded for each compaction pass: Roller ID and Time of compaction pass.

These manually recorded observations (ground truth) were then compared to the data generated by the algorithm. The comparison focused on identifying the number of false positives (Type I errors), which are compaction passes recorded by the algorithm but not observed manually, and false negatives (Type II errors), which are compaction passes observed manually but not recorded by the algorithm.

5.2.3.2. Sensitivity analysis

To evaluate the robustness and reliability of the data processing algorithm, which differs from previous implementations of the PQi methodology, a sensitivity analysis was conducted. Various methodological decisions such as applying the Kalman filter and the number of asphalt nodes employed have been tested and the impact of on the case study dataset was analysed.

This process helps to determine whether alternative input values for these steps yield comparable results, thereby validating the generalisability and accuracy of the methodology. The following steps and parameters are included in the sensitivity analysis:

- **Application of the Kalman filter:** Assessing the impact of using or not using a Kalman filter to improve GPS data accuracy by reducing measurement noise.
- **Number of GPS coordinates used for azimuth smoothing:** Evaluating the effect of different smoothing levels on the azimuth (directional data), with values set at 1, 5, 15, and 20 points.
- **Time between compaction passes:** Investigating the influence of varying the minimum interval time between recorded compaction passes, set at 0, 10, and 30 seconds.
- **Configuration of asphalt nodes:** Testing different configurations of the three asphalt nodes to determine how variations in order and number of temperature cooling curves affect the end result.

5.2.4. Collecting product quality data

The procedure for collecting product quality data is illustrated in Figure 11 and can be summarised as follows. First, the visualised output of the process quality dataset was used to select a set of locations that exhibit a wide variation in process quality (1). This variation was verified by extracting cores along the full length of the asphalt layer, particularly in areas with a varying number of compaction passes. At each selected location, an asphalt core was drilled (2) and its exact position was recorded using a GPS receiver (3). The cores had different heights and therefore were shaped into samples of identical geometry (i.e. equal height), after which the density was determined for each of these samples (5).

Because FO requires a specific waiting time for the samples before any of the laboratory tests can be performed, the samples were placed in a storage facility for at least 2 weeks (6). After the waiting time, the samples were divided into three test groups, and each of the groups underwent a different test for the corresponding mechanical properties (7). The samples were grouped based on density to minimise the influence on the results, thereby isolating the effect of process quality. Finally, the samples were tested, according to the specified procedure (Table 8), to determine their mechanical properties. Due to the destructive nature of the FO laboratory procedures, either water sensitivity (8), stiffness and fatigue resistance (9) or deformation resistance (10) could be determined for each sample.

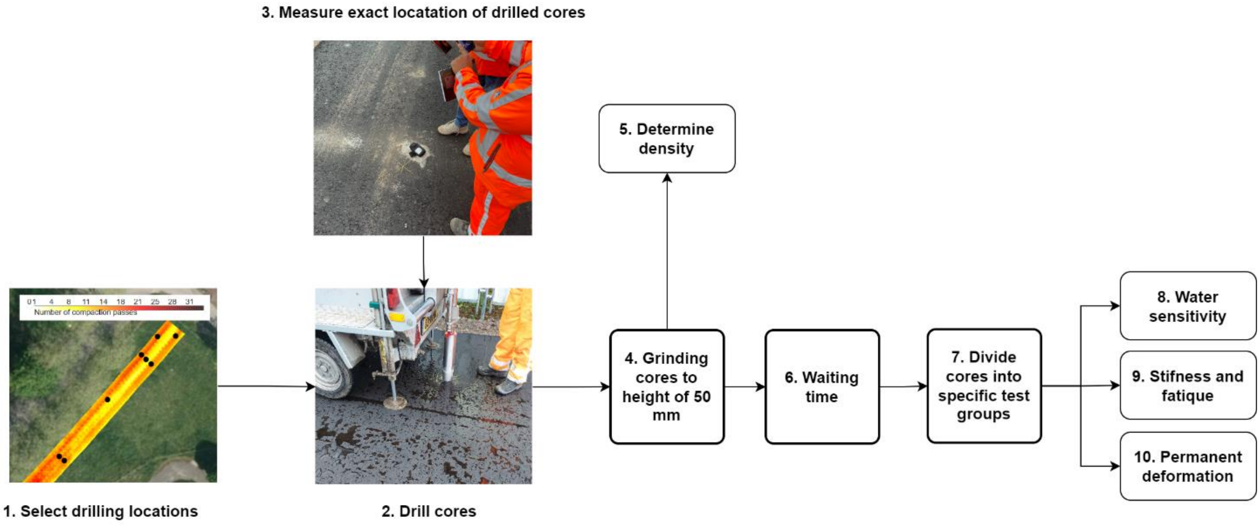


Figure 11: Procedure for collecting product quality data

In total 53 cores were drilled, however, some areas of the constructed asphalt layer had insufficient layer thickness (less than the designed 60mm and less than the required 50mm for the mechanical properties tests). This resulted in only 40 of the 53 cores being suitable for testing. The height of each of the drilled cores can be found in Appendix B4: Height of drilled cores.

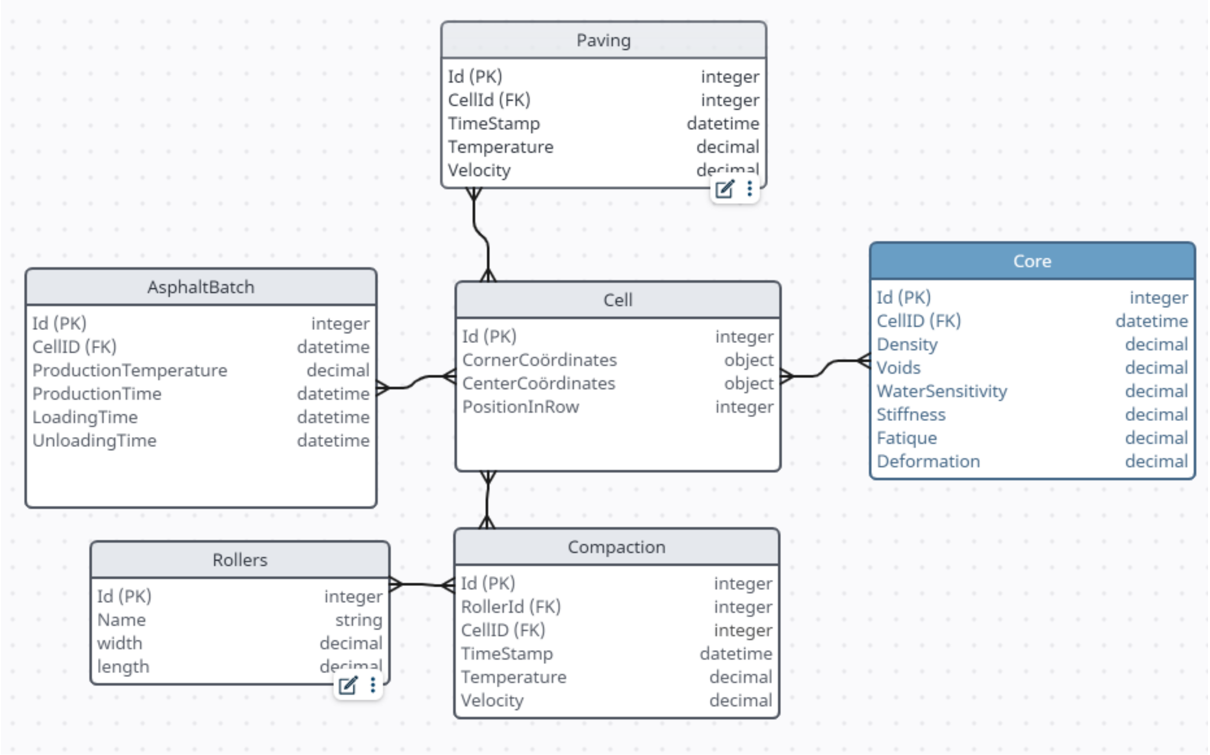
Table 8: Product quality testing procedures

Property	**Test name**	**Number of cores**
Density	NEN-EN12697-5 procedure A	40
Water sensitivity	NEN-EN12697-12 NEN-EN12697-23	20
Stiffness	NEN-EN12697-26 annex F	10*
Resistance to fatigue	NEN-EN12697-24 annex F	10*
Resistance to permanent deformation	NEN-EN12697-25 method B	10

** Stiffness and resistance to fatigue testing is performed on the same samples.*

The FO methodology is currently used to determine the mechanical properties of an entire asphalt layer by generating a single value for each property based on 21 cores [39], this research adapts the methodology by using individual measurements from each core.

The results for the mechanical properties were linked to the asphalt cells based on the location of the drilled cores. The full dataset structure used for assessing the relationship between process and product quality is presented in (Figure 12).



Paving	
Id (PK)	integer
CellId (FK)	integer
TimeStamp	datetime
Temperature	decimal
Velocity	decimal

AsphaltBatch	
Id (PK)	integer
CellID (FK)	datetime
ProductionTemperature	decimal
ProductionTime	datetime
LoadingTime	datetime
UnloadingTime	datetime

Cell	
Id (PK)	integer
CornerCoördinates	object
CenterCoördinates	object
PositionInRow	integer

Core	
Id (PK)	integer
CellID (FK)	datetime
Density	decimal
Voids	decimal
WaterSensitivity	decimal
Stiffness	decimal
Fatique	decimal
Deformation	decimal

Rollers	
Id (PK)	integer
Name	string
width	decimal
length	decimal

Compaction	
Id (PK)	integer
RollerId (FK)	integer
CellID (FK)	integer
TimeStamp	datetime
Temperature	decimal
Velocity	decimal

Figure 12: Database scheme including product quality

5.2.5. The relation between process quality and product quality

In this study, process parameters were categorised into three distinct categories, providing a framework for analysing their influence on product quality. Density-related parameters were hypothesised to affect the final density of the asphalt layer, which was anticipated to serve as an indicator of the layer's mechanical properties. To validate this hypothesis, it was crucial to first investigate the relationship between density and mechanical properties. Once this relationship was established, the main analysis could then focus on exploring the connections between density-related parameters and the resulting density, as well as between direct-related parameters and mechanical properties.

5.2.5.1. Analysis of density and mechanical properties

To evaluate whether density predicts conforming mechanical properties, scatter plots are generated, to visually represent the relationship between density and various mechanical properties across different observations. Furthermore, limits of conforming and non-conforming processes and product quality are visually represented in the scatter plot, to indicate whether a process that is conform specification leads to a product conform specification, and vice versa. Following this visual assessment, the (non-parametric) Spearman's rank correlation coefficient (ρ) and significance (p-value) are calculated to quantify the strength, direction, and significance of the relationship. The hypotheses tested are:

- **Null Hypothesis:** There is no correlation between density and mechanical properties.
- **Alternative Hypothesis:** There is a correlation between density and mechanical properties.

Statistical significance is determined using a p-value threshold of 0.05. A p-value less than 0.05 leads to the rejection of the null hypothesis, indicating a statistically significant correlation. The Spearman's rank coefficient is assessed based on the strength categorisation presented in Table 9. Given the complexity of asphalt construction and the exploratory nature of this study, moderate correlations, in addition to strong and very strong ones, can offer valuable insights and help identify areas that warrant further investigation.

Table 9: Spearman's rank strength categorisation

|ρ|	**Category**
0.80– 1.0	Very Strong
0.60 – 0.79	Strong
0.40 – 0.59	Moderate
0.20 – 0.39	Weak
0.00 – 0.19	Very weak

5.2.5.2. Analysis of product quality and process quality

Following the density-mechanical properties analysis, a comprehensive assessment is conducted to explore the relationship between process quality and product quality. In this phase, the correlation of density-related and direct-related process parameters with the density and mechanical properties of asphalt are examined.

This analysis evaluates whether conforming process quality consistently results in conforming product quality, as measured by both density and mechanical properties. Scatter plots are generated to visualise the relationship between process quality indicators and product quality metrics. The analysis focuses on identifying cases where process quality is conforming but results in non-conforming product quality, and vice versa, ultimately validating the process specification. Following this visual assessment, the Spearman's rank correlation coefficient (ρ) and significance (p-value) are calculated to quantify the strength and significance of the relationship, with the following hypotheses:

- **Null Hypothesis**: There is no correlation between process quality and product quality.
- **Alternative Hypothesis**: There is a correlation between process quality and product quality.

As with the previous analysis, a p-value of less than 0.05 indicates a statistically significant correlation, while a p-value greater than or equal to 0.05 suggests no significant correlation. Also, the categorisation presented in Table 9 is used for assessing the Spearman's rank coefficient.

5.3. Results

5.3.1. Process quality

A comprehensive overview of the construction process is detailed in Appendix B5: Case study process report. The recorded process was assessed against the predetermined specifications (Table 7), and the outcomes are summarised in Table 10.

Table 10: Process quality verification

Process parameter	**conform specification**
Production temperature	100%*
Paver speed	100%
Temperature during paving	2%
Time between production and construction	40%
Temperature compaction window	5%
Number of compaction passes within TCW	14%
Time between paving and first compaction pass	65%

** Could not be verified for the entirety of the project.*

Both the production temperature and paver speed conformed to the specified limits for the entire project. The production temperature, maintained by the asphalt plant, was required to be a minimum of 155°C. However, maintaining the paving temperature, managed by the asphalt crew, at a minimum of 150°C proved challenging. Given the transport duration of 20-30 minutes, it was unlikely that the paving temperature was still above 150°C after transport. As a result, only 2% of the project met the specified temperature requirements during paving, significantly diminishing the likelihood that any section of the constructed asphalt fully adhered to the process specifications. Additionally, it is important to note that the production temperature could not be fully verified, as only a single temperature reading was provided from the asphalt plant, despite the production process involving multiple batches.

Furthermore, only 40% of the project adhered to the specified time between production and construction. The remaining 60% of the asphalt was produced the evening before the project and stored for more than 8 hours before construction, thus not meeting the specification.

Regarding compaction, only 5% of the project met the specified limits for compaction passes. Most compaction passes occurred at temperatures below the specified lower limit, with only a few exceeding the upper limit. The low percentage of conforming compaction passes can be attributed to the average paving temperature being 127°C, leaving limited time for compaction before the asphalt cooled to 80°C. This introduced the need for performing compaction passes below the specified TCW to achieve the desired degree of compaction. This is a clear example of where the indirectly related process parameter (paving temperature) impacts the ability of a density related process parameter to be conform specification (number of compaction passes in the TCW).

Only 14% of the project achieved the minimum number of compaction passes within the TCW. This low percentage is due to 95% of the compaction passes occurring outside the specified temperature window. Finally, 65% of the project received the first compaction pass within the specified 5-minute timeframe.

Finally, no single location in the entire project was fully compliant with all specified process parameters.

5.3.1.1. Validation of process quality

Table 11 presents the results of comparing the compaction passes recorded by the data processing algorithm with the manually observed passes. In total, five locations were selected for validation purposes, however only three locations were recorded[8]. At the first location, all manually recorded passes were also present in the processed dataset, indicating perfect accuracy. At the second location, 16 out of 17 actual passes were correctly present in the dataset, with one pass not recorded manually (Type I error) and one pass not available in the dataset (Type II error). At the final validation point, all compaction passes were correctly present in the dataset except for one additional pass (Type I error).

Table 11: Comparing actual compaction passes with available passes in the dataset.

Location	Actual	Tracked	Type I errors	Type II errors	Accuracy
1	11	11	0	0	100%
2	17	17	1	1	94%
5	13	14	1	0	93%

5.3.1.2. Sensitivity analysis of process quality

The sensitivity analysis was conducted to assess the impact of various algorithmic choices on the process data related to the compaction activities. The reference case established baseline values with a minimum temperature during compaction of 41.7°C, a maximum temperature of 148°C, a mean

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[8] The other two locations could not be observed due to the limited number of observers

number of 4.9 compaction passes within the TCW, and an overall mean of 12.4 passes (regardless of the temperature). At validation locations 1, 2, and 5, the number of passes was 11, 17, and 14, respectively.

The impact of algorithmic choices on the registration of roller passes was assessed by considering the effects of the Kalman filter, azimuth smoothing, and the minimum time between compaction passes. At both locations 1 and 2, these algorithmic choices did not affect the number of compaction passes registered. Alternatively, setting the minimum time between two subsequent roller passes to 0 seconds, effectively removing this filter, resulted in a significant increase of compaction passes introducing many type I errors. In contrast, location 5 showed more visible differences when the algorithmic settings were adjusted. The Kalman filter and azimuth smoothing are intended to reduce noise in the GPS data and increase accuracy. Location 5, unlike locations 1 and 2, was situated in an area with more tree cover, leading to higher GPS signal interference. Reducing the Kalman filter decreased the number of compaction passes registered at location 5 from 14 to 12. Not smoothing the azimuth or smoothing it by 10 or 20 points also reduced the number of passes from 14 to 13, while smoothing it by 15 points did not change this outcome. Changing the minimum time between roller passes from the standard 5 seconds to either 10 or 30 seconds did not alter the number of compaction passes at any of the three locations.

Secondly, the impact of different asphalt node configurations on the average minimum and average maximum temperature during compaction was examined (Figure 14), and the impact on the average number of compaction passes within the TCW was also examined (Figure 15).

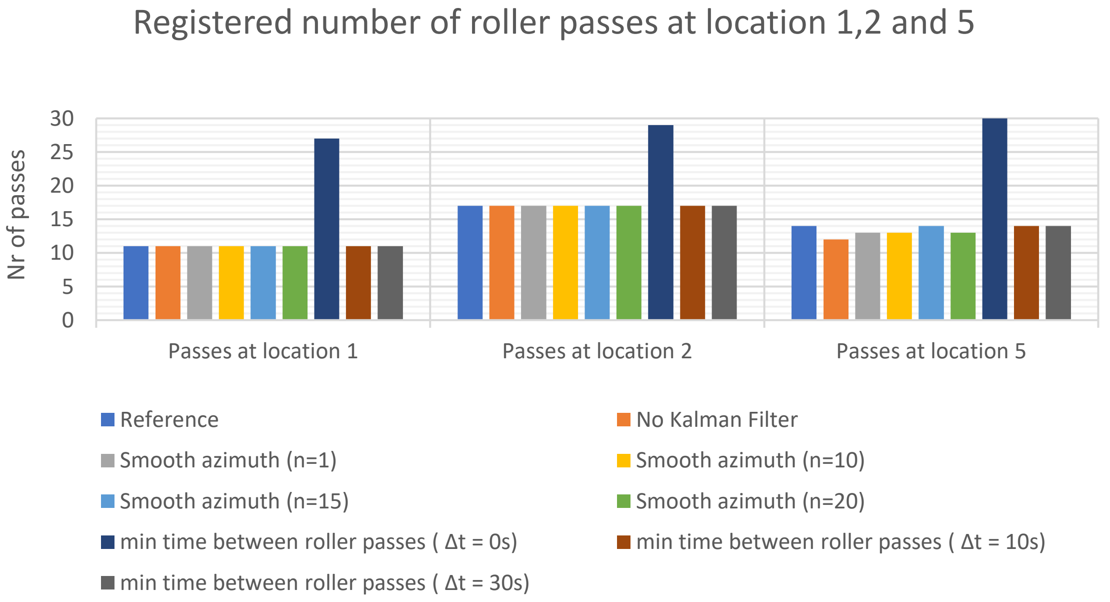


Figure 13: Sensitivity analysis for registering roller passes

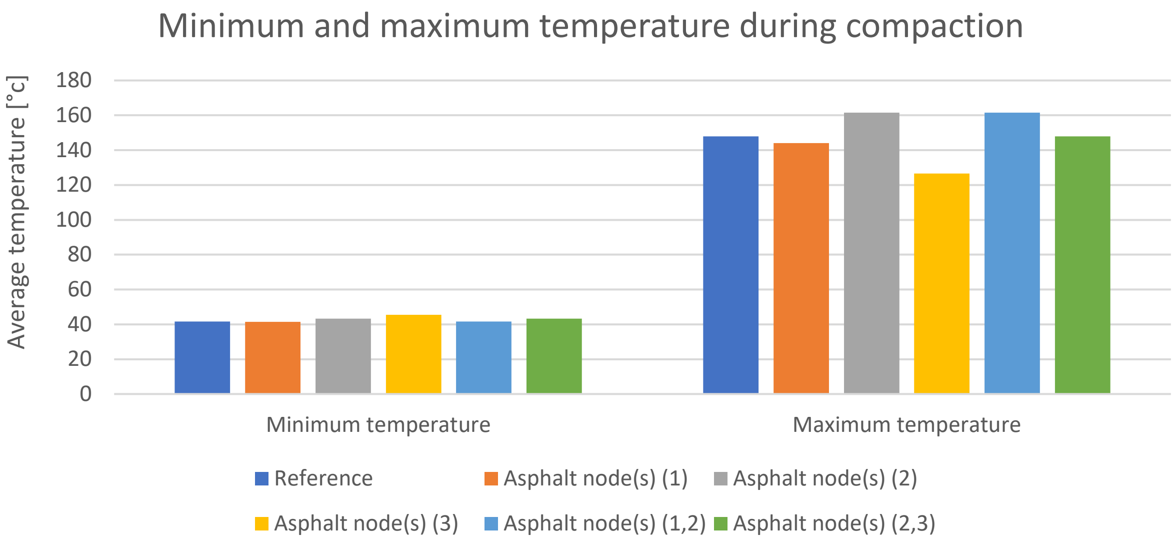


Figure 14: Sensitivity analysis for the temperature during compaction passes

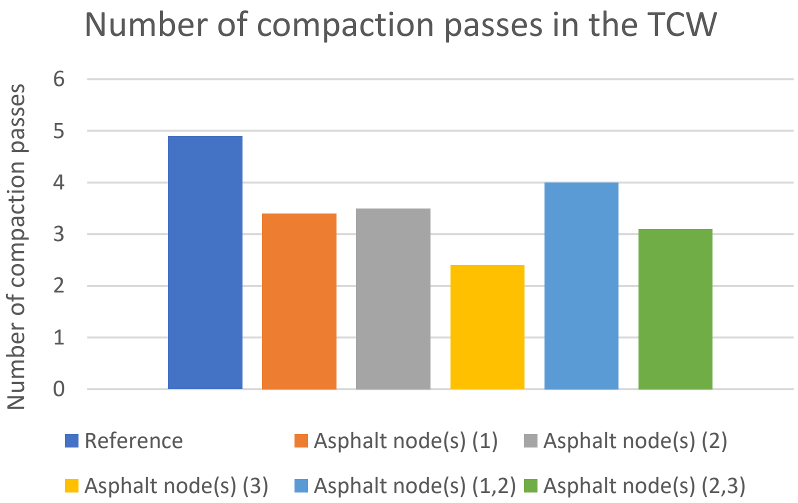


Figure 15: Sensitivity analysis for the number of compaction passes in the TCW

When a single asphalt node was used, the minimum temperature registered was slightly lower at 41.5°C, and the maximum temperature decreased to 144°C, resulting in an average of 3.4 compaction passes within the TCW. Using two nodes increased the minimum temperature to 43.2°C and the maximum to 161.6°C, with 3.5 average passes. Employing three nodes further raised the minimum temperature to 45.5°C, but reduced the maximum temperature to 126.6°C, and lowered the average passes to 2.4.

When configurations combined nodes 1 and 2, the minimum and maximum temperatures were recorded at 41.7°C and 161.6°C respectively, with an average of 4 passes within the TCW. Combining nodes 2 and 3 showed a slight decrease in both the minimum (43.2°C) and maximum (147.96°C) temperatures, with an average of 3.1 passes.

In summary, adjusting the asphalt node configuration impacted the temperature registrations. The use of multiple nodes generally increased the minimum temperatures recorded but showed varied effects on the maximum temperatures and the average number of compaction passes within the TCW.

The sensitivity analysis revealed that variations in both the number of temperature nodes and the data processing steps have a significant impact on the output dataset. In practice, this means that when data from different projects is processed using differing methodologies, comparisons between these projects may lead to misleading conclusions. To use the PQi methodology in QC/QA practices, methodological steps such as data processing and the number of asphalt nodes should be standardised.

5.3.2. Product quality

The product quality of the constructed asphalt layer in the case study has been determined in the laboratory of Ballast Nedam. The results from the 40 investigated asphalt cores are summarised and verified based on the product specification (Table 6) in Table 12. The researcher emphasises that the interpretation of product quality verification should be approached with caution, as the current product specification is not officially applicable to drilled cores, and a valid specification for this purpose does not yet exist. The FO project represents a critical step toward developing such a specification.

Table 12: Product quality summary and verification

	Degree of compaction	**Water sensitivity**	**Stiffness**	**Fatigue resistance**	**Deformation resistance**
Project average	98.3%	62%	10283 MPa	120000	0.58 µm/m/n
Conform specification	73%	10%	100%	-	10%

** The full dataset can be found in Appendix B7: Results from product quality tests*

The density of 73% of the cores was according to specification, averaging a degree of compaction of 98.3%. For stiffness, 100% of the cores had a value within the product specification limits, averaging a stiffness of 10,283 MPa. However, for both water sensitivity and deformation resistance only 10% of the cores had a value within the limits of the product specification. Finally, the result for the lab tests on resistance to fatigue resulted in an average of 120,000 load cycles before failure. Since this result does not correspond directly to the value specified in the product standards, it is not possible to determine the percentage of cores that conform to the fatigue resistance specification.

Table 13 presents scatter plots comparing density with various mechanical properties, along with the upper and lower specification limits, Spearman's rank correlation coefficient (ρ) and p-value. Enlarged versions of the scatterplots can be found in Appendix B8: Scatterplots.

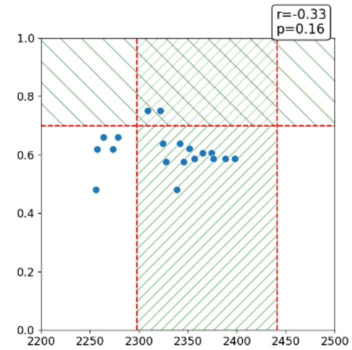
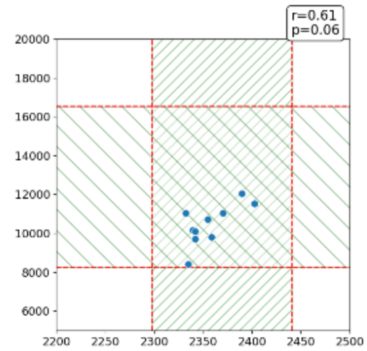
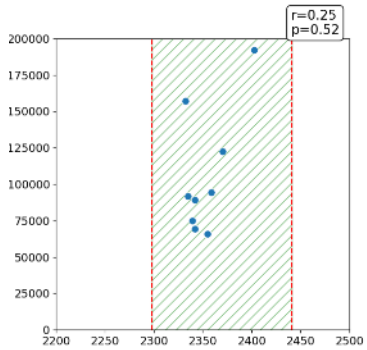
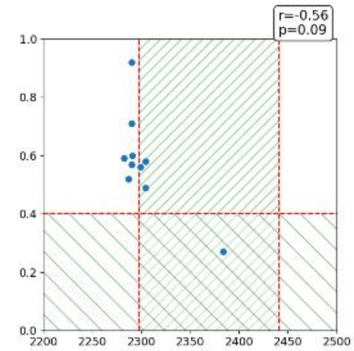
The correlation between density and water sensitivity is weakly positive, but with a p-value of 0.16 not statistically significant, thus the null hypothesis is not rejected. In contrast, the relation between stiffness and density is strongly positive. Yet, it is also not significant and the null hypothesis is therefore not rejected. The results for resistance to fatigue show a weak positive correlation with density, but this too is insignificant based on the p-value of 0.5, leading to a retention of the null hypothesis. Lastly, the relationship between deformation resistance and density is moderately positive, but the p-value of 0.09 indicates insignificance, so the null hypothesis remains unchallenged.

Assessing whether achieving density conform the product specification leads to mechanical properties conform the product specification is meaningful primarily for stiffness and resistance to permanent deformation, given the weak correlations observed for water sensitivity and fatigue resistance. All the cores tested for stiffness had densities within specification, meaning that in this study, compacting to the specified density consistently resulted in stiffness meeting the specification. However, since no cores fell below the specified density limits, it remains unclear whether stiffness would still meet the specification if the density were below the required limit.

For resistance to permanent deformation, only one core fell within the specified limits, while the other nine exceeded the upper limit. Notably, these nine cores had densities close to the lower limit of the specification. This suggests that the current density limits may be too broad when a specific resistance to permanent deformation is expected.

In conclusion, a strong positive correlation was revealed between density and the stiffness and resistance to permanent deformation, Despite not providing scientific significance, the strong Spearman correlation coefficient does suggest a potential relation that requires further investigation. In contrast, a correlation for water sensitivity and resistance to fatigue with density was not found and the results indicate that these properties are not directly related to density.

Table 13: Correlation matrix of density and mechanical properties

	Density [kg/m^3]	
Water sensitivity [%]		ρ=-0.33, p=0.16
Stiffness [MPa]		ρ=0.61, p=0.06
Fatigue resistance [-]		ρ=0.25, p=0.52
Deformation resistance [µm/m/n]		ρ=-0.56, p=0.09

5.3.3. Process quality vs product quality

In the final step of this research, the relation between process quality and product quality is investigated. The correlation matrix including the specification limits for both process and product quality is presented in Table 14. Additionally, the spearman's rank and significance score are provided. Enlarged versions of the scatterplots can be found in Appendix B8: Scatterplots.

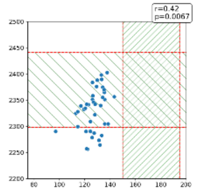
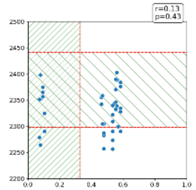
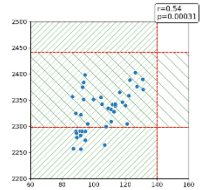
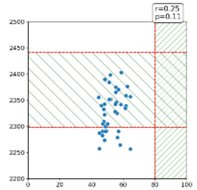
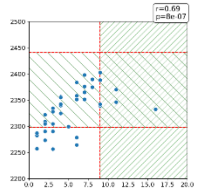
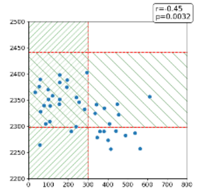
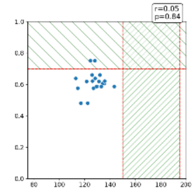
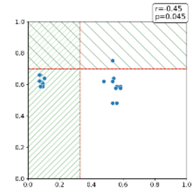
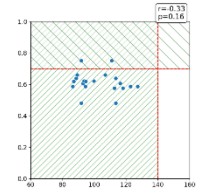
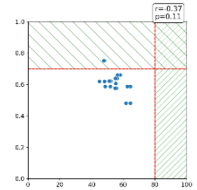
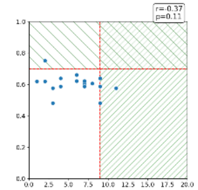
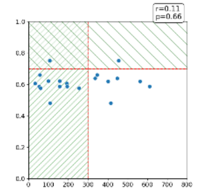
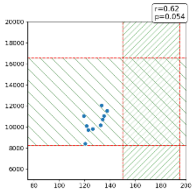
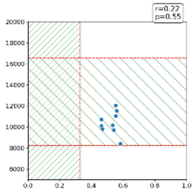
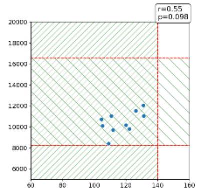
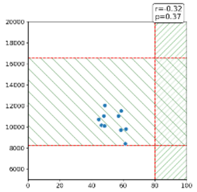
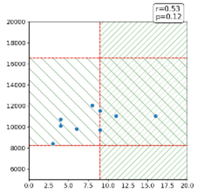
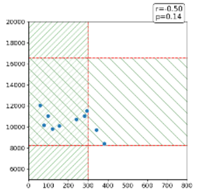
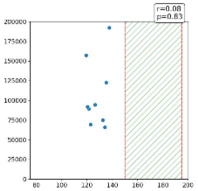
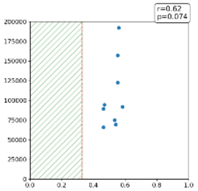
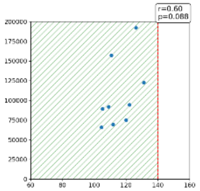
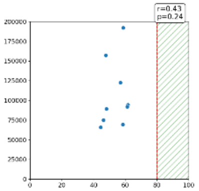
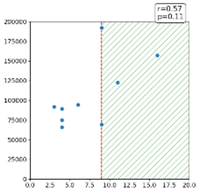
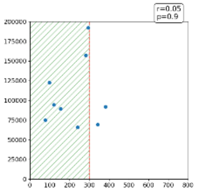
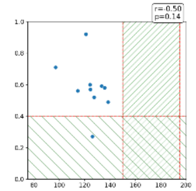
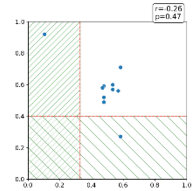
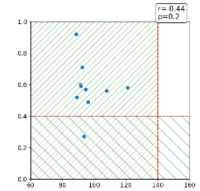
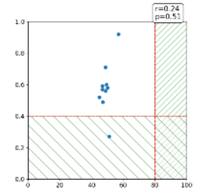
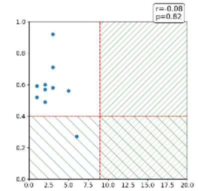
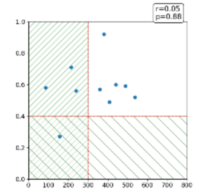
5.3.3.1. Process quality vs density

Significant correlations were identified between density and the process parameters: paving temperature, temperature during the first compaction pass, the number of passes in the TCW, and the time between paving and the first compaction pass. (1) The correlation between paving temperature and density is moderately positive, supporting expert opinions that lower paving temperatures may reduce compaction time within the TCW, though this effect is not always consistent. Importantly, no clear threshold was identified for adjusting the paving temperature specification, as the data does not show a specific temperature range at which density consistently meets standards. (2) Similarly, the highest temperature during the first compaction pass is moderately positively correlated with density, indicating that higher temperatures during this pass are associated with better compaction results. (3) The strongest correlation is observed between the number of compaction passes within the TCW and density, suggesting that achieving the correct density for this specific mixture and design is more likely with at least seven passes, even though the current specification calls for more. (4) Lastly, a moderately negative correlation was found between the time between paving and the first compaction pass and density, reinforcing that shorter intervals lead to better compaction, with the current 5-minute specification appearing appropriate for achieving the desired density. The time between production and paving of the asphalt and the lowest temperature during compaction does not seem to affect the final density of the asphalt. The null hypothesis cannot be rejected for these process parameters.

5.3.3.2. Process quality vs water sensitivity

In examining the relationship between process quality and water sensitivity, only one significant and moderately positive correlation was identified: the time between production and paving. This correlation suggests that a longer interval between asphalt production and paving negatively impacts the water sensitivity ratio, leading to poorer performance on this parameter. No significant or moderate correlations were found for the other process parameters. Further, the null hypothesis could not be rejected for the process parameters other than the time between production and paving. This contradicts the expectations of the expert panel, which associated an extended time between production and paving with reduced stiffness and fatigue resistance. Meerkerk [34] did, in line with this study, suggest a link between the period between production and construction and increased water sensitivity, attributing it to segregation in the asphalt mixture.

Table 14: Correlation matrix of process quality and product quality

	Paving temperature [°c]	**Time between production and paving** [-]	**Highest compaction temperature** [°c]	**Lowest compaction temperature** [°c]	**Number of passes within compaction window** [-]	**Time between paving and first compaction pass** [seconds]
Density [kg/m^3]	 ρ=0.42, p=0.0067	 ρ=-0.13, p=0.43	 ρ=0.54, p=0.00031	 ρ=0.11, p=0.25	 ρ=0.69, p=0.000008	 ρ=--0.45, p=0.0032
Water sensitivity [%]	 ρ=0.05,p=0.84	 ρ=-0.45, p=0.045	 ρ=-0.33, p=0.16	 ρ=-0.37, p=0.11	 ρ=-0.37, p=0.11	 ρ=0.11, p=0.66
Stiffness [MPa]	 ρ=0.62, p=0.054	 ρ=0.22, p=0.55	 ρ=-0.55, p=0.092	 ρ=-0.32, p=0.37	 ρ=0.53, p=0.12	 ρ=-0.14, p=0.50
Fatigue [-]	 ρ=0.08, p=0.83	 ρ=0.62, p=0.074	 ρ=-0.60, p=0.088	 ρ=0.43, p=0.24	 ρ=-0.57, p=0.11	 ρ=0.05, p=0.90
Permanent deformation [µm/m/n]	 ρ=0.50, p=0.14	 ρ=-0.26, p=0.47	 ρ=-0.44, p=0.20	 ρ=0.24, p=0.51	 ρ=-0.08, p=0.82	 ρ=0.05, p=0.88

The experts anticipated that a compaction temperature that is too low would result in lower water sensitivity values. While this expectation aligns with the overall results shown in Table 14, there is an inconsistency: one observation compacted at a too-low temperature still showed a conforming value for water sensitivity.

5.3.3.3. Process quality vs stiffness

None of the process parameters showed a statistically significant relationship with the stiffness of the drilled cores, preventing rejection of the null hypothesis for all evaluated relationships. Despite this, the data did reveal a strong positive correlation between paving temperature and stiffness, as well as moderate positive correlations between stiffness and both the highest temperature during compaction and the number of compaction passes within the TCW. Although these correlations were not statistically significant, they suggest potential trends that may need further investigation.

According to the experts in phase 2, a too-long period between construction and compaction was likely to lead to a reduction in stiffness, the same goes for compacting below the specified minimum compaction temperature. However, in both cases, the stiffness conformed to the specification for all process parameters outside of the specified limits. This suggests that, for this mixture, the stiffness is ‘forgiving’ and not directly related to the process, but rather through density related process parameters.

5.3.3.4. Process quality vs fatigue resistance

None of the process parameters demonstrated statistically significant correlations with fatigue resistance, resulting in the null hypothesis being retained across all examined relationships. However, the analysis revealed strong correlations between fatigue resistance and two process parameters: a strong positive correlation with the time between production and paving, and a strong negative correlation with the highest temperature during compaction. Additionally, moderately positive correlations were observed with both the lowest compaction temperature and the number of compaction passes within the TCW. Although these correlations are not statistically significant, they suggest that longer times between production and paving may improve fatigue resistance, while higher compaction temperatures might adversely affect it. This is in line with the work of Bijleveld [25], who indicated that a higher compaction temperature can adversely affect properties related to fatigue resistance. In practice, this could indicate that fatigue resistance could benefit from a waiting period after production and starting compaction at lower temperatures. Similarly, maintaining appropriate compaction temperatures and ensuring sufficient passes within the compaction window appear to positively influence fatigue resistance, indicating potential areas for further study.

Similarly to stiffness, experts indicated that a long period between production and paving, and compacting below the specified minimum compaction temperature was likely to lead to a reduction in fatigue resistance. However, the time between production and paving indicated a strong positive correlation, which contrary to the expert's statement, would indicate a better resistance to fatigue when this period is longer. On the other hand, the moderate positive correlation between fatigue resistance and the minimum compaction temperature aligns with expert expectations, confirming that lower compaction temperatures could potentially negatively impact fatigue resistance.

5.3.3.5. Process quality vs deformation resistance

None of the process parameters exhibited statistically significant correlations with permanent deformation resistance, leading to the retention of the null hypothesis for all relationships. However, the analysis revealed moderate correlations between permanent deformation resistance and two specific process parameters: a moderate positive correlation with paving temperature and a moderate negative correlation with the highest compaction temperature. These correlations, although not statistically significant, suggest that higher paving temperatures may be associated with improved resistance to permanent deformation, while higher compaction temperatures could potentially reduce this resistance. The reduction in resistance to permanent deformation by higher compaction temperatures is supported by the work of Bijleveld [25]. The absence of significant correlations across all process parameters indicates that other factors may also play a critical role in determining permanent deformation resistance, deserving further investigation.

A visualisation of the correlations between process and product quality can be found in Figure 16.

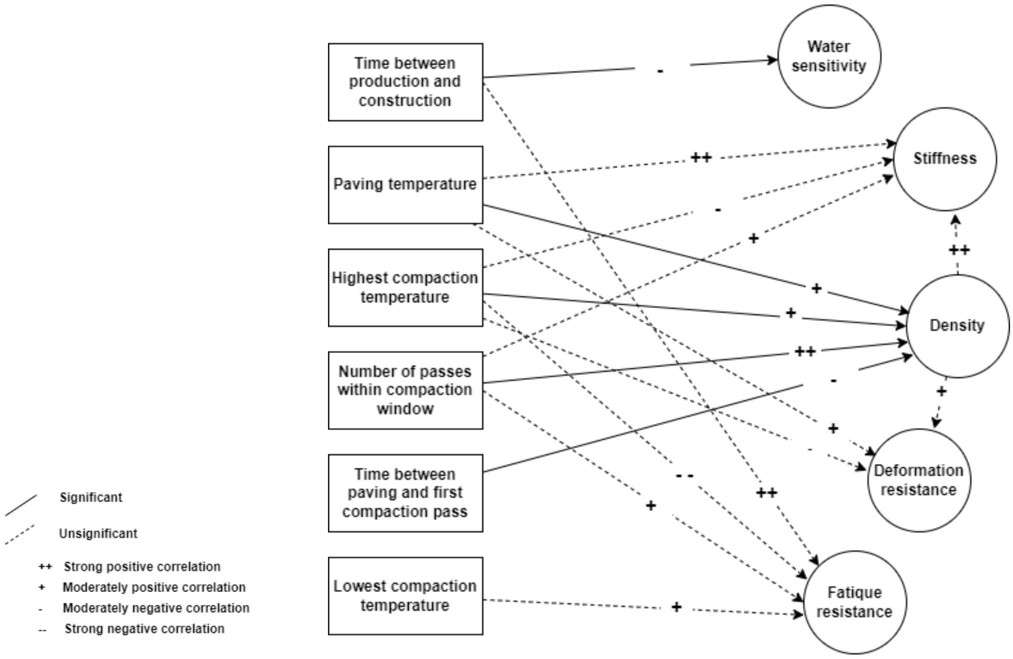


Figure 16: Correlation overview process vs product quality

5.4. Discussion

Overall, the construction process was not executed conform the specified process, with only 2% of the paving operations meeting the required specification for paving temperature and just 14% of the compaction passes taking place within the specified TCW. Moreover, not a single location in the entire project was constructed completely conform process specification. Despite the process being not conform specification, 73% of the asphalt cores had densities according to specification and 100% of the stiffness measurements where conform specification. However, both water sensitivity and deformation resistance of the asphalt were not conform specification, with only 10% of the samples being within the specified limits.

The correlation analysis between density and mechanical properties indicates a moderate to strong relationship between density and both stiffness and deformation resistance. However, the evidence was not strong enough to provide significance, and therefore the null hypothesis could not be rejected. For both water sensitivity and fatigue resistance a weak and statistically insignificant correlation was found. Indicating that density is not likely to be a predictor for water sensitivity and fatigue resistance. In practice, this would mean that the density related process parameter: number of roller passes in the TCW, impacts stiffness and deformation resistance, but not water sensitivity and fatigue resistance. This challenges the work of Bijleveld [25], where a relation between density and deformation resistance was not found. The insight that density is not likely to be an indicator of water resistance may be an explanation for the result that 73% of the asphalt cores had densities conform specification where only 10% of the water sensitivity values were within the specified limit.

Although some correlation was found between process quality and product quality, for most correlations, the evidence is not strong enough to support a significant relation. The paving temperature, highest compaction temperature, number of roller passes in the TCW and the time between paving and the first compaction pass have a significant and moderate to strong correlation with density. Additionally, the time between production and paving is significant and moderately correlated with water sensitivity.

Moreover, paving temperature, the time between production and paving, the highest temperature during compaction, and the number of passes in the TCW showed moderate correlations with one or more mechanical properties. Although these correlations were not statistically significant, they provide a foundation for future research with a larger dataset. It is important to note that weak correlations and the lack of statistical significance in some cases may be due to the limitations of one project. Therefore, the results should be viewed as potential indicators for identifying key predictors and guiding future research priorities, rather than as a justification for dismissing process parameters.

The findings obtained in the second part of the research are used to answer the second sub-research question:

To what extent can the asphalt construction process be used as a predictor of product quality?

Correlations revealed through the case study provide sufficient evidence that the asphalt process is not unsuitable as a predictor for the product quality of an entire asphalt layer. However, the case study has shown that with the current methodologies, the process cannot yet be used as a predictor of product quality.

This case study is limited to a single asphalt mixture from one project. Different mixtures and varying project conditions, such as weather, may produce different results. Additionally, while the ability to drill 40 cores within a 600-meter project is unique, the sample size remains limited, which could explain the lack of scientifically significant correlations. Despite the project’s relatively small scale (600 meters), the asphalt was produced in two separate batches, and differences in the mixture quality between the batches may have influenced the product quality.

The validation and sensitivity analysis of the data collection and processing steps indicate that the collected data sufficiently represents the actual construction process. However, the accuracy of the process data is inherently constrained by the current ASPARi equipment and PQi methodology. For instance, the roller's crab mode was not recorded, and a clear protocol for sensor setup was lacking. Improving the repeatability and accuracy of the methodology could lead to stronger evidence of significant relationships between process quality and product quality.

Furthermore, the paving process is inherently complex as indicated in the introduction of this research. Process parameters are not completely independent of each other. For instance, a higher paving temperature is most likely to result in a higher temperature during the first compaction pass, and more compaction passes within the TCW. Also, a shorter time between the paving and the first compaction time is likely to result in a higher temperature during the first compaction pass. Additionally, the decision to use Spearman’s correlation coefficient was appropriate given the sample size and the exploratory nature of this study. However, the assumption that the variables move in a monotonic relationship may not be valid in all cases.

Finally, the process specification is based on the Delphi study from the first phase of this research, though additional parameters not covered by expert input may exist. Some specification limits were derived from construction guidelines and a single expert's experience, which may render them invalid. However, this aligns with the feedback loop in Figure 2, where process validation informs adjustments to the process specification if necessary.

6. Conclusion

This research aimed to address the limitations of current CQ/QA procedures, which offer limited insights into asphalt pavement quality and insufficient feedback on how construction quality issues affect the final product. The goal was to synthesise HTLC, FO, and KB methodologies into a systematic approach that links process quality to product quality, ultimately using process quality as an indicator of product quality.

The proposed framework that links the HTLC and FO within the KB methodology starts with the pre-construction phase, focussing on mixture-based product and process specifications. During construction, the process is monitored, followed by process verification to ensure adherence to the pre-defined process specification. Product verification is performed based on constructed product quality and the specified product quality. Finally, the process specification is validated by confirming whether a process conform specification consistently results in a product conform specification. Once validated, the process can serve as the primary verification method, eliminating the need for destructive product quality testing like drilling cores.

By integrating the methodologies of HTLC, FO and KB with the proposed framework, a systematic approach was developed, and implemented in a case study, for verifying product quality using process quality. ASPARi's PQi methodology related to HTLC was used for monitoring the construction process and the FO methodology was used for measuring the product quality of the constructed asphalt layer. Although the systematic approach was practically successful, the current HTLC and FO methodologies are not yet fully sufficient to use process quality as the sole indicator for product quality in QC/QA practices, as originally hypothesised. However, the research did reveal trends suggesting which process parameters may be more influential in determining product quality.

The Delphi study, presented in the first phase, effectively identified a set of critical process parameters. However, it also revealed that the current PQi methodology is inadequate for measuring the full range of parameters critical to product quality. While the PQi method focuses on reducing overall process variation, it lacks the detailed and accurate process dataset necessary for fully integrating HTLC, FO, and KB methodologies.

The case study proved to be an excellent tool for uncovering issues in the integration of HTLC and FO within a novel QC/QA approach. It identified specific areas in need of further investigation and refinement to achieve the ideal scenario where a verified process can verify product quality, potentially eliminating the need for destructive product verification.

7. Recommendations

Given these findings, further research is recommended, particularly through projects like “asphalt delta plan duurzame wegverhardingen”. The outcomes of this research, along with the recommendations presented in the next chapter, serve as a foundation for future studies aimed at establishing a clear relationship between process quality and product quality in the remaining 99 projects of the “Asphalt Delta Plan”.

Focus on trends

This research has revealed that some process parameters are more likely to predict mechanical properties than others. Based on the correlation analysis, paving temperature, time between production and paving, highest temperature during compaction and number of compaction passes in the TCW indicated potential trends. Focussing on these parameters and attempting to isolate their variation, while keeping the rest of the process constant, may yield more accurate and insightful results.

Develop a protocol for setting up the PQi equipment

To enhance the accuracy and reliability of the PQi methodology, it is essential to develop clear protocols for sensor positioning and data recording. Variations in the test setup can lead to significant errors in the data. For example, discrepancies in the placement of GPS antennas and IR cameras can lead to an offset of metres. A well-defined protocol will allow the construction team to properly mount equipment, minimising deviations and ensuring data consistency. Additionally, streamlining the setup process, particularly for asphalt nodes, by developing automated methods to capture cooling curves without manual interference, is expected to significantly reduce the likelihood of data collection errors and the need for extra personnel.

Addressing gaps in the PQi methodology

The PQi methodology is primarily designed to assess the effectiveness and uniformity of the asphalt construction process and identify potential areas for improvement. However, this purpose differs from the use of the PQi methodology in this research, which focused on linking process parameters directly to product quality. As a result, the PQi methodology currently lacks the capability to record certain process parameters identified as critical in the first phase of this study. For instance, pre-compaction effort, a key density-related parameter, cannot be recorded using the existing PQi setup. Additionally, roller characteristics such as the roller mass and drum dimensions, which are known to impact the compaction effort of a roller pass [34], are not included. Key parameters like tamper speed and screed temperature, which the expert panel highlighted as directly affecting the mechanical properties of the asphalt, are also omitted. To ensure comprehensive process monitoring, it is recommended that additional methods be explored and implemented to capture these missing parameters.

Increasing the level of detail in the PQi methodology

The PQi methodology was originally designed for what it was named "*process quality improvement*". The level of detail it provides is adequate for its original purpose. However, using the PQi methodology for verifying product quality may yield better results when the level of detail is increased.

First, the sensitivity analysis highlighted the need for a more accurate method of collecting core temperature data across the entire asphalt layer, instead of a limited number of nodes that are used to reflect the cooling curve of the entire asphalt layer. The prediction model proposed by Makarov [37], is also based on data from an asphalt node, and therefore limited to the number of asphalt nodes. Substantially increasing the number of asphalt nodes could be a potential solution, although that might be hindered by the fact that the current method for setting up the asphalt node and retrieving the data is time-consuming. An alternative approach might be the use of a prediction model that is based on continuous data covering the entire asphalt layer such as a cooling curve based on mixture type, sub-base temperature and weather conditions. Such a model known as PaveCool [40] exists in the United States. However, the model is not valid for Dutch mixtures.

Secondly, in the current PQi methodology, all compaction passes are treated uniformly as roller passes, without distinguishing between the different rollers used on the compactor. Additionally, factors like crab mode and roller mass are not accounted for. Adopting an approach similar to that of Meerkerk [34], who considered compaction energy, may provide a stronger correlation with product quality. Further improvements could include extending the analysis of compaction energy by factoring in variables such as temperature during compaction, previously applied compaction energy (including pre-compaction), layer thickness, and mixture type. This could significantly enhance the level of detail in understanding the compaction process and its impact on asphalt quality.

Develop a protocol for processing the data

The first step in data processing is to convert the various file formats into a standardised format for each data type. Without such standardisation, significant effort is required to ensure that all data fields are correctly formatted for processing. The Mic 4.0 initiative [11], which aims to standardise communication between construction equipment, has highlighted the importance of including construction process data in future standardised communication protocols, although this is still part of their long-term vision. In the United States, a software tool called VETA [41] allows the upload of asphalt construction process data in its proprietary .veta format. It is recommended to explore whether this standard could be adopted or adapted for use in the Netherlands, particularly in alignment with the pavement lifecycle management ontology proposed by Sadeghian [42].

Furthermore, the validation and sensitivity analysis of product quality data collection have shown that the recorded and processed data provide only an approximation of reality. The steps taken during processing greatly influence the accuracy and reliability of the output. Therefore, it is essential to develop a protocol that clearly defines each data processing step to ensure consistent and validated results from the PQi methodology. This protocol should also include clear criteria for distinguishing between valid and invalid data, thus minimising subjective decision-making and ensuring a minimum required level of accuracy.

Lastly, several research projects have utilised the PQi methodology, but often with newly developed algorithms in separate codebases. To avoid “reinventing the wheel” in each new project, it is recommended to develop an open-source coding library that includes all the data processing steps in a widely accepted programming language such as Python. This approach would promote continuous development, facilitate collaboration among researchers, and naturally improve error detection. Additionally, it would reduce the time spent on coding, allowing researchers to focus more on analysing the data and exploring new research topics.

Adapt the FO methodology

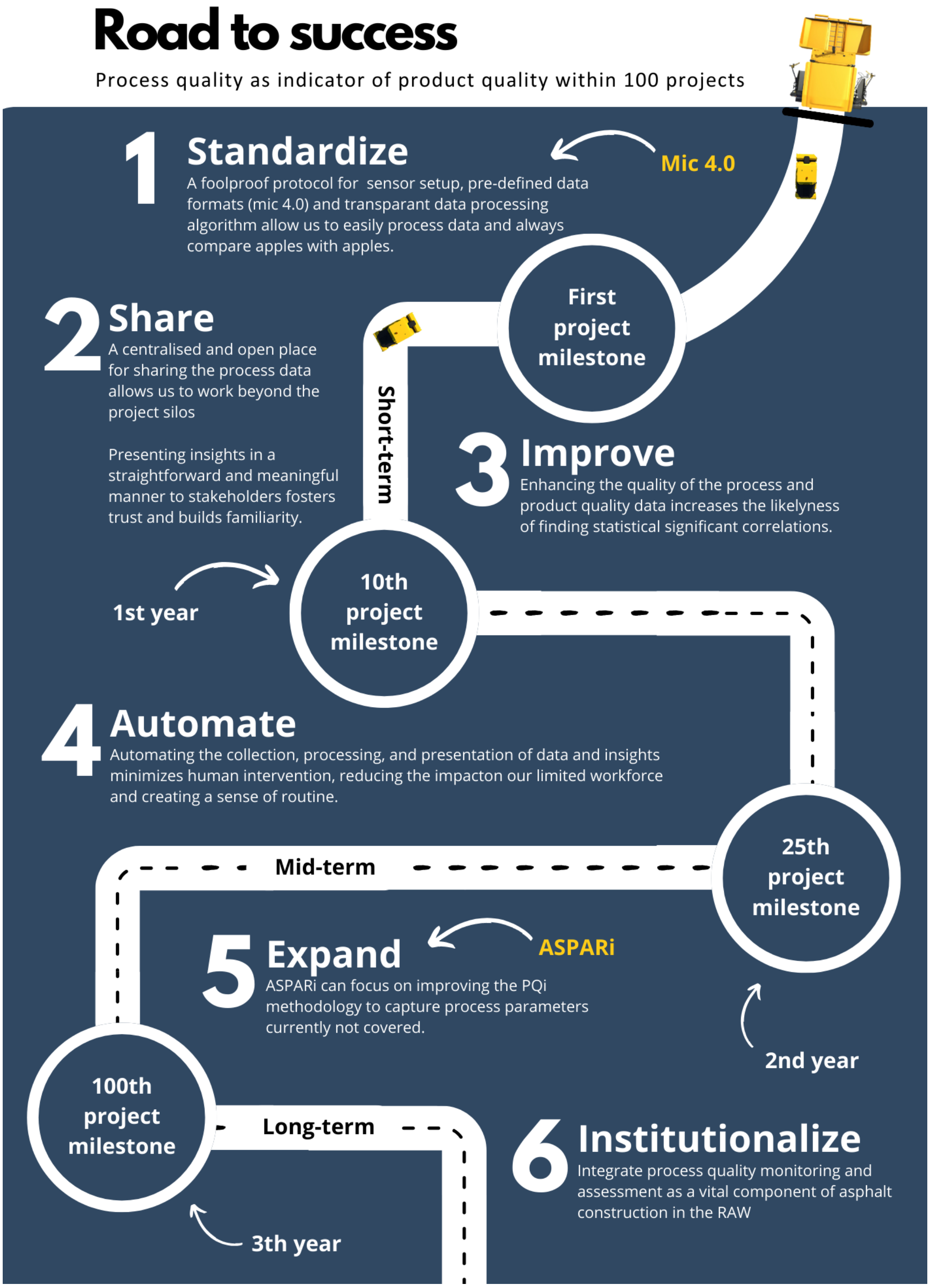
The FO methodology is based on verifying the mechanical properties of an entire asphalt layer by finding a single value based on multiple cores. This requires 21 cores to determine 4 mechanical properties. In this research, individual values of drilled cores were used instead of the average for the asphalt layer. Therefore, further insights must be obtained to ascertain the extent to which using individual cores is reliable and what part of the variation can be attributed to both measurement errors and natural variation between samples.

Verifying mixture quality

Due to the limited time available, this research was conducted under the assumption that the mixture quality met the specified standards and had the potential to support the required product quality. While basic quality assessments were carried out to support this assumption, it is recommended that future studies provide robust evidence to attribute any issues in the asphalt layer's product quality to the construction process rather than to production flaws in the production process. This approach will help eliminate ambiguity and prevent debates over whether the root cause lies in the production or the construction process.

8. Future outlook

The previously indicated recommendations can be converted into a roadmap for using process quality as an indicator of product quality in QC/QA (Figure 17). This roadmap contains six steps to go from the current status to the standard application in practice, using the insights gained from the remaining 99 projects in the “Deltaplan duurzame wegverhardingen”.



Road to success

Process quality as indicator of product quality within 100 projects

1 Standardize
A foolproof protocol for sensor setup, pre-defined data formats (mic 4.0) and transparant data processing algorithm allow us to easily process data and always compare apples with apples.

2 Share
A centralised and open place for sharing the process data allows us to work beyond the project silos

Presenting insights in a straightforward and meaningful manner to stakeholders fosters trust and builds familiarity.

3 Improve
Enhancing the quality of the process and product quality data increases the likelyness of finding statistical significant correlations.

4 Automate
Automating the collection, processing, and presentation of data and insights minimizes human intervention, reducing the impacton our limited workforce and creating a sense of routine.

5 Expand
ASPARi can focus on improving the PQi methodology to capture process parameters currently not covered.

6 Institutionalize
Integrate process quality monitoring and assessment as a vital component of asphalt construction in the RAW

Figure 17: Roadmap for using process quality as indicator for product quality in QC/QA

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Appendix

During the preparation of this work the author(s) used ChatGPT in order to improve spelling and grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work.

Appendix A: Expert panel documents

Appendix A1: Invitation for participation in expert panel

Beste ASPARi-lid,

Mijn naam is Bas van der Zande, en ik ben momenteel bezig met mijn Master afstudeeronderzoek binnen ASPARi, dat in februari van dit jaar is gestart. Ik voer dit onderzoek uit bij Ballast Nedam en krijg ook nog ondersteuning van BAM en Dura Vermeer. In het kader van mijn onderzoek ben ik op zoek naar deskundigen en ervaringsdeskundigen die zich bezighouden met de impact van parameters in het asfalteerproces op de uiteindelijke kwaliteit van verwerkte asfaltlagen.

Het Onderzoek

Het hoofddoel van mijn onderzoek is om met behulp van een kwantitatieve methodologie de relatie tussen proceskwaliteit en productkwaliteit te onderzoeken. Het onderzoek is opgedeeld in drie fasen. In de eerste fase, die momenteel plaatsvindt, verzamel ik door middel van een vragenlijst de percepties van experts over hoe specifieke parameters tijdens het asfalteerproces de kwaliteit van verwerkte asfaltlagen kunnen beïnvloeden. In de tweede fase zal ik een casestudy uitvoeren waarbij PQi-metingen worden verricht en boringen worden gedaan om eigenschappen (zoals dichtheid en mechanische eigenschappen) van verwerkt asfalt in kaart te brengen. Ten slotte zal de derde fase bestaan uit een statistische analyse om de relatie tussen proceskwaliteit en productkwaliteit kwantitatief te onderbouwen, kijkend naar de proces parameters geïdentificeerd in de eerste fase.

Waar ben ik naar opzoek?

Ik ben op zoek naar expertise binnen uw organisatie met betrekking tot hoe het proces van asfaltverwerking naar verwachting de fysieke en mechanische eigenschappen van het uiteindelijke asfalt beïnvloedt. Kunt u mij laten weten met wie binnen uw organisatie ik hierover kan spreken?

De experts/ervaringsdeskundigen zullen een vragenlijst ontvangen in de eerste ronde, en een samenvatting van de antwoorden voor feedback in een tweede ronde. De antwoorden worden anoniem samengevat.

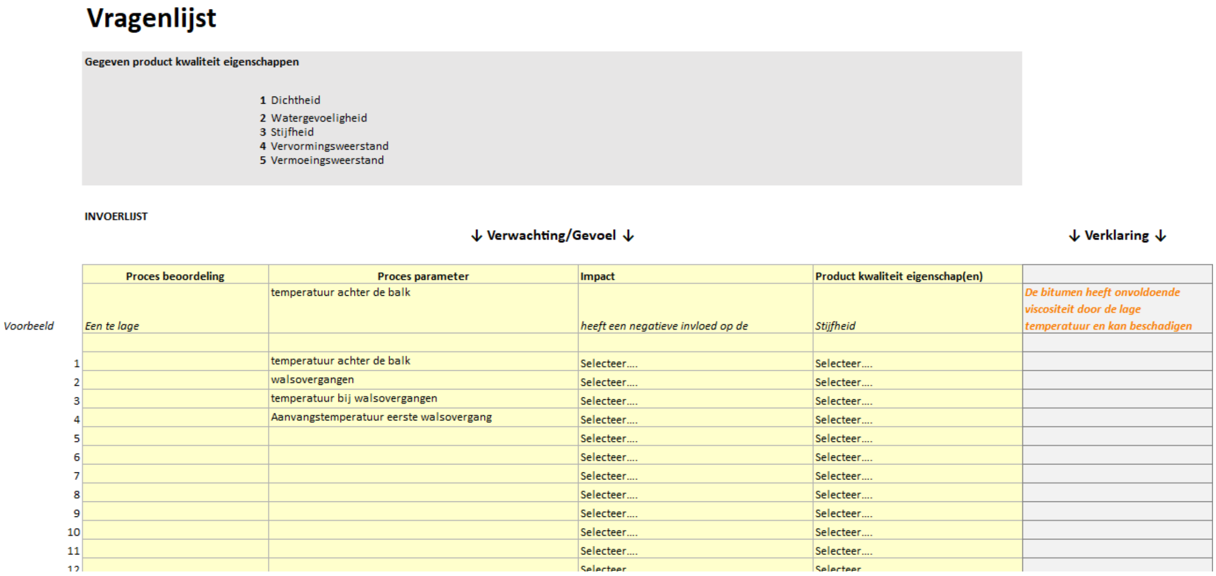
Ik waardeer uw medewerking bij het identificeren van relevante experts binnen uw organisatie die mogelijk kunnen bijdragen aan mijn onderzoek.

Met vriendelijke groet,

Bas van der Zande

Appendix A2: Questionnaire 1

Figure 18 contains a screenshot from the questionnaire of the first round of the Delphi study. The format provides freedom for the participant to enter any process parameter that he/she expects to influence product quality. However, the format for answering is restricted to prevent deviations from the research topic.



Vragenlijst

Gegeven product kwaliteit eigenschappen

1 Dichtheid
2 Watergevoeligheid
3 Stijfheid
4 Vervormingsweerstand
5 Vermoeingsweerstand

INVOERLIJST

↓ Verwachting/Gevoel ↓ **↓ Verklaring ↓**

	Proces beoordeling	**Proces parameter**	**Impact**	**Product kwaliteit eigenschap(en)**	
Voorbeeld	*Een te lage*	temperatuur achter de balk	*heeft een negatieve invloed op de*	*Stijfheid*	*De bitumen heeft onvoldoende viscositeit door de lage temperatuur en kan beschadigen*
1		temperatuur achter de balk	Selecteer....	Selecteer....	
2		walsovergangen	Selecteer....	Selecteer....	
3		temperatuur bij walsovergangen	Selecteer....	Selecteer....	
4		Aanvangstemperatuur eerste walsovergang	Selecteer....	Selecteer....	
5			Selecteer....	Selecteer....	
6			Selecteer....	Selecteer....	
7			Selecteer....	Selecteer....	
8			Selecteer....	Selecteer....	
9			Selecteer....	Selecteer....	
10			Selecteer....	Selecteer....	
11			Selecteer....	Selecteer....	
12			Selecteer	Selecteer	

Figure 18: Questionnaire round 1

The participants are asked to answer with process parameters that affect product quality in a standardised structure. First, they should answer the "process beoordeling", indicating when the process parameter impacts product quality (e.g. too high, too low, too slow, etc…). Next, the participant is asked to indicate what the process parameter is, after which should be indicated what type of impact it has on product quality. Finally, they are asked to indicate on which product quality characteristic the process parameter has an influence. Context can be added in a free column behind every process parameter.

Appendix A3: Summary of results questionnaire 1

Translation of the Dutch version which has been sent to the participants

Based on the results of the first round, the process parameters are divided into three categories: density-related parameters, directly related parameters, and indirectly related parameters. Figure 19 illustrates the different types of process parameters and their relationship to product quality.

Density-related process parameters are factors that pertain to density, which is an indicator of product quality. These parameters are crucial for achieving the correct compaction, which should lead to the desired product quality.

Example: The number of roller passes within the temperature window has a direct impact on density.

Directly related process parameters concern the mechanical properties of the processed asphalt, apart from density.

Example: Roller passes at too low a temperature can lead to deviating mechanical properties despite the correct asphalt density.

Indirectly related process parameters are parameters that influence the temperature and compaction window but do not directly affect density or product quality. These parameters can expand or shrink the temperature and compaction window, thus changing the likelihood of achieving the correct density. As such, moderating process parameters can ultimately affect product quality.

Example: An asphalt supply temperature that is too low results in less time for compaction.

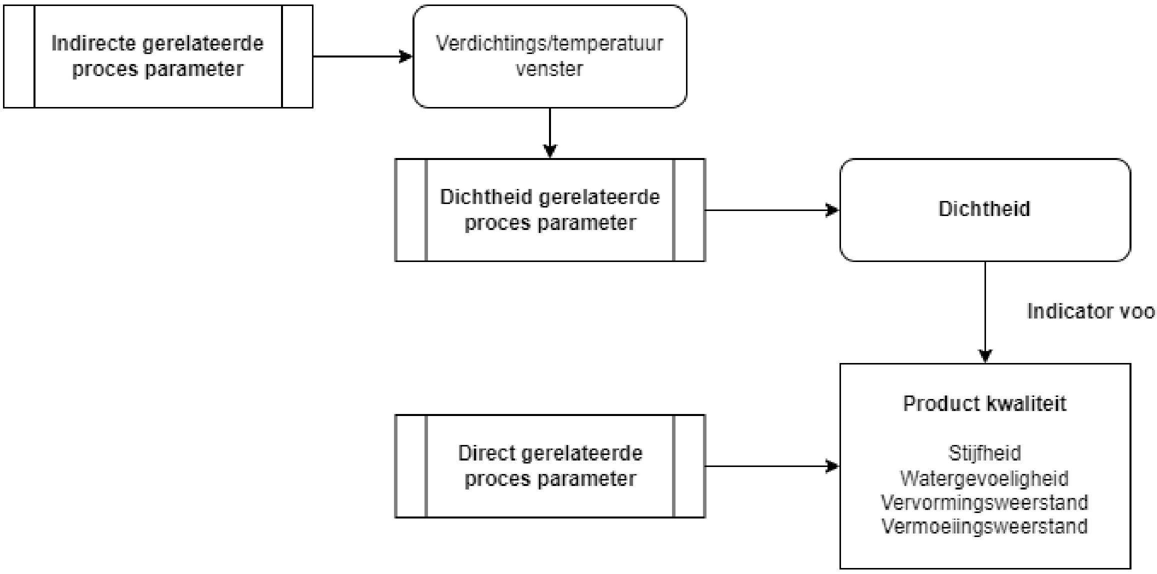


Figure 19: Relation between process parameters and product quality

Indirectly-related process parameters

The following process parameters presented in Table 15 affect the available temperature/compaction window after processing.

Table 15: Indirect process parameters (questionnaire round 1)

Process parameter	*Description*
A too low temperature behind the paver	A too low starting temperature causes the temperature/compaction window to shrink, resulting in insufficient roller capacity to compact within the window's limits.
A too high speed of the paver	A too high travel speed of the asphalt paver relative to the roller capacity creates too large a surface area to compact within the temperature/compaction window.
Stopping of the paver during construction	Stop locations cause the temperature/compaction window to shrink, resulting in insufficient roller capacity to compact within the window's limits.
A too cold base surface	A too cold substrate accelerates the cooling process. The temperature/compaction window shrinks, resulting in insufficient roller capacity to compact within the window's limits.
A too cold outside temperature	Too cold outside temperature during the processing and compaction process accelerates the cooling process. The temperature/compaction window shrinks, resulting in insufficient roller capacity to compact within the window's limits.
Too much wind	Too much wind during the processing and compaction process accelerates the cooling process. The temperature/compaction window shrinks, resulting in insufficient roller capacity to compact within the window's limits.
Too much rain	Too much rain during the processing and compaction process accelerates the cooling process. The temperature/compaction window shrinks, resulting in insufficient roller capacity to compact within the window's limits.

Density-related process parameters

The following process parameters are presented in Table 16 influence achieving the target density. Density is currently used to ensure the quality of asphalt constructions and is therefore the indicator of product quality.

Under-compaction: A higher risk of the penetration of water (Water sensitivity)**,** a lower stiffness, a lower resistance to fatigue**,** a higher risk of secondary compaction in the use phase (resistance to permanent deformation)

Over-compaction: Crushing of aggregate particles (water sensitivity, deformation resistance),(Micro) cracking (stiffness, fatigue resistance)

Table 16: Density related process parameters (Questionnaire round 1)

Process parameter	*Description*
Not enough compaction passes within the temperature/compaction window	Under compaction
Too many compaction passes within the temperature/compaction window	Over compaction
Time between paving and first compaction pass	The target density cannot be achieved despite the correct temperature/compaction window.
Worn out screed	Too little pre-compaction leading to under compaction
Too cold screed	Too little pre-compaction leading to under compaction
Not sufficient pre-compaction effort of the screed	Too little pre-compaction leading to under compaction
Too low speed of the tampering knives	Too little pre-compaction leading to under compaction
A too high paving speed	Too little pre-compaction leading to under compaction

Directly related process parameters

The following process parameters are presented in Table 17 have a direct impact on the mechanical properties of the processed asphalt.

Table 17: Directly related process parameters (Questionnaire round 1)

Process parameter	*Description*	*Mechanical property*
Too low temperature during compaction	At too low a temperature during compaction, the adhesive bonds in the asphalt are damaged. The fracture surfaces are not covered with bitumen, creating a risk of water infiltration.	Water sensitivity
	At too low a temperature during compaction, (micro) cracks develop, causing the asphalt to be damaged and lose cohesion.	Stiffness Resistance to fatigue
Too high temperature during compaction	At too high a temperature during compaction, the bitumen between the stones is displaced, resulting in fewer adhesive bonds between the stones.	Water sensitivity Resistance to fatigue
	At too high a temperature during compaction, (micro) cracks develop, causing the asphalt to be damaged and lose cohesion (high roller characteristic).	Water sensitivity Stiffness Resistance to fatigue
Too heavy roller	A high roller characteristic causes (micro) cracks, leading to asphalt damage and loss of cohesion.	Stiffness Resistance to fatigue
Too high temperature during paving	At too high a temperature during production, the binder ages faster and may even burn. This causes the binder to lose its flexible properties.	Water sensitivity Stiffness Resistance to fatigue
Too long period between production and paving	A long time between production and application results in binder ageing.	Stiffness Resistance to fatigue

Too high speed of tampering knives	Excessive speed of the screed blades on the asphalt paver opens the texture of the asphalt. This causes (micro) cracks, damaging the asphalt and leading to a loss of cohesion.	Water sensitivity Resistance to fatigue
Too cold screed	A too-cold screed on the asphalt paver opens the texture of the asphalt. This causes (micro) cracks, damaging the asphalt and leading to a loss of cohesion.	Water sensitivity Resistance to fatigue

Other Responses

This study focuses on the relationship between the asphalt processing process and the mechanical properties of water sensitivity, stiffness, fatigue resistance, and deformation resistance. The above list provides a summary of the responses with relevance within the scope of the study. However, some responses are interesting but fall outside the scope of my research. These are explained below:

Temperature Homogeneity

Temperature homogeneity: This refers to the extent to which the quality of the asphalt layer is consistent. In this study, we consider the road as separate segments of a certain size. We investigate whether, when the process within a segment meets the specifications, the product quality also meets the specifications, assuming that the mixture has the correct properties. This study does not address the homogeneity between individual segments.

Segregation

Segregation of asphalt can lead to gravel nests, which negatively affect water sensitivity and fatigue resistance. This study examines the process from the point of paving, assuming that the mixture with the correct properties is delivered to the construction site. Segregation of the mixture can have various causes, such as incorrect adjustment of the augers on the asphalt paver or improper loading of the truck. We consider it a prerequisite that no segregation occurs in the asphalt and will also monitor this during processing.

Excessive Production Temperature

At too high a temperature during production, the binder ages faster and may even burn. This causes the binder to lose its flexible properties. Since this study assumes that a mixture with the correct properties is delivered to the construction site, it is assumed that the product is produced within the correct temperature window.

Layer Thickness

Layer thickness affects the mechanical properties of the asphalt. Because this study uses cut samples of a predetermined height to measure these properties, the impact of layer thickness falls outside the scope of this study.

Smoothness

When rolling at too high a temperature, deep roller marks can occur, and asphalt may be pushed aside from the roller, leading to unevenness. While this is important for the quality of the finished work, this aspect falls outside the scope of this study.

Resistance to cracking

In addition to the mentioned mechanical properties, resistance to cracking has also been mentioned several times. However, this property of processed asphalt falls outside the scope of this study as it is not used in the current functional specifications.

Appendix A4: Explanation second round

The responses from the first round have been summarised and categorised. To validate the answers and reach a consensus among the various experts involved in this research, we request your cooperation in a second round of this study.

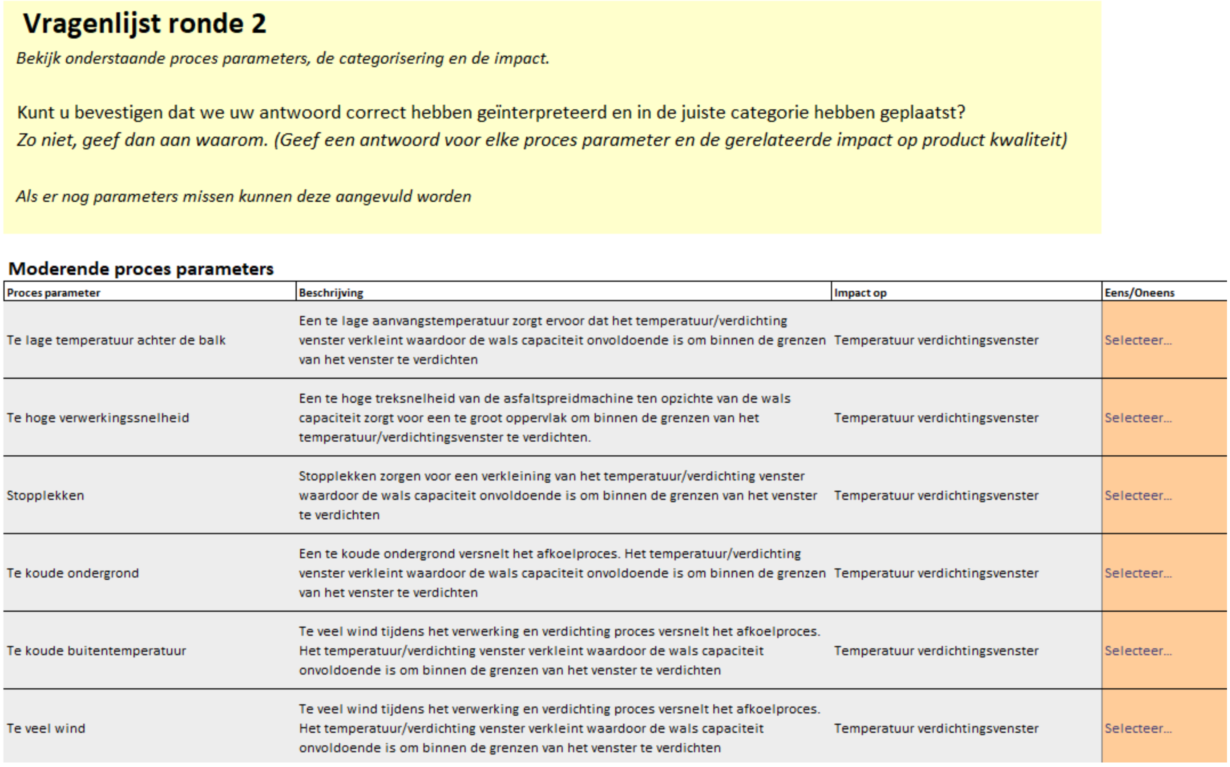
1. Can you confirm that we have correctly interpreted your answer and placed it in the appropriate category? If not, please specify why. (Provide an answer for each process parameter and its related impact on product quality.)

2. Are there any process parameters that are missing? If so, please add them.

Appendix A5: Questionnaire round 2

In the second phase of the Delphi study, a second questionnaire containing the consolidated and categorised process parameters and their impact on product quality is returned to the participants. The sent questionnaire can be found in Figure 20.

For each of the process parameters, the participants are asked whether they agree and if not, why there is no agreement.



Vragenlijst ronde 2

Bekijk onderstaande proces parameters, de categorisering en de impact.

Kunt u bevestigen dat we uw antwoord correct hebben geïnterpreteerd en in de juiste categorie hebben geplaatst?
Zo niet, geef dan aan waarom. (Geef een antwoord voor elke proces parameter en de gerelateerde impact op product kwaliteit)

Als er nog parameters missen kunnen deze aangevuld worden

Moderende proces parameters

Proces parameter	Beschrijving	Impact op	Eens/Oneens
Te lage temperatuur achter de balk	Een te lage aanvangstemperatuur zorgt ervoor dat het temperatuur/verdichting venster verkleint waardoor de wals capaciteit onvoldoende is om binnen de grenzen van het venster te verdichten	Temperatuur verdichtingsvenster	Selecteer...
Te hoge verwerkingssnelheid	Een te hoge treksnelheid van de asfaltspreidmachine ten opzichte van de wals capaciteit zorgt voor een te groot oppervlak om binnen de grenzen van het temperatuur/verdichtingsvenster te verdichten.	Temperatuur verdichtingsvenster	Selecteer...
Stopplekken	Stopplekken zorgen voor een verkleining van het temperatuur/verdichting venster waardoor de wals capaciteit onvoldoende is om binnen de grenzen van het venster te verdichten	Temperatuur verdichtingsvenster	Selecteer...
Te koude ondergrond	Een te koude ondergrond versnelt het afkoelproces. Het temperatuur/verdichting venster verkleint waardoor de wals capaciteit onvoldoende is om binnen de grenzen van het venster te verdichten	Temperatuur verdichtingsvenster	Selecteer...
Te koude buitentemperatuur	Te veel wind tijdens het verwerking en verdichting proces versnelt het afkoelproces. Het temperatuur/verdichting venster verkleint waardoor de wals capaciteit onvoldoende is om binnen de grenzen van het venster te verdichten	Temperatuur verdichtingsvenster	Selecteer...
Te veel wind	Te veel wind tijdens het verwerking en verdichting proces versnelt het afkoelproces. Het temperatuur/verdichting venster verkleint waardoor de wals capaciteit onvoldoende is om binnen de grenzen van het venster te verdichten	Temperatuur verdichtingsvenster	Selecteer...

Figure 20: Questionnaire round 2

Appendix B: Case study

Appendix B1: Data collection

For clarity purposes, the case study has been split into 4 areas Figure 21. Splitting the areas is based on geometry. Area A is from the start until a 90-degree corner. Area B is from the end of Area A until where the road gets smaller in width. Area C is from the end of Area B until the road gets to its original width again and Area D is from the end of Area C until the end of the project. In total 5 locations were assigned for asphalt nodes, compaction passes and nuclear density. Location 1, 2 and 3 are in Area B, Location 4 in Area C and Location 5 in Area D. Area A does not contain any asphalt node since this would be too close to either the start or the turn.

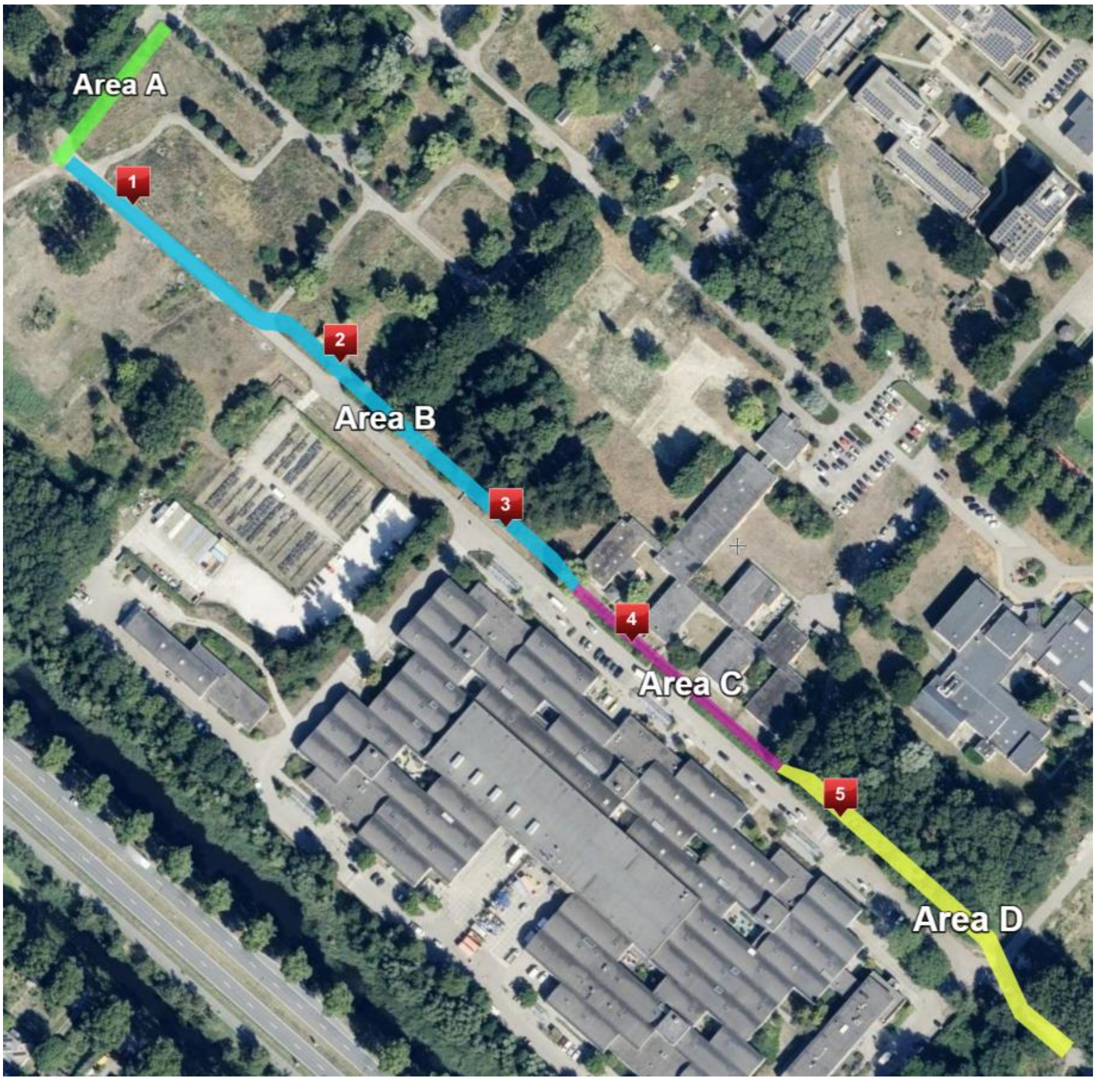


Figure 21: Case study layout

Paver node

On the paving equipment (Figure 22) an extended beam was mounted on which on the other end both the GPS receiver and wide-angle IR camera were positioned (Figure 23). The extended beam was used to prevent a discrepancy between the actual location of the GPS, and the temperature readings on the asphalt mat (Figure 24, Figure 25). Directly mounting the IR camera on the paver could potentially create a discrepancy of 1 to 2 metres in the direction of the road.

Figure 22: Paver

Figure 23: Location of the IR camera and GPS

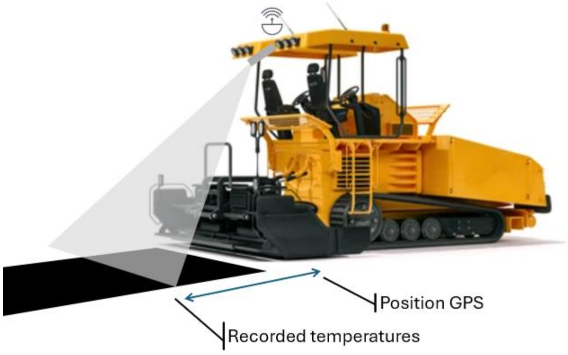


Figure 24: Paver node mounted directly on paver

Figure 25: Paver node mounted on extended beam

Roller node

Each of the rollers was equipped with a GPS antenna. The positioning of the antenna was exactly in the centre point (Figure 26), when that was not possible, above the rear axle (Figure 27, Figure 28). The position in the width direction of the roller was in all cases in the centre.

Figure 26: Large tandem roller

Figure 27: Three-drum roller

Figure 28: Small tandem roller

Asphalt node

The asphalt node consisted of a set of thermocouples positioned in the asphalt using a stand (Figure 29) and a handheld IR camera mounted to a holder. The thermocouples measured the temperature within the asphalt at different heights, and the handheld IR camera recorded the surface temperature.

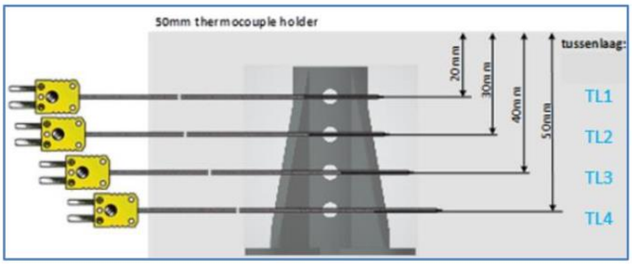


Figure 29: Thermocouples in holder

Figure 30: IR camera during a roller pass

Asphalt batch information

Production information is retrieved through a contact person at the asphalt plant and is not directly available to the researcher. The transport loading times are registered automatically in the pavement information model (PIM), and unloading times are retrieved manually through a time-lapse video of the front of the paver.

Appendix B2: Data processing

Convert data to a standardised format

Different measuring equipment provided different types of data that were also structured in various ways. The first step was to convert the data from the various encodings and convert it to a simple data structure where each value was stored in an individual column. Furthermore, coordinates and timestamps were converted to a single uniform format. Finally, the timing of the measuring equipment was not always synchronised. Therefore, based on the recorded offsets, the timestamps were corrected.

Process data using the Kalman filter

The output from the GPS rovers is a single location on an interval of 1 Hz. Plotting these coordinates provides a trajectory, which includes for every point: a velocity and a direction. In other words, a trajectory is created by comparing the current location with the next location in terms of distance and angle compared to the Earth. The distance travelled between two locations determines the velocity, and the angle is the direction.

However, the accuracy of GPS coordinates can vary significantly due to weather conditions, availability of satellites and interference of objects between the receiver and satellites [43]. In order to increase the accuracy of the trajectory, different types of filters can be applied that can increase the accuracy of the GPS coordinate. In this research, a Kalman filter has been employed. The effect of the Kalman filter is shown in Figure 31 and Figure 32.

Kalman filtering can increase the accuracy of the coordinates significantly [43], however, there still remain errors in the data that are too large to be filtered out using Kalman filtering. For this, a simple filtering is applied that considers actual boundaries in reality related to the machinery. The paver is expected to not reach speeds over 10 meters per minute. The roller is not expected to reach speeds over 50 km/h while compacting.

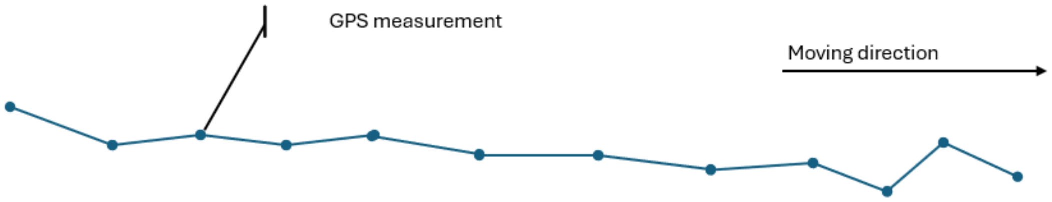


Figure 31: Raw GPS trajectory

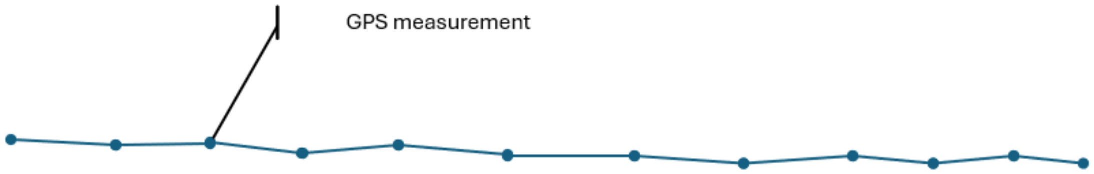


Figure 32: GPS trajectory with Kalman filtering

Perform azimuth smoothing (Only for the paver GPS)

Next, before the asphalt cells can be created based on the GPS trajectory of the paver. A second preprocessing step should be taken. Each of the cell locations is determined by taking the location and direction of the rover on the paver and calculating the new location based on the location of the individual cell in each measurement. However, after the Kalman filter is applied, there always remains some inaccuracy in the GPS locations. While this may be acceptable when considering the individual locations, small inaccuracies in the azimuth can lead to significant issues in determining the cell structure. Because the width of the paved section behind the paver can easily reach over 10m, a small error in the paver location may lead to large errors in the calculated locations of points closer to the edge of the screed. This is shown in Figure 33 and Figure 34.

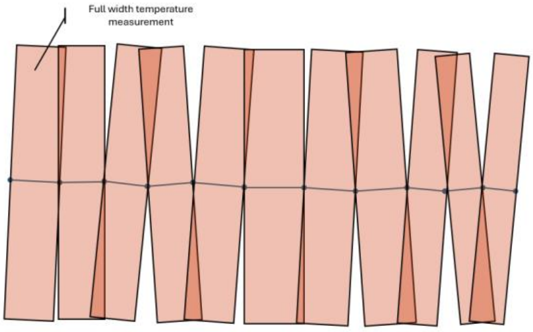


Figure 33: Cells structure without Azimuth smoothening

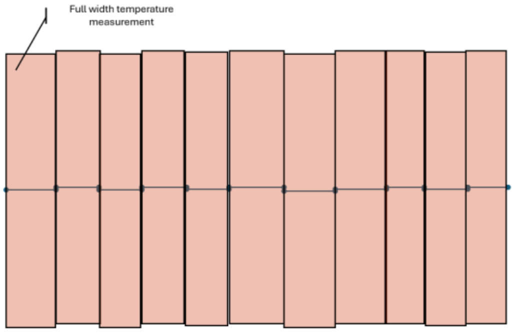


Figure 34: Cell structure with azimuth smoothing

Generate georeferenced asphalt cells

In the next step in the data processing. The asphalt layer is divided into cells (Figure 35). The cell size is based on the speed of the paver, the width of the IR camera and the number of cells selected for the width of the road. In the case study, the IR camera recorded a width of 4.8 meters and 20 cells. Making the cell size 24cm in width. The paver speed was in most cases between 5 and 5.5 m/s, making the cell length between 8 cm and 9 cm on average. Although the PQi methodology often refers to a cell size of 25x25 cm (resolution) [37], in the practical implementations of the PQi methodology, the dynamic-sized raster described by [30], [37], [38] is applied.

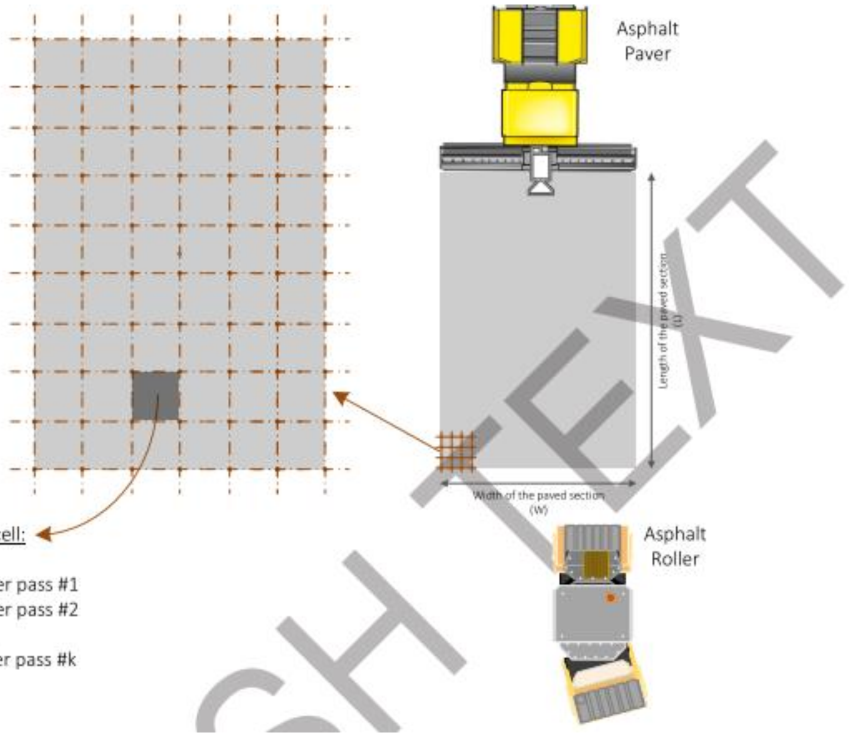


Figure 35: Approach to rasterising the asphalt mat [38]

Although a fixed grid of 25x25 cm is generally preferred over a dynamic grid size due to its compatibility with asset management systems and the benefits of having a dataset with consistent intervals, the current PQi methodology does not specify how this grid should be implemented. In practice, establishing a 25x25 cm grid requires generating the grid before construction activities. This grid can either be aligned with a larger national grid, such as one covering the entirety of the Netherlands or be developed as a project-specific grid. Figure 36 illustrates an example of a potential project-based grid configuration.

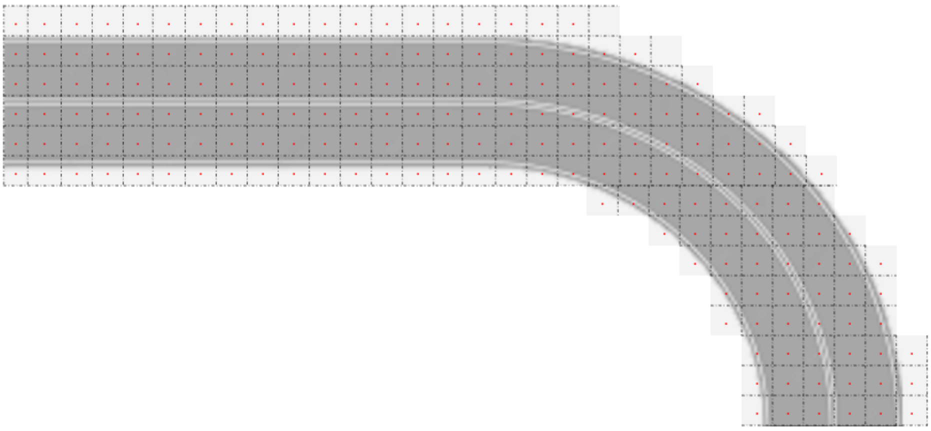
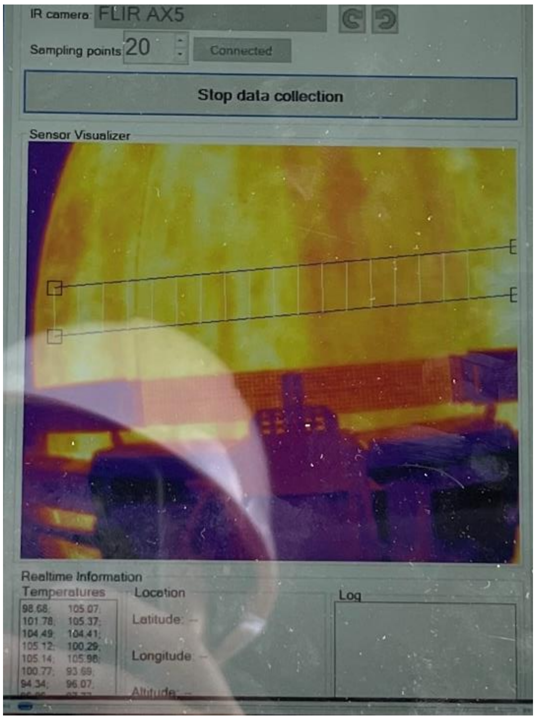


Figure 36: Example of a project-based grid

The IR camera records a fixed width (Figure 37). In the case study, at the widest pieces of asphalt road, the IR camera did not have a wide enough angle for recording the entire asphalt pavement. A maximum of 4.8m (2.4m to every side from the middle) was recorded. At the smaller width area, the IR camera width was adequate for recording the entire paved width and even some of the area next to the paved section. The cells that are fully or partly recorded at the side of the area next to the paved area, do not contain an accurate estimate of the temperature during paving and are filtered out by setting the minimum paved temperature to 60 degrees.



IR camera: FLIR AX5

Sampling points: 20

Realtime Information

Temperatures

```
98.68;   105.07;
101.78;  105.37;
104.49;  104.41;
105.12;  100.29;
105.14;  105.98;
100.77;  93.69;
94.34;   96.07;
```

Location

Latitude: --

Longitude: --

Altitude: --

Figure 37: View of the wide angle IR camera

Generate compaction areas

The compacted areas are determined based on the geometry of the roller and the trajectory (Figure 38). Each time, a rectangle is created based on two consecutive GPS location readings of the roller. This provides the area that is compacted in at that moment. However, when the roller is moving at a slower speed than its length in seconds, the areas may overlap. Therefore, a filter is applied after the compaction passes are related to an asphalt cell, to remove any consecutive passes within a 5 second time frame.

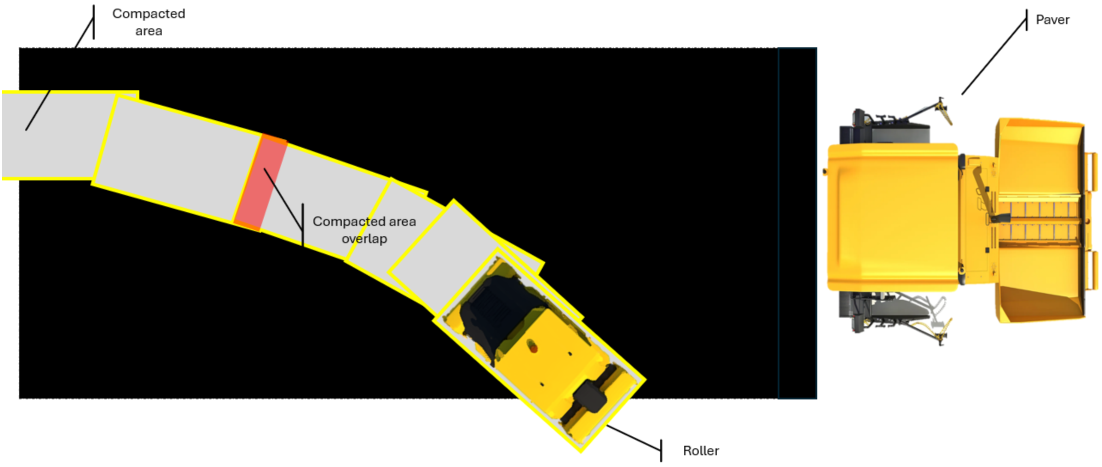


Figure 38: Roller trajectories

Although this approach to registering compaction passes is simple, it does have an issue. One of the rollers used during the case study (a type used by all contractors) can move in “crab mode” (Figure 39), which means that the rectangular geometry of the roller changes and therefore also the compacted area. This mode is however not registered using the GPS antenna. Therefore, errors are introduced.

Figure 39: Tandem roller in crab mode

Link the compaction passes to the asphalt cells

In the final data processing step, the individual compaction passes need to be assigned to the individual asphalt cells. Because for every roller, the type is known, the geometry is also known. Each of the trajectories gets expanded to the width of the roller as can be seen in Figure 40. All the centre points of each of the cells that fall within this trajectory get marked as a compaction pass, when the centre is outside that area it is not marked as a compaction pass. What can be seen is that some inaccuracy is induced here since partly compacted cells are either registered as fully compacted or not compacted. One potential solution to this issue is to reduce the cell size or modify the shape of the cell from a square to a triangle, which would also result in a smaller cell size. However, this approach would significantly increase the volume of data generated. Additionally, if the cell size becomes smaller than the GPS accuracy, it may create a misleading impression of precision, as the smaller cells would not accurately reflect the true positional accuracy provided by the GPS.

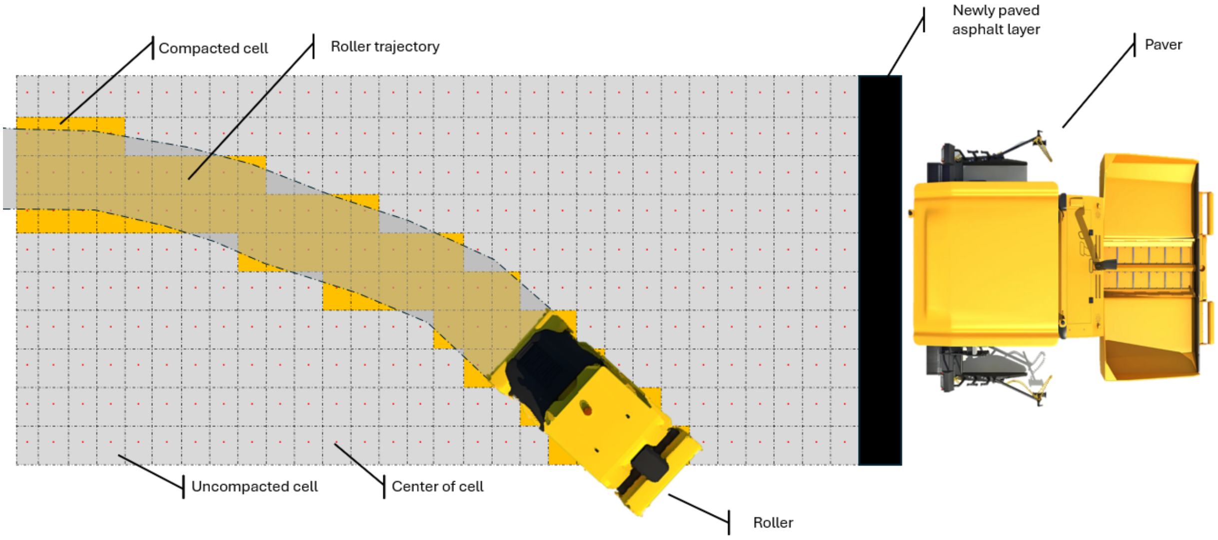


Figure 40: Example roller pass

Fit temperature curves

Of the 5 locations selected for the asphalt nodes, 3 locations provided a complete and useful dataset. The raw data contains a temperature for the surface and at least three thermocouples (bottom, middle and top). Figure 41 shows the cooling curves. What can be seen is that the cooling curves do not follow a smooth curve (which is expected) and the surface temperature is also interfered with due to the roller passing through the camera. Furthermore, the thermocouples are measured at a certain location, it could be that this location was paved at a temperature lower than other cells. All this combined makes it beneficial to do a fitting of the cooling curve to generate a usable curve for other paved cells.

The cooling process of asphalt can be divided into two distinct phases. In the first phase, the asphalt cools rapidly, while in the second phase, the cooling rate slows down significantly. The double decay function accounts for this by incorporating two components, each with its decay rate and amplitude. This allows the function to accurately capture both the fast initial cooling and the slower, sustained cooling, offering a more precise representation of the overall cooling behaviour compared to a single decay model.

$$T(t) = {A_1}^{-k_1 t} + {A_2}^{-k_2 t} + C \tag{1}$$

With:

A_1 = Amplitude first exponential decay component

K_1 = Decay rate first exponential decay component

A_2 = Amplitude second exponential decay component

K_2 = Decay rate second exponential decay component

C = Constant

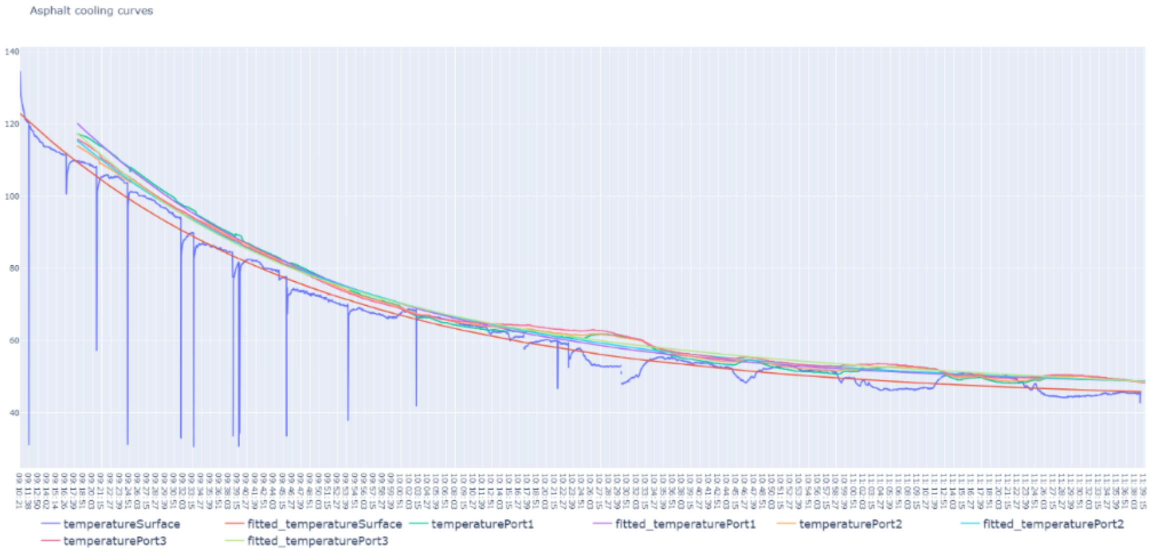


Figure 41: Fitted cooling curve at Location 3

The three locations where a valid dataset was collected have been fitted with the double decay function and the goodness of fit can be checked using the R^2 score. Table 18 contains the R^2 scores for each of the locations and each of the individual cooling curves. The fits can be described as an excellent fit.

Table 18: Adjusted R^2 scores for the fitted temperature curves

Location	Temperature surface	Temperature Top	Temperature Middle	Temperature Bottom
1	0.9947	0.9994	0.9995	0.9997
2	0.9770	0.9958	0.9966	0.9965
5	0.9610	0.9724	0.9775	0.9922

Determine compaction temperatures

The temperature during each roller pass is calculated using the double decay functions from the asphalt nodes, the initial paving temperature, and the time elapsed between paving and the roller pass. First, the asphalt node closest in time to the moment of paving is identified. Based on the double decay function of this node and the initial paving temperature, the initial time on the cooling curve (T_0) is determined. By factoring in the time difference between paving and the roller pass, the time on the cooling curve of the roller pass (T_1) is determined. T_1 corresponds to the temperature during the roller pass. Figure 42 illustrates this process. Each asphalt node contains temperature data from at least three thermocouples, and the average of these readings is used as the temperature during the roller pass.

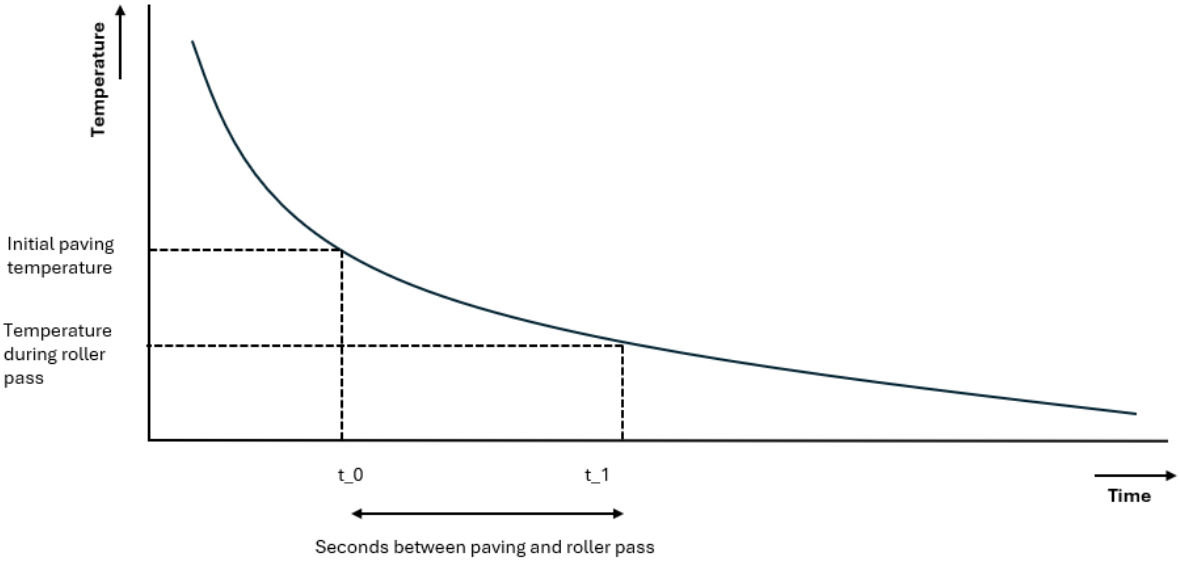
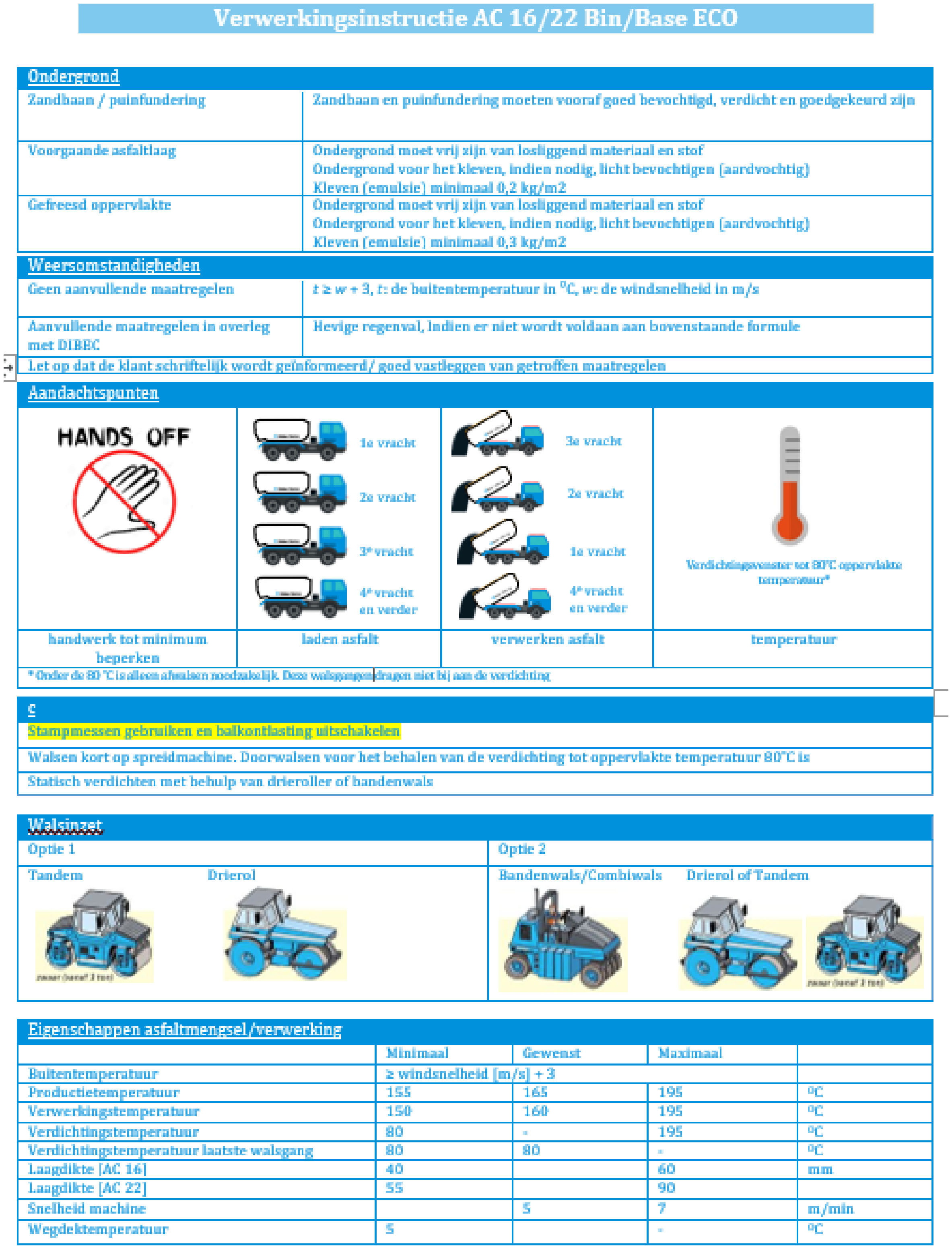


Figure 42: Method for determining the temperature during a roller pass

Link asphalt batches to asphalt cells

The batches are separated into truckloads. For each truck, a record is kept containing the production time at the asphalt plant, the loading time, and the unloading time. Based on the time of paving, the closest truckload before the paving time is selected as the current batch that is being paved.

Appendix B3: Construction advice AC 16 bin/base ECO



Verwerkingsinstructie AC 16/22 Bin/Base ECO

Ondergrond	
Zandbaan / puinfundering	Zandbaan en puinfundering moeten vooraf goed bevochtigd, verdicht en goedgekeurd zijn
Voorgaande asfaltlaag	Ondergrond moet vrij zijn van losliggend materiaal en stof Ondergrond voor het kleven, indien nodig, licht bevochtigen (aardvochtig) Kleven (emulsie) minimaal 0,2 kg/m2
Gefreesd oppervlakte	Ondergrond moet vrij zijn van losliggend materiaal en stof Ondergrond voor het kleven, indien nodig, licht bevochtigen (aardvochtig) Kleven (emulsie) minimaal 0,3 kg/m2

Weersomstandigheden	
Geen aanvullende maatregelen	$t \geq w + 3$, t: de buitentemperatuur in ^{0}C, w: de windsnelheid in m/s
Aanvullende maatregelen in overleg met DIBEC	Hevige regenval, Indien er niet wordt voldaan aan bovenstaande formule
Let op dat de klant schriftelijk wordt geïnformeerd/ goed vastleggen van getroffen maatregelen	

Aandachtspunten			
HANDS OFF	1e vracht 2e vracht 3e vracht 4e vracht en verder	3e vracht 2e vracht 1e vracht 4e vracht en verder	Verdichtingsvenster tot 80°C oppervlakte temperatuur*
handwerk tot minimum beperken	laden asfalt	verwerken asfalt	temperatuur

* Onder de 80 °C is alleen afwalsen noodzakelijk. Deze walsgangen dragen niet bij aan de verdichting

c
Stampmessen gebruiken en balkontlasting uitschakelen
Walsen kort op spreidmachine. Doorwalsen voor het behalen van de verdichting tot oppervlakte temperatuur 80°C is
Statisch verdichten met behulp van drieroller of bandenwals

Walsinzet	
Optie 1	Optie 2
Tandem Drierol	Bandenwals/Combiwals Drierol of Tandem

Eigenschappen asfaltmengsel/verwerking	Minimaal	Gewenst	Maximaal	
Buitentemperatuur	≥ windsnelheid (m/s) + 3			
Productietemperatuur	155	165	195	ºC
Verwerkingstemperatuur	150	160	195	ºC
Verdichtingstemperatuur	80	-	195	ºC
Verdichtingstemperatuur laatste walsgang	80	80	-	ºC
Laagdikte (AC 16)	40		60	mm
Laagdikte (AC 22)	55		90	
Snelheid machine		5	7	m/min
Wegdektemperatuur	5		-	ºC

Appendix B4: Height of drilled cores

In preparation for the case study, the minimum height of a drilled core is set at 50mm. The construction of the road would be 60mm and 50mm would provide a margin of 10mm in the thickness of the asphalt layer. However, during the drilling of the layer, some of the cores showed to be less than the designed 60mm in height. Resulting in a core of even 39mm (>33% less thickness than designed). From the 53 cores drilled, only 40 were suitable for testing in this research.

Table 19: Heights of drilled cores

Core ID	Height	Core ID	Height	Core ID	Height
1	69	**19**	66	**37**	55
2	69	**20**	74	**38**	53
3	64	**21**	66	**39**	53
4	68	**22**	70	**40**	54
5	89	**23**	53	**41**	60
6	67	**24**	45	**42**	47
7	68	**25**	39	**43**	50
8	72	**26**	52	**44**	48
9	55	**27**	62	**45**	58
10	65	**28**	62	**46**	33
11	77	**29**	45	**47**	55
12	65	**30**	64	**48**	41
13	66	**31**	54	**49**	76
14	45	**32**	55	**50**	72
15	49	**33**	49	**51**	63
16	53	**34**	54	**52**	62
17	70	**35**	53	**53**	74
18	74	**36**	53		

Appendix B5: Case study process report

Production temperature

However in a typical production process of asphalt, the production temperatures are monitored. However, the researcher has not been able to retrieve these temperatures from the asphalt plant. However, from the production tests, it is seen that the sample taken from the production was only 154 degrees. Which is already below the minimum production temperature of 155 degrees. This indicates that the asphalt is produced very close to the lower limit of the production temperature. Because the production check is a spot measurement, it provides an indication but does not provide sufficient grounds for analysis. However, given the circumstances, it is expected that the production temperature has not exceeded its upper limit of 195 degrees.

100% of the production temperature was according to the specification

Paver speed

The construction of the asphalt started approximately around 7:30 and ended around 12:45. Within the timeframe of 5:15 hours the c.a. 550m have been paved, averaging 1.7m/min. However, as the paver has been moving at 5m/min, many stopping points can be seen with three major stops between 8:15 – 9:00, 10:00 -10:15 and 11:30 – 12:30. The cause for the machine to stop is due to the fact that there was not sufficient supply capacity of the asphalt to pave at 5-6 m/min.

100% of the paver speed was according to specification, any of the spikes just above the upper limit were likely caused by discrepancies in the GPS signal.

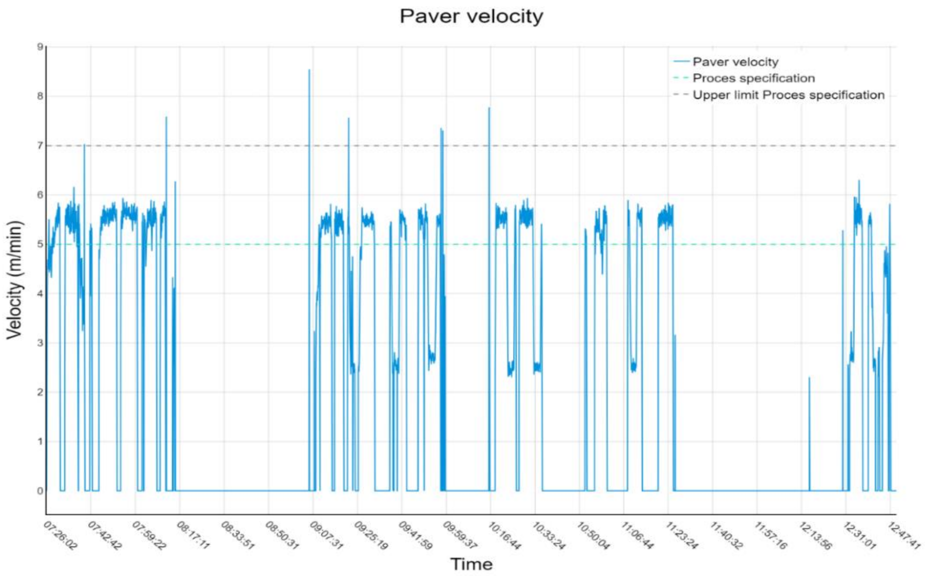


Figure 43: Paver speed over the time

Paving temperature

Throughout the day, the average temperature measured was 127 degrees, with a standard deviation of 11.5 degrees. Initially, the temperature was slightly lower and rose marginally as the project progressed. A notable increase to above 145 degrees was observed only at the end of the fourth section. Interestingly, temperatures were cooler than average in the middle of this section. Overall, the process specification of 155 degrees was rarely achieved. From the paved area, only 2% was paved within specified limits for paving temperature.

Stopping points were identified by a paver speed of 0 m/min. In total, there were 3 major stopping points and a handful of minor stopping points (a couple of minutes). These stopping points are visible in the visualisation of the paving temperature in Figure 44 to Figure 47. The major stopping points caused the asphalt to decrease to around 110 degrees with the longest stopping point registering a temperature of below 100 degrees.

Figure 44: Temperature during paving area A

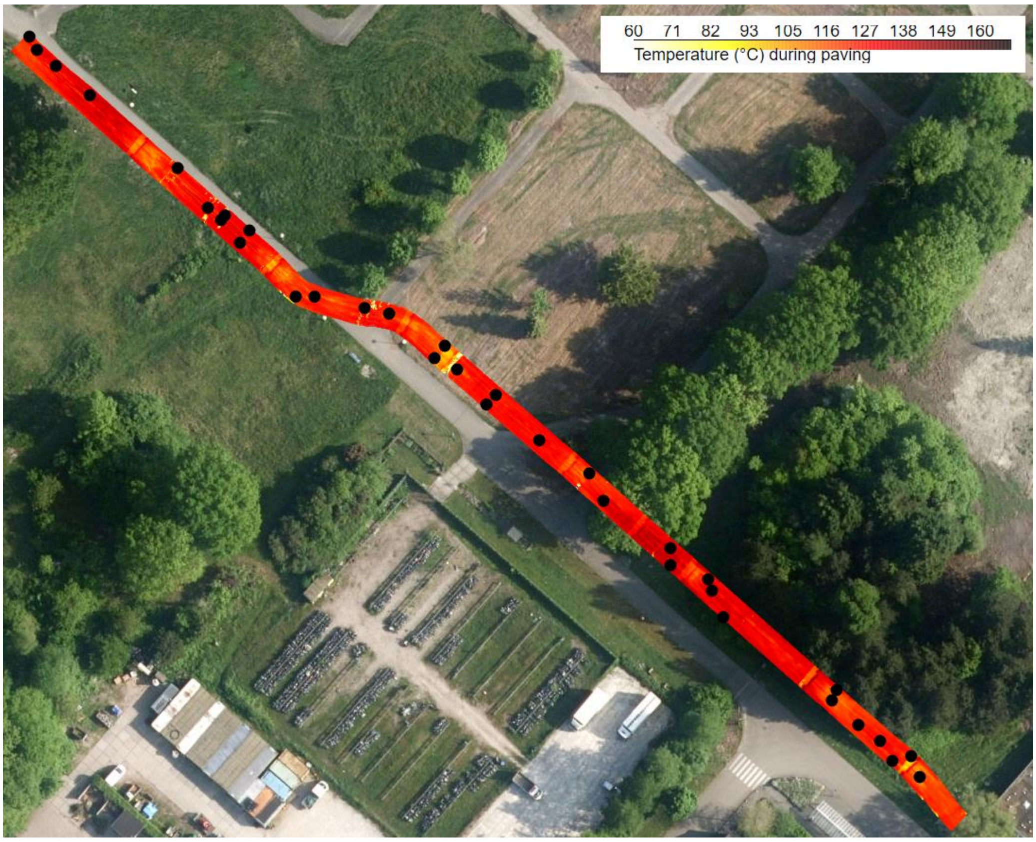


Figure 45: Temperature during paving area B

Figure 46: Temperature during paving area C

Figure 47: Temperature during paving area D

Time between production and construction

The asphalt has been produced in two batches. The first batch (300ton) was produced the evening before the construction from 20:46u to 21:44u. The rest was produced on the day itself starting at 08:45u to 10:25u. As the specification indicated a maximum time between production and paving, the first batch was not conform. 40% of the produced asphalt was paved within 8 hours in accordance with the specification.

Temperature compaction window

The average temperature during the first compaction pass was 102 degrees, with 95% of the data (std = 13.5) falling between 75 and 127 degrees, which is lower than the maximum compaction temperature of 140 degrees. The maximum temperature recorded during the first compaction pass is 147.9 degrees and can be found at the end of the second section. In some areas, the temperature reached around 150 degrees, with the roller positioned directly behind the paver. However, these elevated temperatures were observed only in a few isolated spots. The minimum temperature recorded during the first compaction pass was 50 degrees. A visual representation of the temperature during the first compaction pass can be found in Figure 48 to Figure 51. The temperature of the first compaction pass also reveals the roller trajectory of the first compaction pass.

Figure 48: Maximum temperature during compaction area A

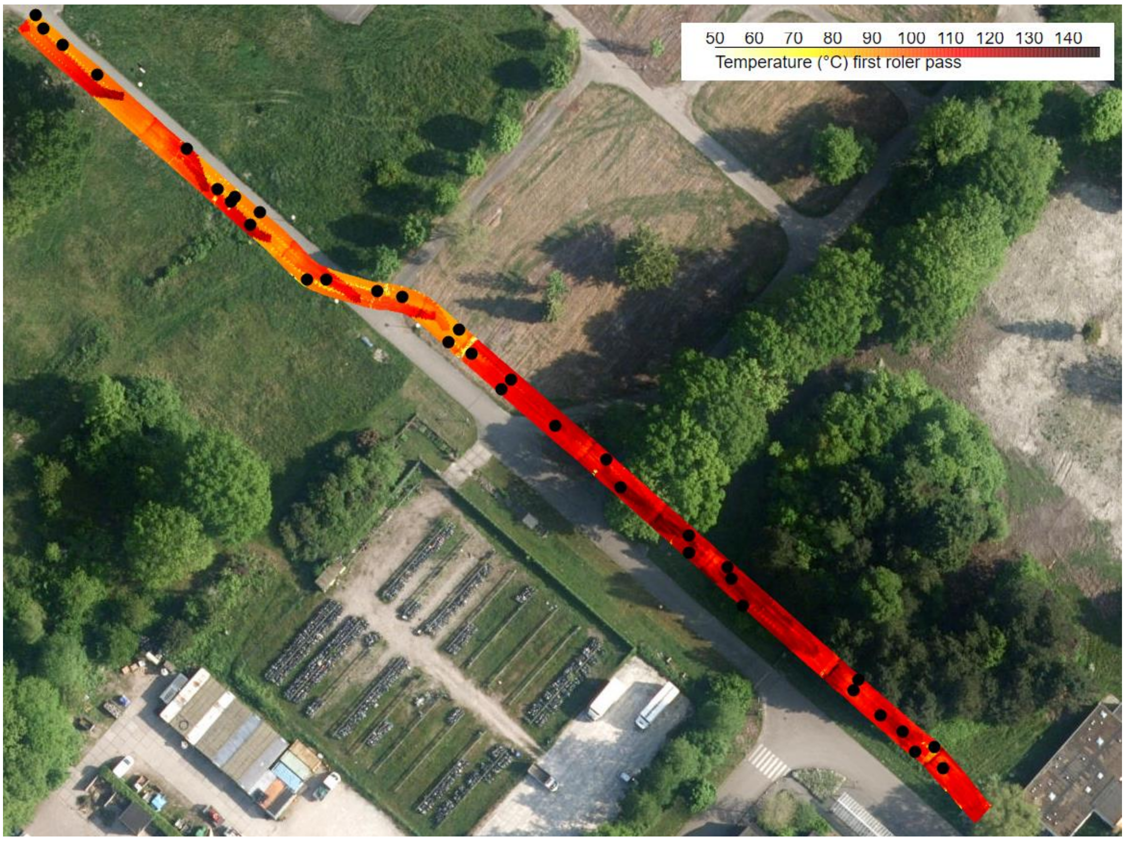


Figure 49: Maximum temperature during compaction area B

Figure 50: Maximum temperature during compaction area C

Figure 51: Maximum temperature during compaction area D

The average temperature for the last compaction pass was 56 degrees, with 95% of measurements (Std = 10.5) falling between 35 and 77 degrees. During this pass, the minimum temperature was 42 degrees, and the maximum reached 103 degrees. Nearly all areas compacted before the final major stopping point, before the last 2 batches of asphalt, experienced a pass at temperatures below the specified minimum of 80 degrees. After the stopping point, this was no longer the case, as the asphalt crew stopped the compaction efforts quickly after the paver finished the last batch. Additionally, a compaction trajectory at a very low temperature, around 45 degrees, occurred because the small tandem roller was moved from the start to the end of the project, resulting in a single low-temperature compaction path. This path is important as experts mentioned that compacting at low temperatures may have adverse effects on the mechanical properties of the asphalt. A visual representation of the compaction temperature during the last pass can be found in Figure 52 to Figure 55.

A significant proportion of the passes are below the minimum compaction temperature of 80 degrees. Combining the maximum and minimum temperature during compaction, only 5% of the paved area was compacted solely within this TCW.

Figure 52: Minimum temperature during compaction area A

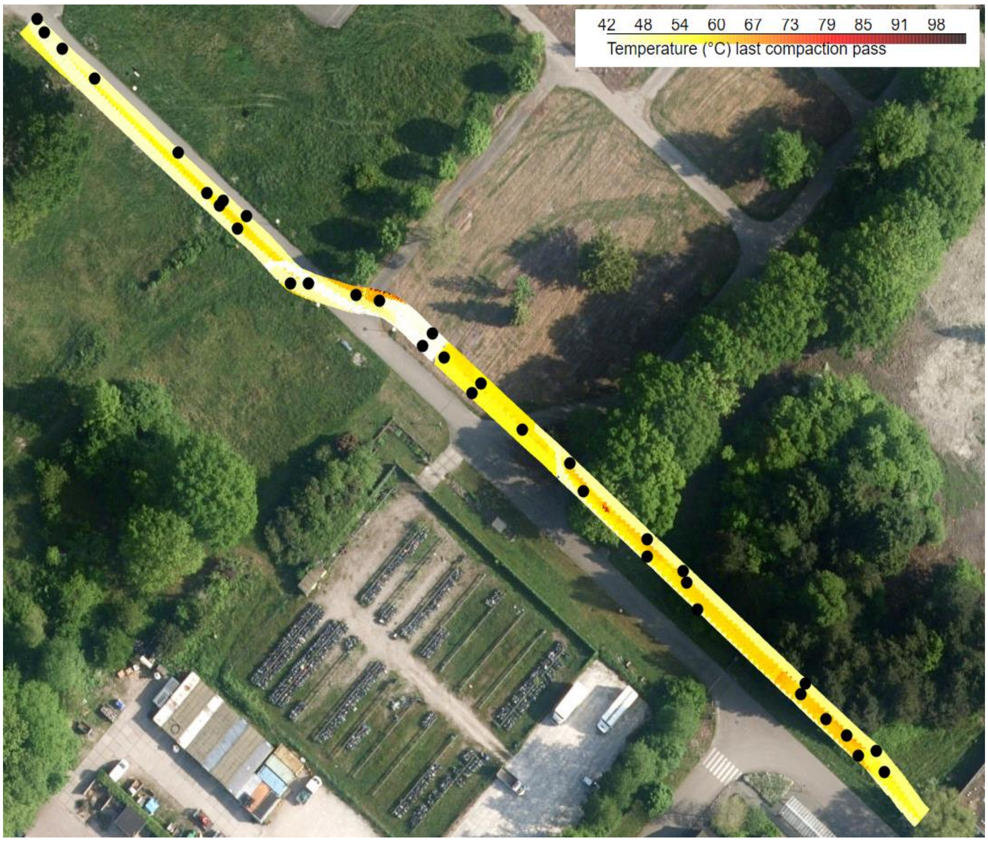


Figure 53: Minimum temperature during compaction area B

Figure 54: Minimum temperature during compaction area C

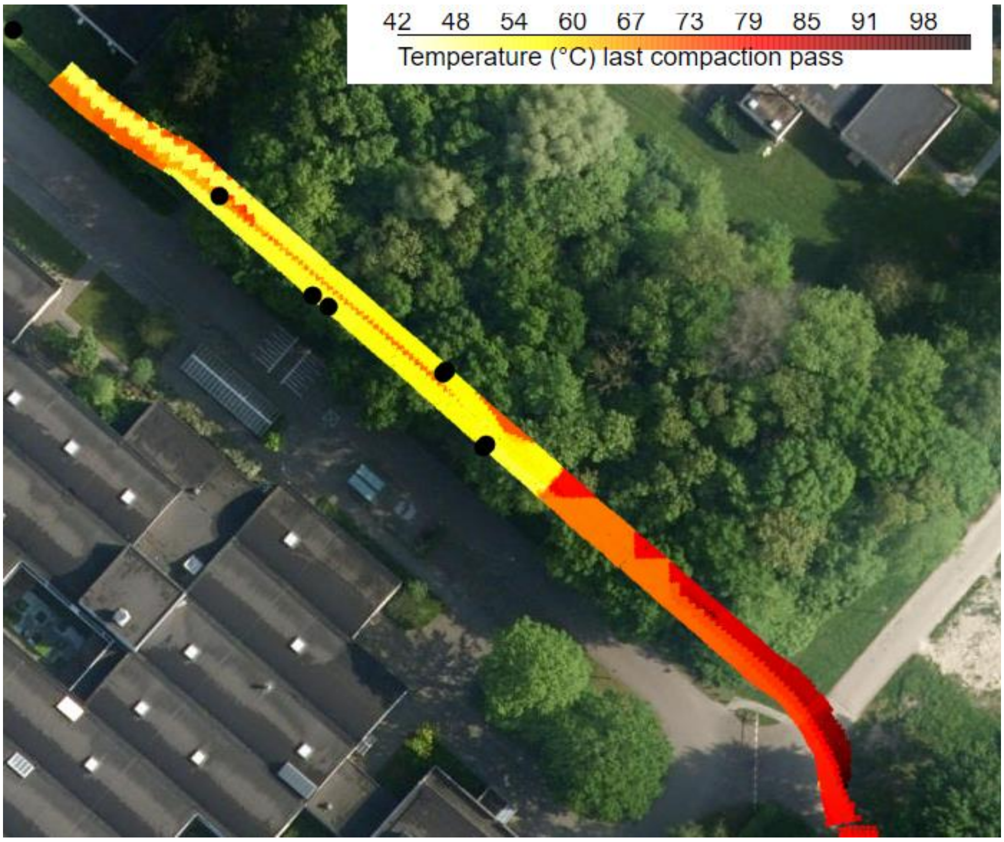


Figure 55: Minimum temperature during compaction area D

Compaction passes in TCW

On average, there are 5 compaction passes within the TCW, 95% (std of 3.3) is between 0 and 11.6 compaction passes. With a minimum of 0 and a maximum of 20 passes. The low paving temperature may have caused the time for compacting to be limited. However, the large number of stopping points could have allowed for the rollers to catch up. That effect can also be seen after the first stopping point. Certain hotspots can be seen where more compaction passes have taken place either due to the roller moving more often at that location, the paving temperature being higher, or the roller rolling closer to the paver. A full visualisation of the number of compaction passes in the TCW is visualised in Figure 56 to Figure 59.

Figure 56: Number of compaction passes in TCW area A

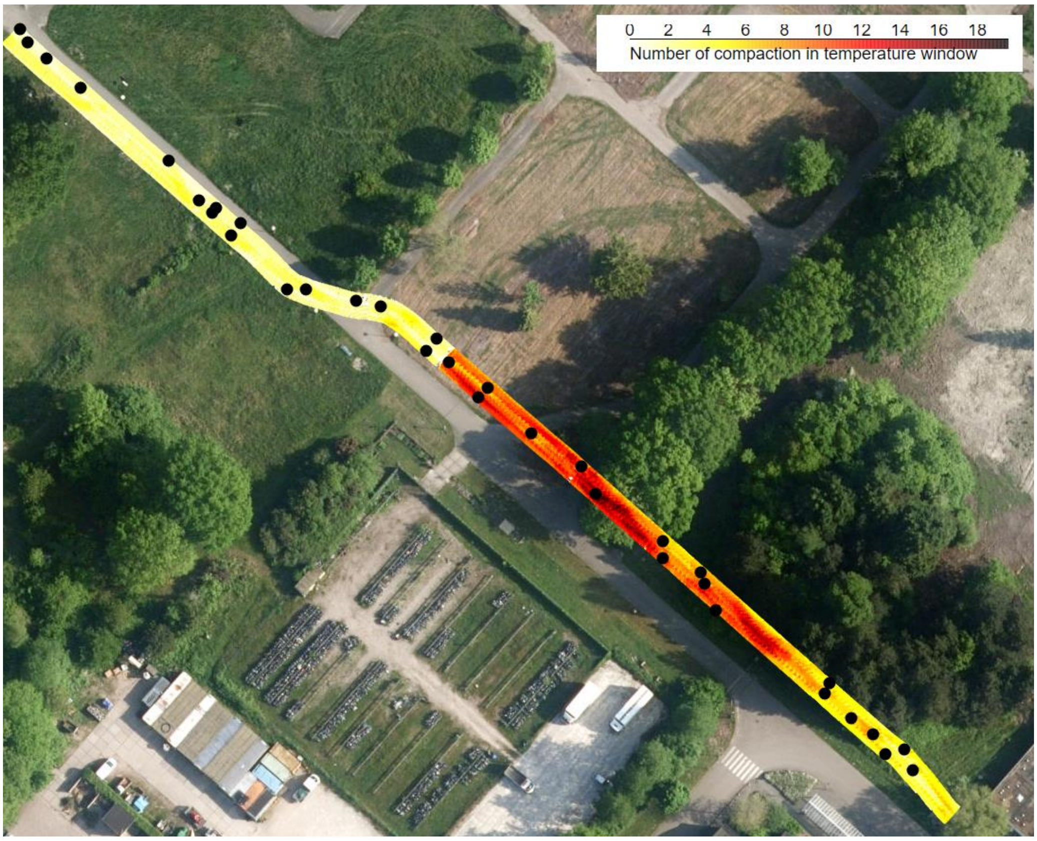


Figure 57: Number of compaction passes in TCW area B

Figure 58: Number of compaction passes in TCW area C

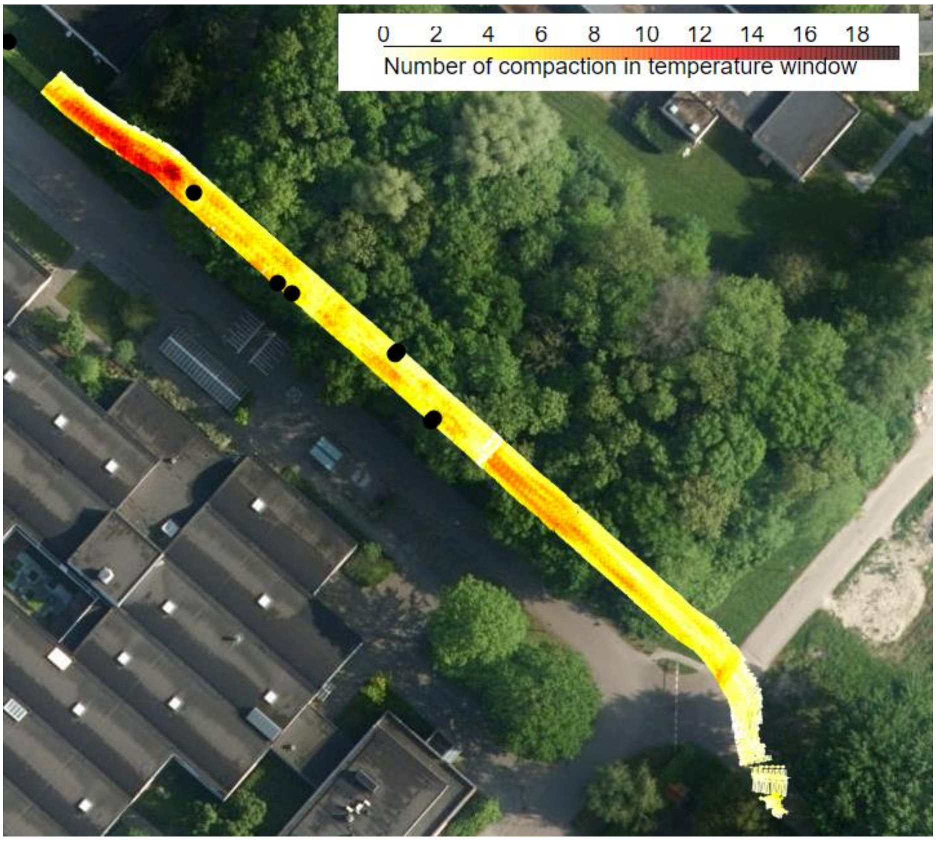


Figure 59: Number of compaction passes in TCW area D

Seconds between paving and first compaction pass

On average, the first compaction pass takes place after 5 minutes with a standard deviation of (4 minutes). Therefore 95% of the passes take place between 0 minutes and 15 minutes after paving. The fastest compaction pass is registered 17 seconds after the paver and the longest time until the first compaction pass took place 85 minutes after paving. A visualisation of the time between compacting and paving can be found in Figure 60 to Figure 63.

Only 65% of the passes occurred within the specific 5 minutes after paving.

Figure 60: Seconds between paving and compacting area A

Figure 61: Seconds between paving and compacting area B

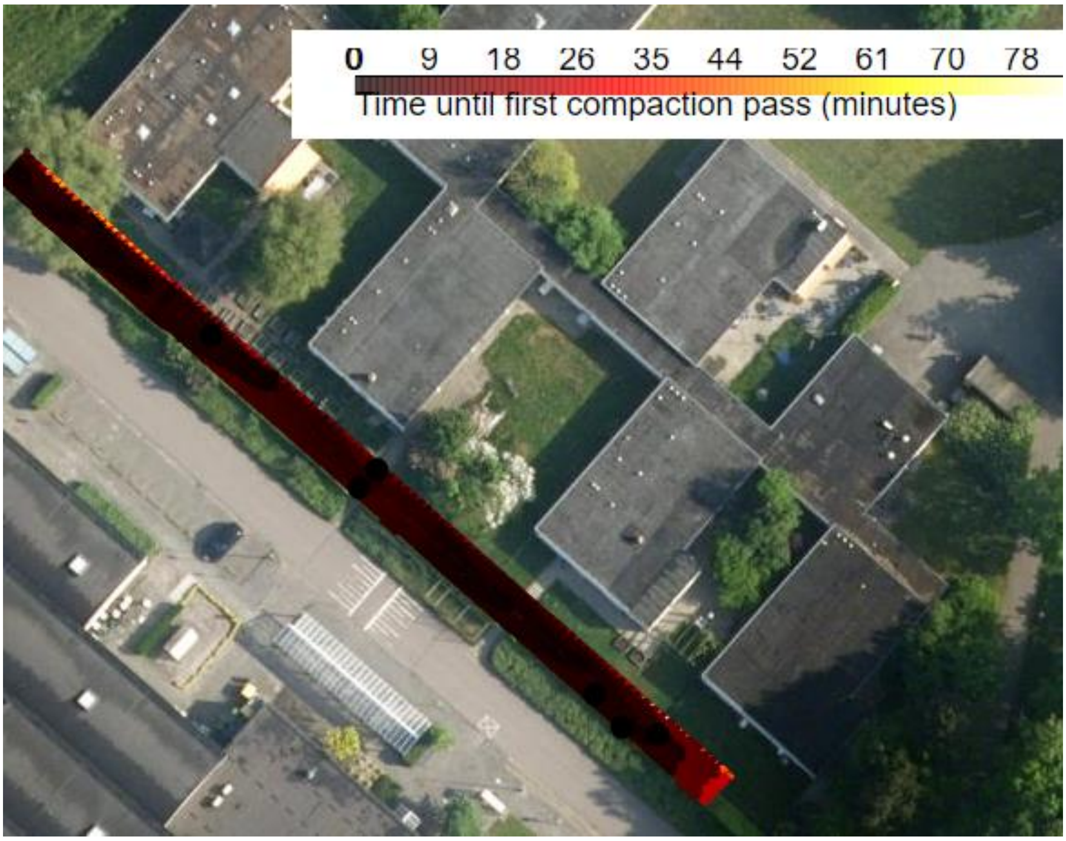


Figure 62: Seconds between paving and compacting area C

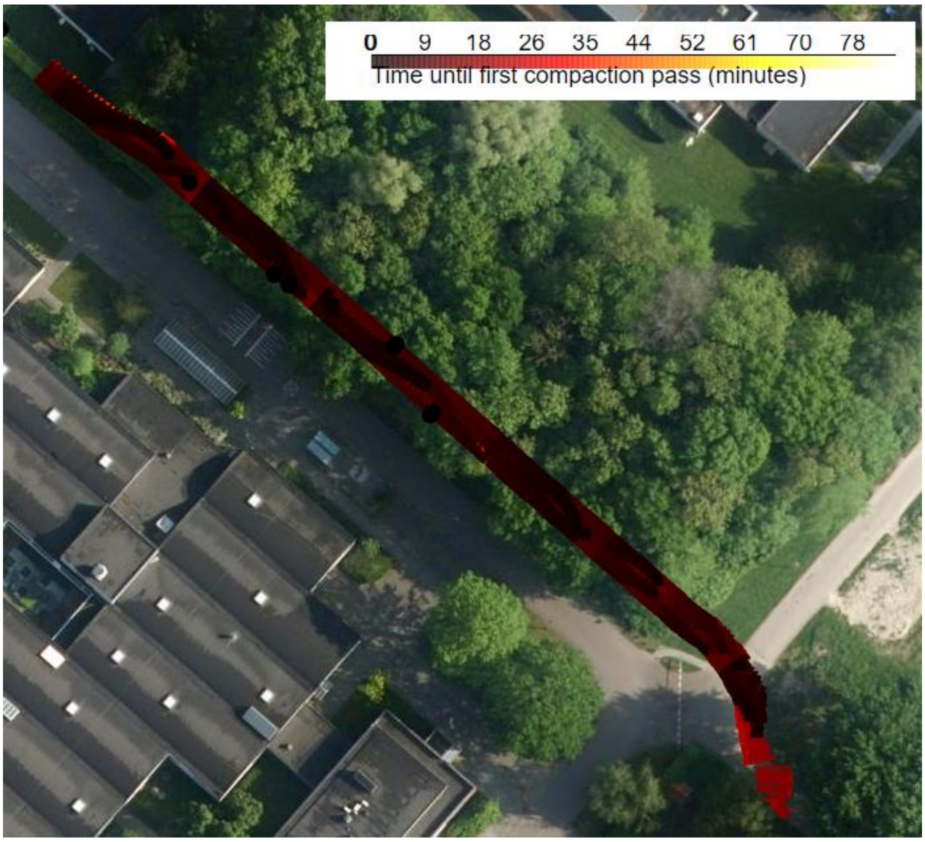


Figure 63: Seconds between paving and compacting area D

Appendix B6: Sensitivity analysis

Table 20: Results sensitivity analysis

Parameter	Minimum temperature [°c]	Maximum temperature [°c]	Mean number of passes in temperature compaction window [-]	Mean number of passes [-]	Passes at location 1 [-]	Passes at location 2 [-]	Passes at location 5 [-]
Reference	**41.7**	**148**	**4.9**	**12.4**	**11**	**17**	**14**
No Kalman Filter	41.7	148	4.9	12.5	11	17	12
Smooth azimuth (n=1)	41.7	148	4.9	12.4	11	17	13
Smooth azimuth (n=5)	41.7	148	4.9	12.4	11	17	13
Smooth azimuth (n=15)	41.7	148	4.9	12.4	11	17	14
Smooth azimuth (n=20)	41.7	148	4.9	12.4	11	17	13
min time between roller passes (Δt = 0s)	41.7	148	8.6	10.3	27	29	30
min time between roller passes (Δt = 10s)	41.7	148	4.8	12.1	11	17	14
min time between roller passes (Δt = 30s)	41.7	148	4.4	11.2	11	17	14
Asphalt node(s) (1)	41.5	144	3.4	12.4	11	17	14
Asphalt node(s) (2)	43.2	161.6	3.5	12.4	11	17	14
Asphalt node(s) (3)	45.5	126.6	2.4	12.4	11	17	14
Asphalt node(s) (1,2)	41.7	161.6	4	12.4	11	17	14
Asphalt node(s) (2,3)	43.2	147.96	3.1	12.4	11	17	14

Appendix B7: Results from product quality tests

Table 21: Physical and mechanical properties of drilled asphalt cores

Id	Pair [-]	Degree of compaction [%]	Stiffness [Mpa]	Fatigue [-]	Deformation [µm/m/n]	ITS [N/mm²]	Water sensitivity [%]
1	1 dry	98.1				2.43	63.79%
2	-	96.6			0.92		
3	2 wet	99.8				1.79	60.68%
4	2 dry	100.2				2.95	60.68%
5	3 wet	99.4				1.85	58.73%
6	4 wet	95.5				1.05	66.04%
7	5 wet	99.2				1.69	62.13%
8	6 dry	101.2				3.21	58.57%
9	4 dry	96.1				1.59	66.04%
10	5 dry	99.2				2.72	62.13%
11	-	100.6			0.27		
12	-	97.0			0.56		
13	7 dry	98.7				2.39	48.12%
16	6 wet	100.8				1.88	58.57%
17	-	100.8	12037	478715[9]			
18	-	101.4	11526	192217			
19	-	100.0	11048	122324			
20	-	98.4	11029	157080			
21	8 dry	99.0				2.36	57.63%
22		98.8	9709	192217			
23	1 wet	98.8				1.55	63.79%
27	7 wet	95.2				1.15	48.12%
28	-	96.7			0.60		
30	-	96.6			0.57		
31	-	98.7	10178	74757			
32	9 dry	95.9				1.94	61.86%
34	10 dry	98.0				2.21	75.11%
36	10 wet	97.4				1.66	75.11%
37	-	97.2			0.49		
38	-	96.3			0.59		
39	-	96.5			0.52		
40	9 wet	95.2				1.20	61.86%
41	-	99.4	10720	65940			
45	-	98.8	10113	89234			
47	-	97.2			0.58		
49	-	99.5	9806	94396			
50	3 dry	100.3				3.15	58.73%
51	-	98.5	8419	91768			
52	-	96.6			0.71		
53	8 wet	98.2				1.36	57.63%
Average		98.3%	10283	120000	0.58		62%
Conform specification:		**73%**	**100%**		**10%**		**10%**

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[9] The first measurement is done at a different test setting, and therefore not included in this analysis

Appendix B8: Scatterplots

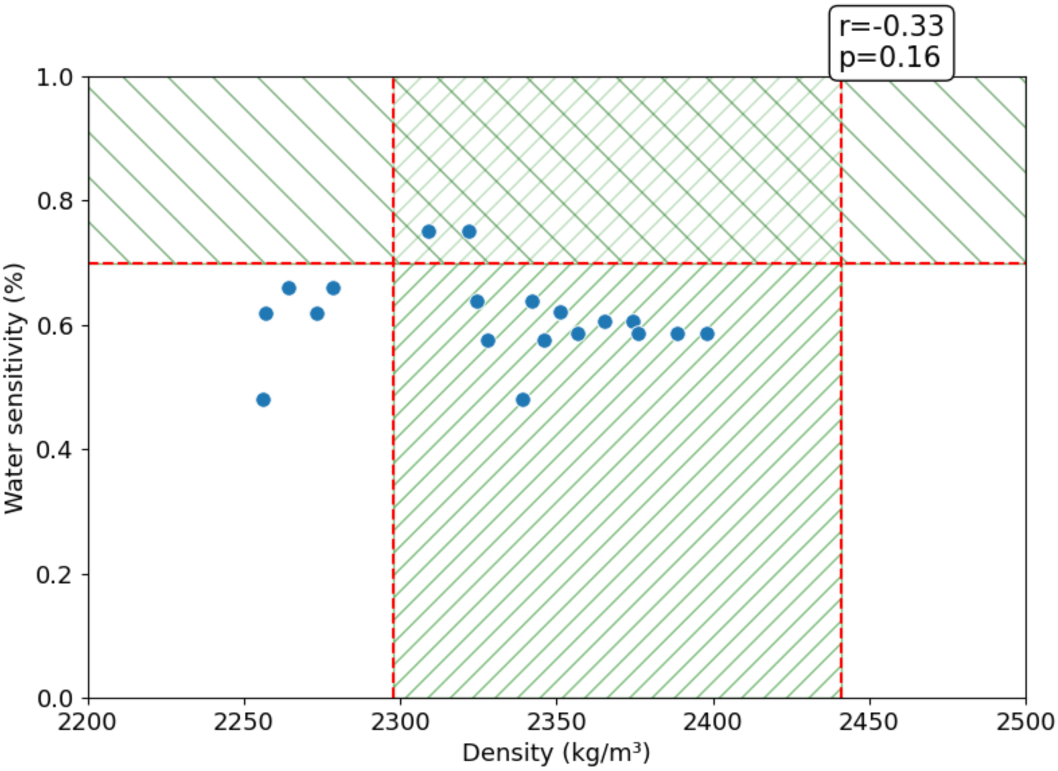

Figure 64: Scatterplot density vs water sensitivity

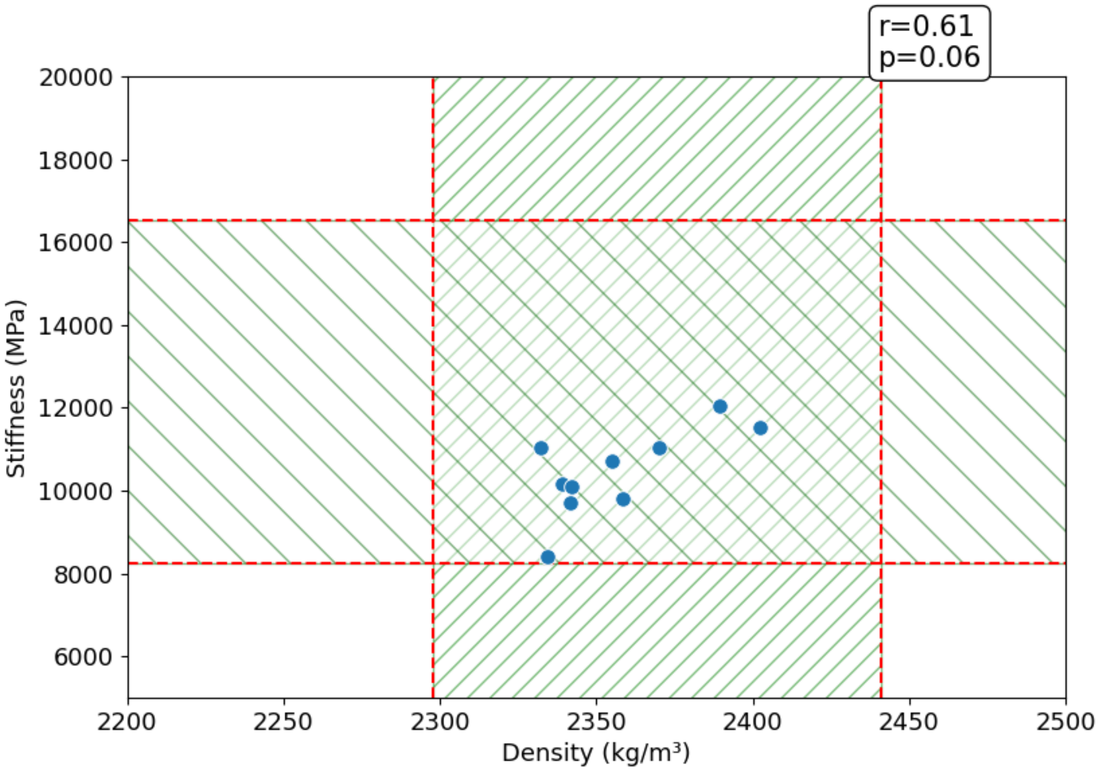

Figure 65: Scatterplot density vs stiffness

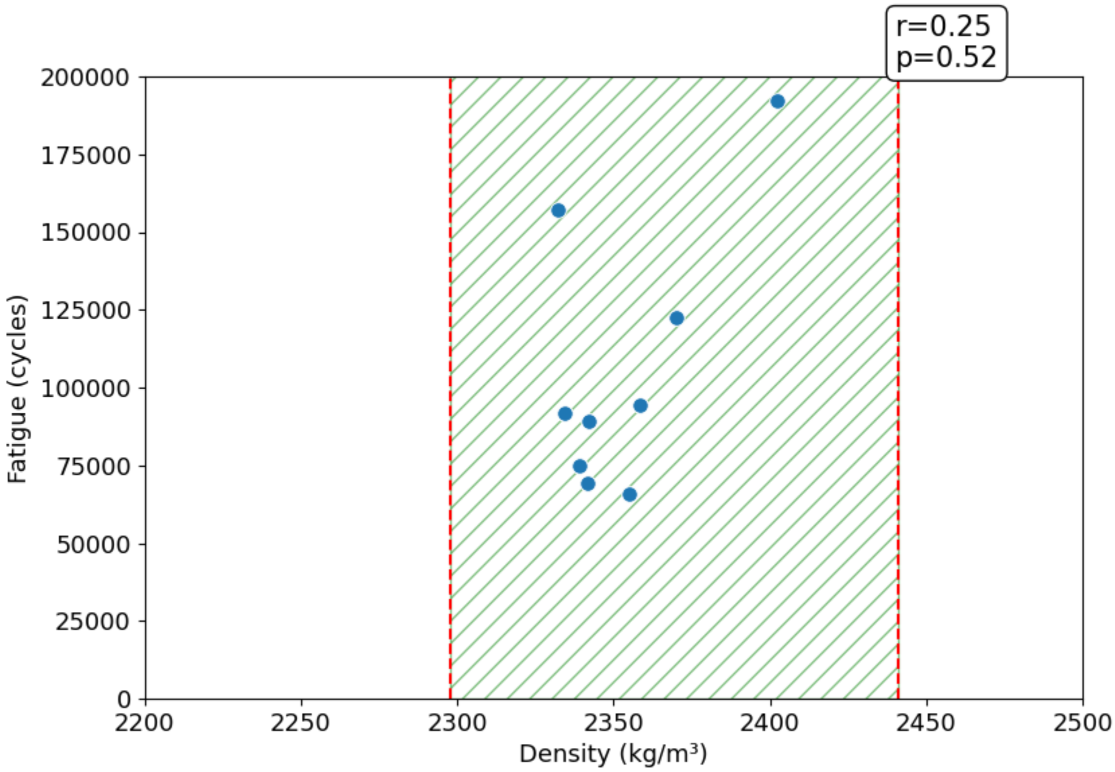

Figure 66: Scatterplot density vs fatigue

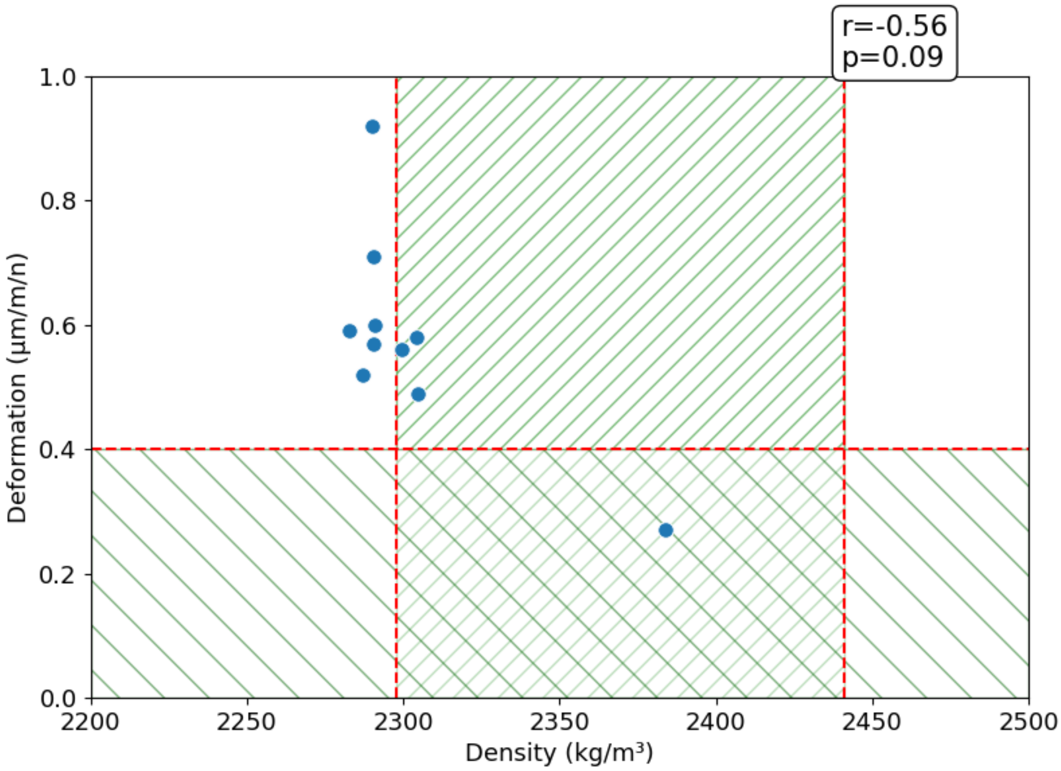

Figure 67: Scatterplot density vs deformation

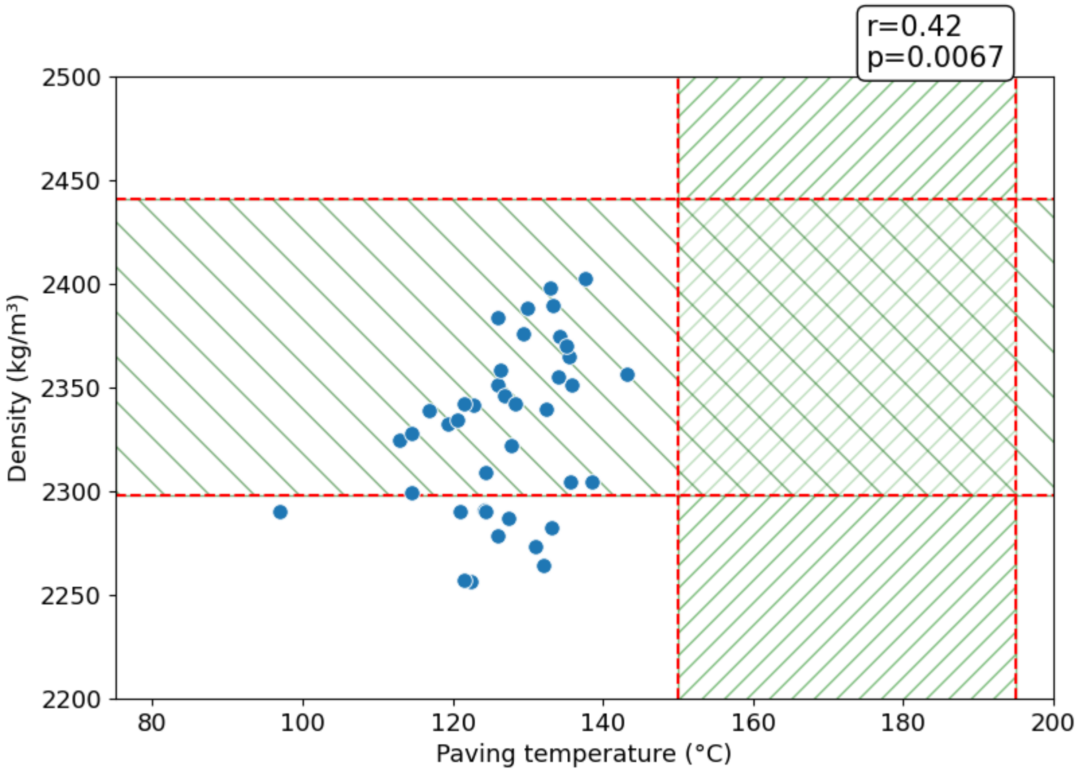

Figure 68: Scatterplot paving temperature vs density

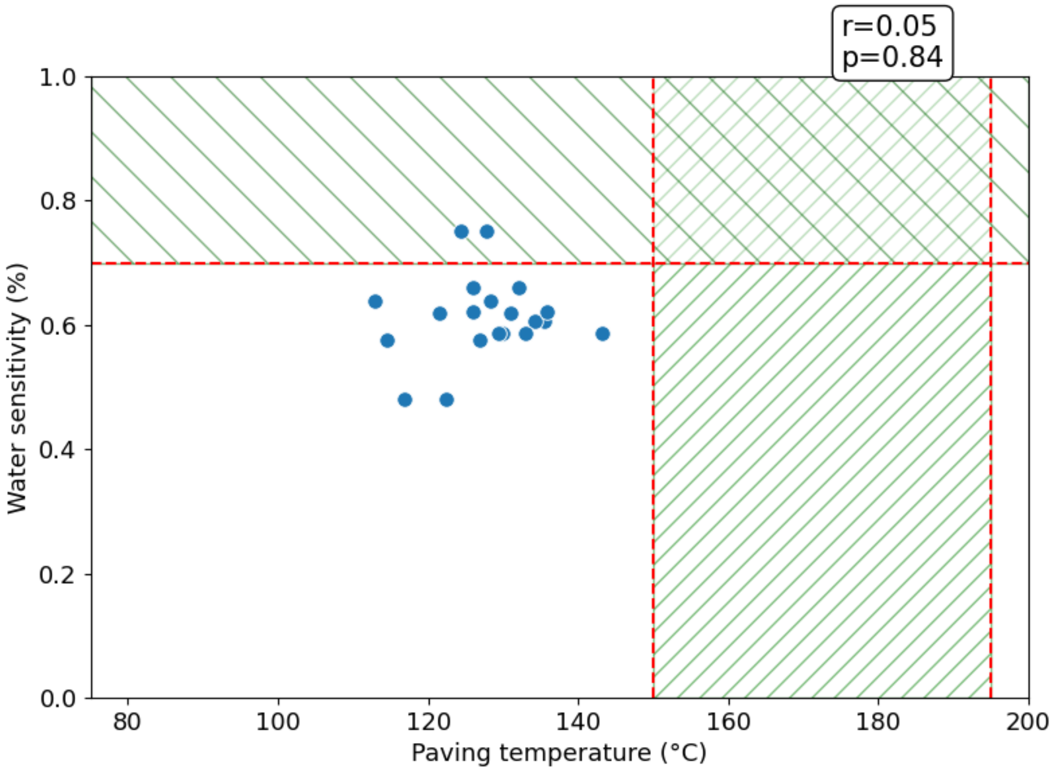

Figure 69: Scatterplot paving temperature vs water sensitivity

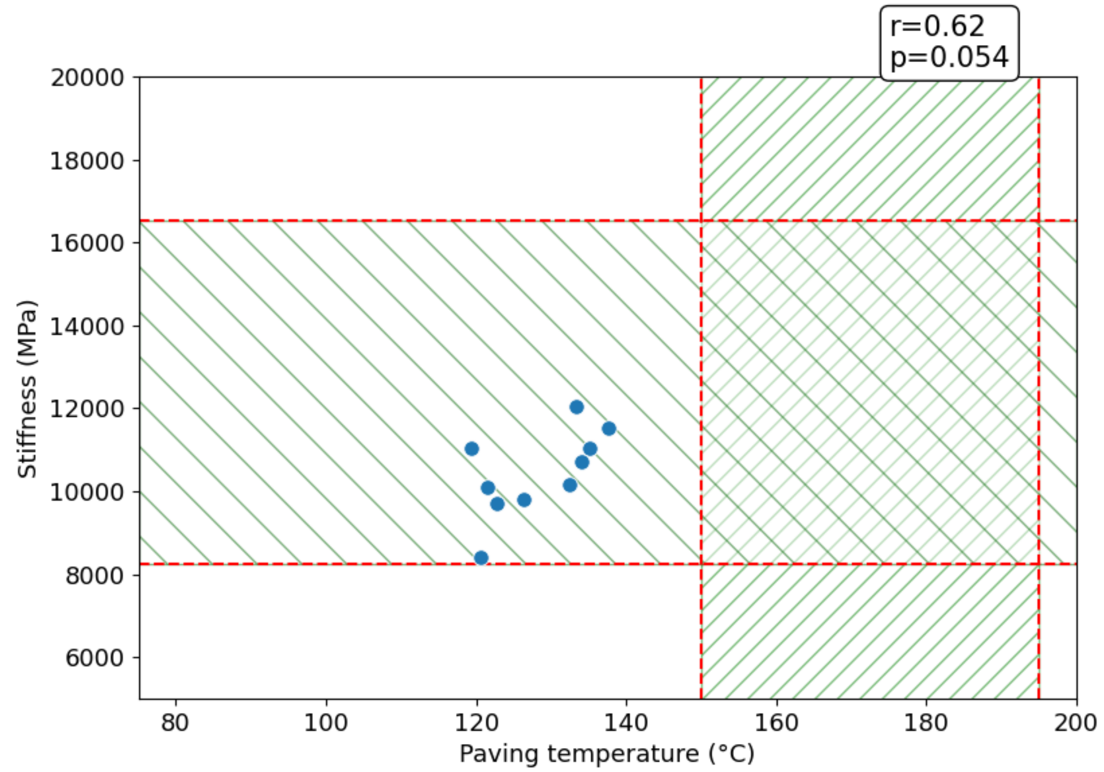

Figure 70: Scatterplot paving temperature vs stiffness

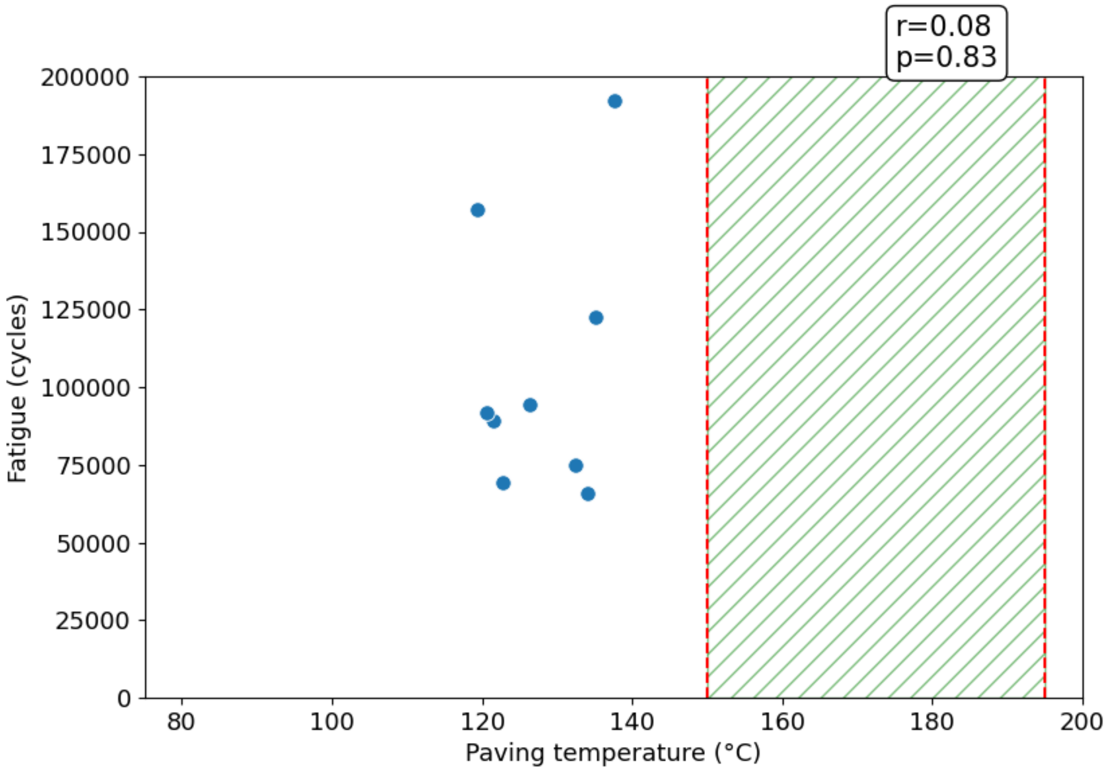

Figure 71: Scatterplot paving temperature vs fatigue

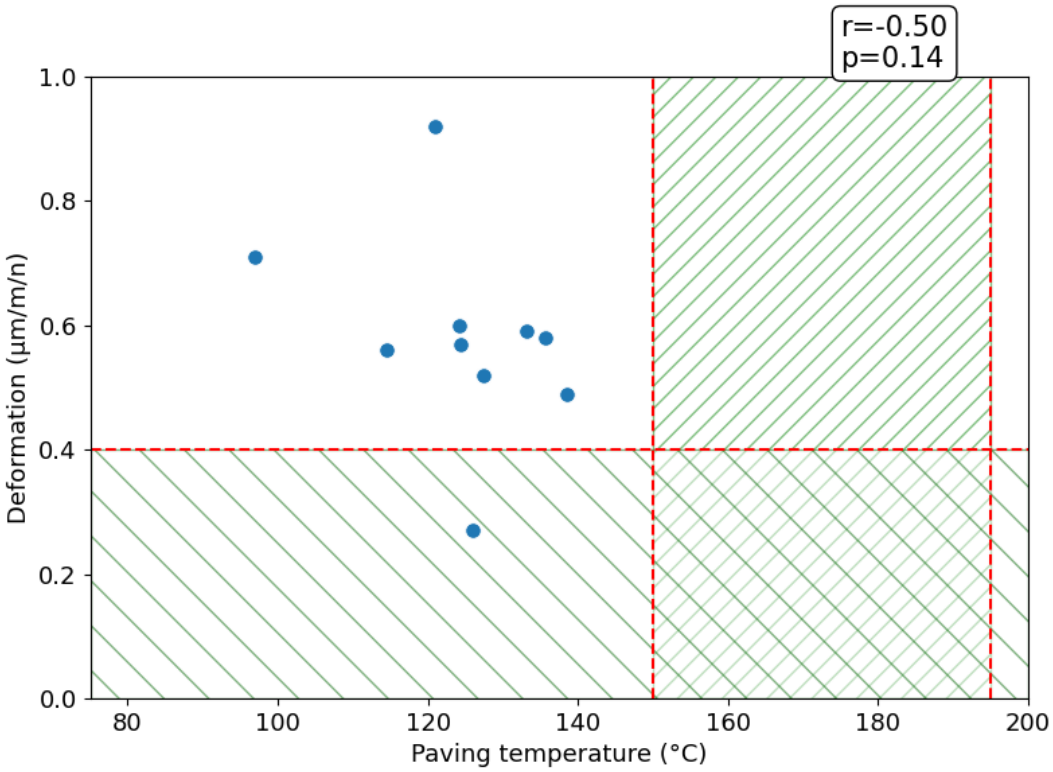

Figure 72: Scatterplot paving temperature vs deformation

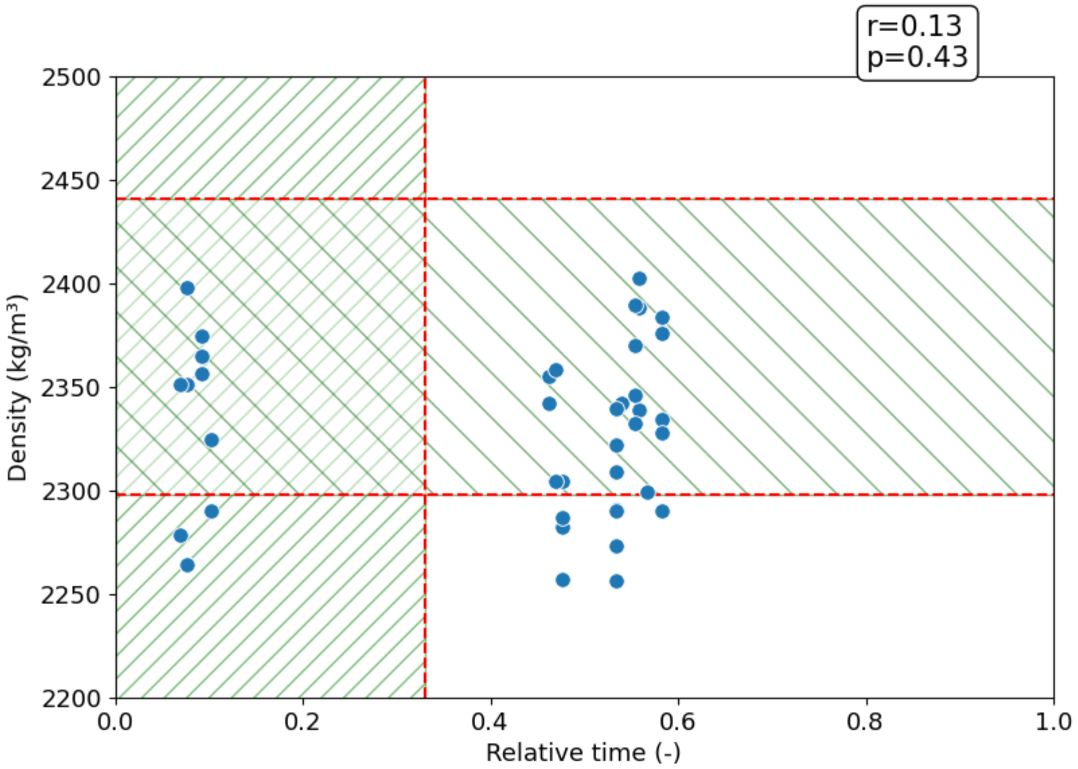

Figure 73: Scatterplot time been production and construction vs density

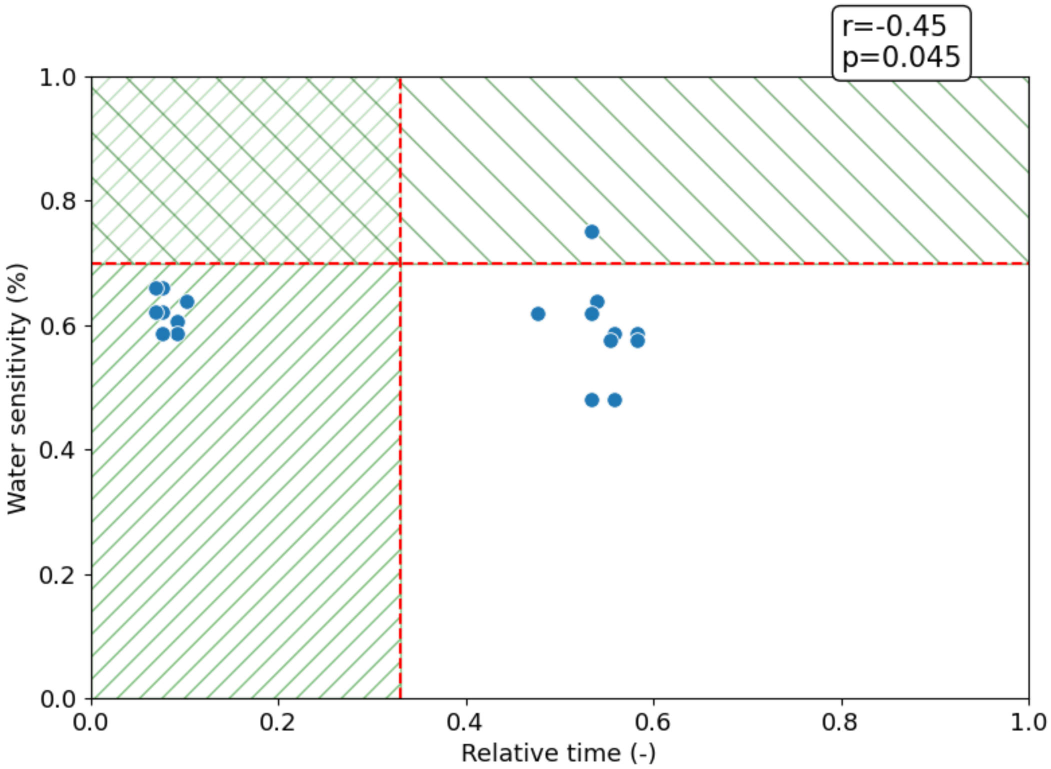

Figure 74: Scatterplot time been production and construction vs water sensitivity

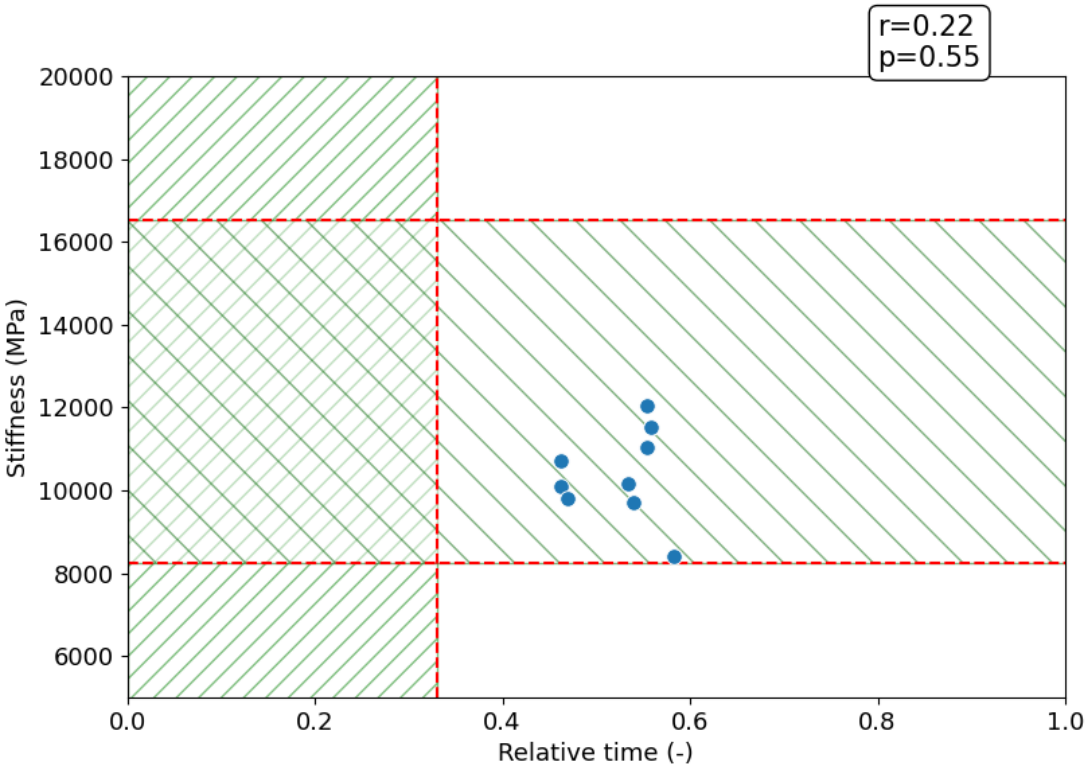

Figure 75: Scatterplot time been production and construction vs stiffness

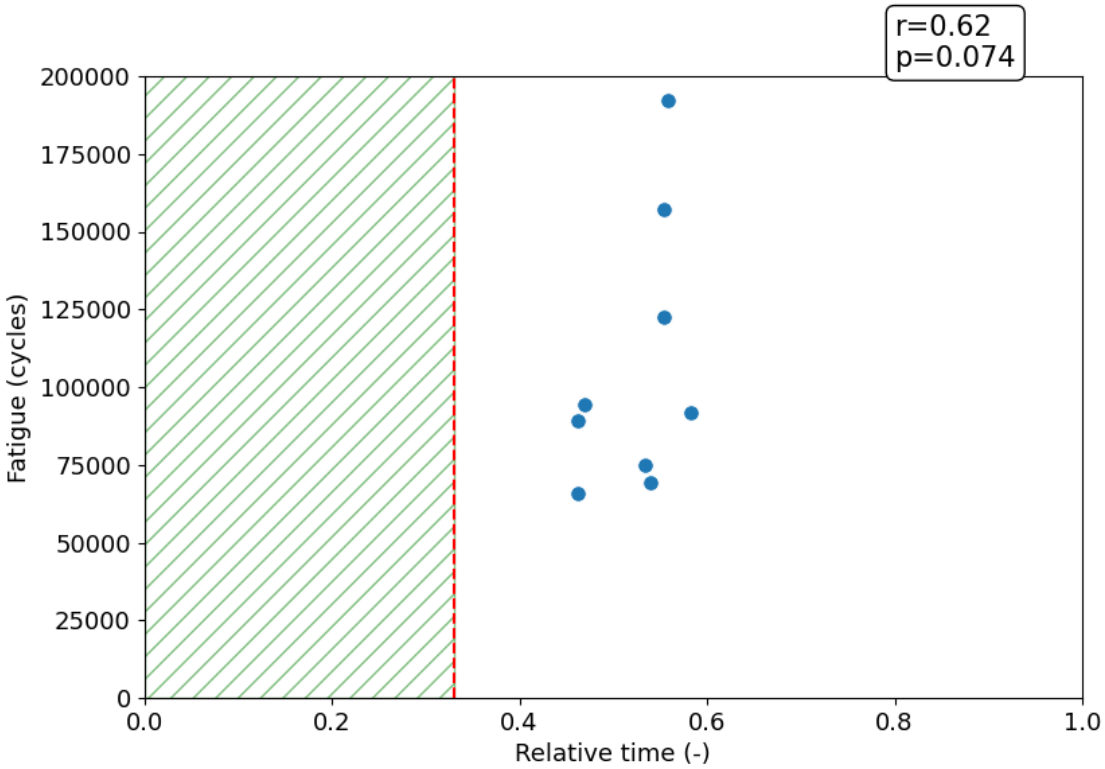

Figure 76: Scatterplot time been production and construction vs fatigue

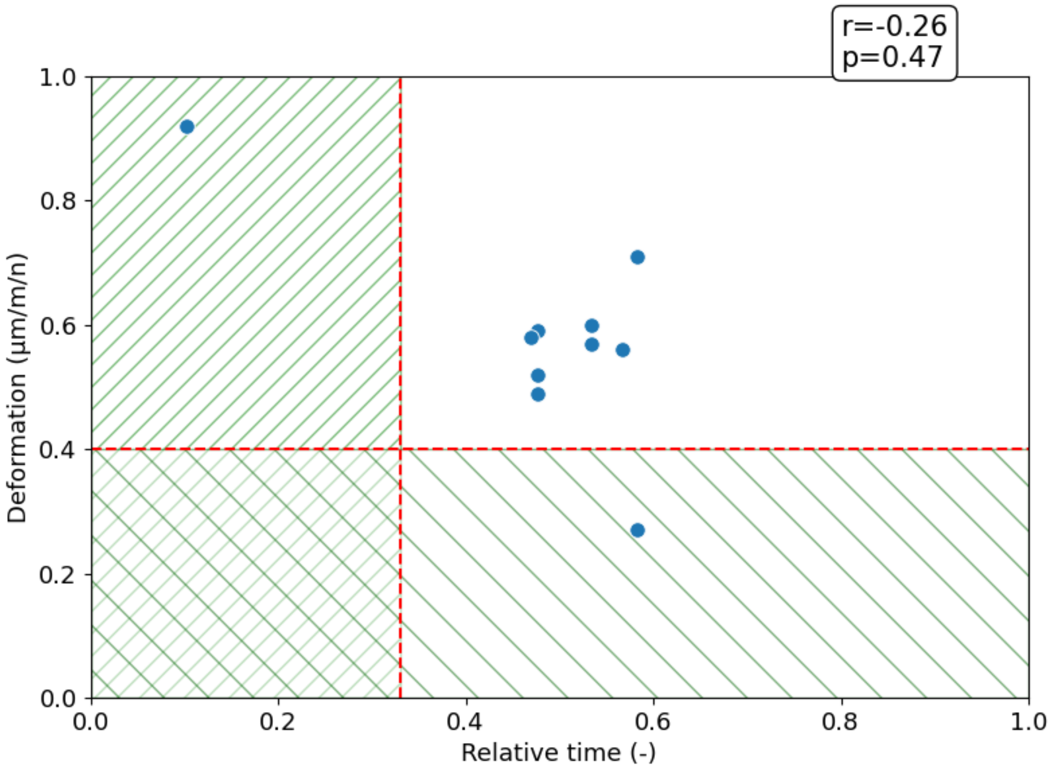

Figure 77: Scatterplot time been production and construction vs deformation

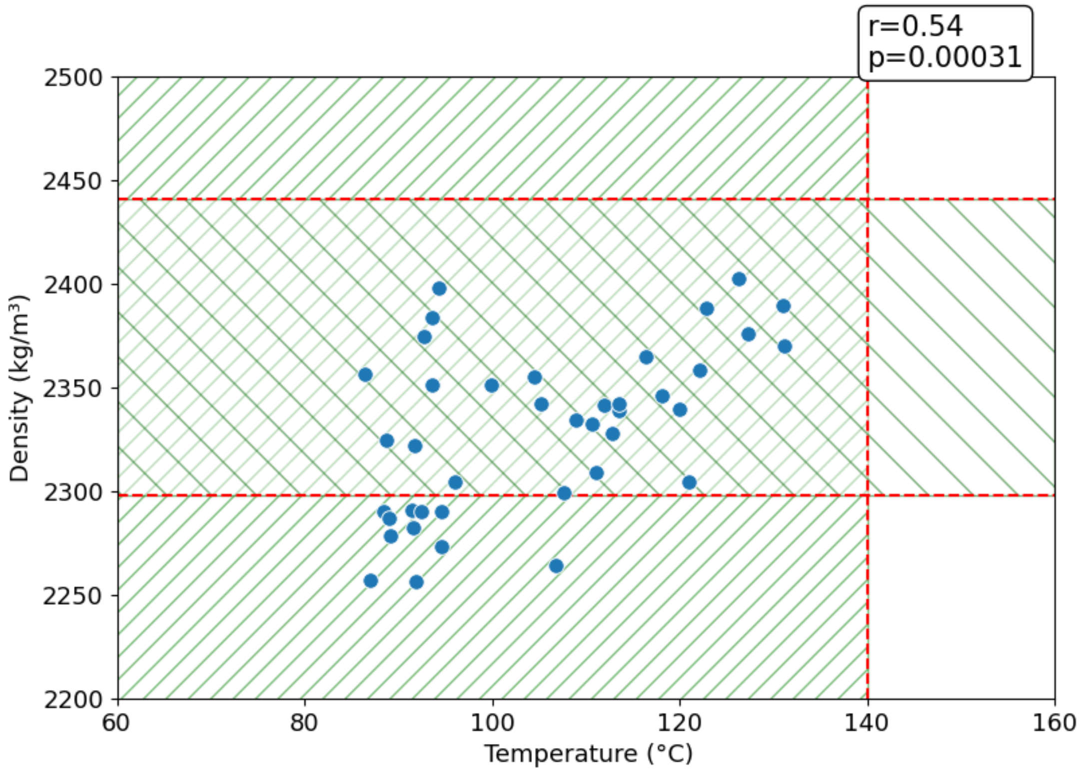

Figure 78: Scatterplot highest compaction temperature vs density

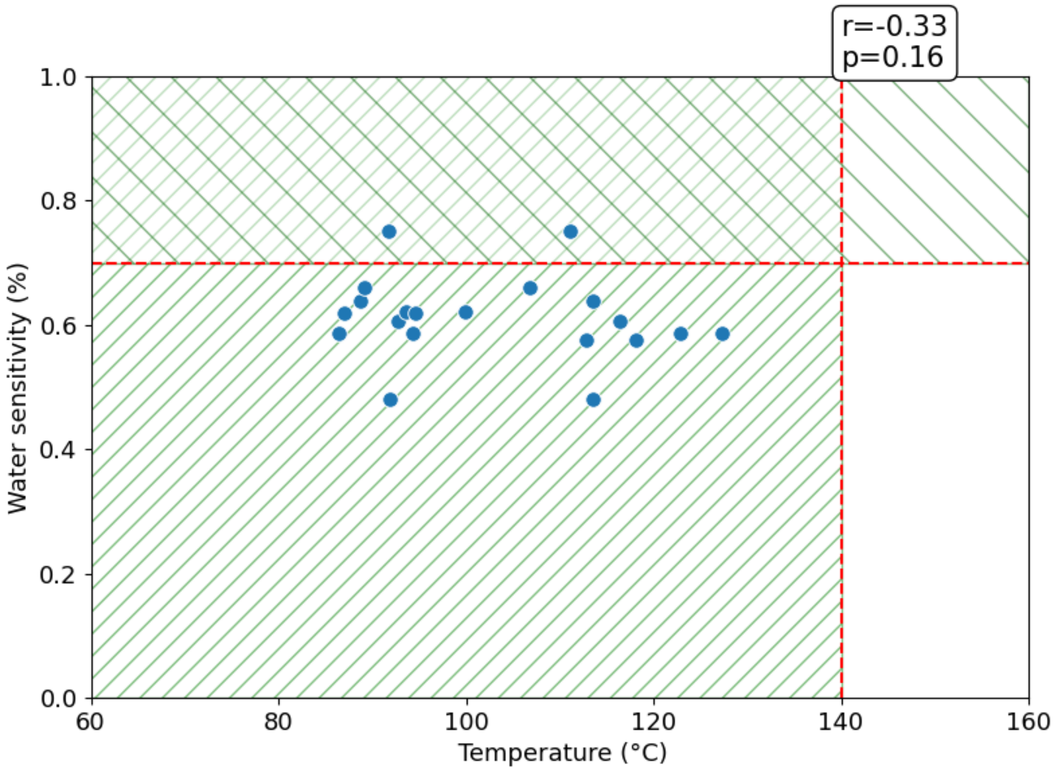

Figure 79: Scatterplot highest compaction temperature vs water sensitivity

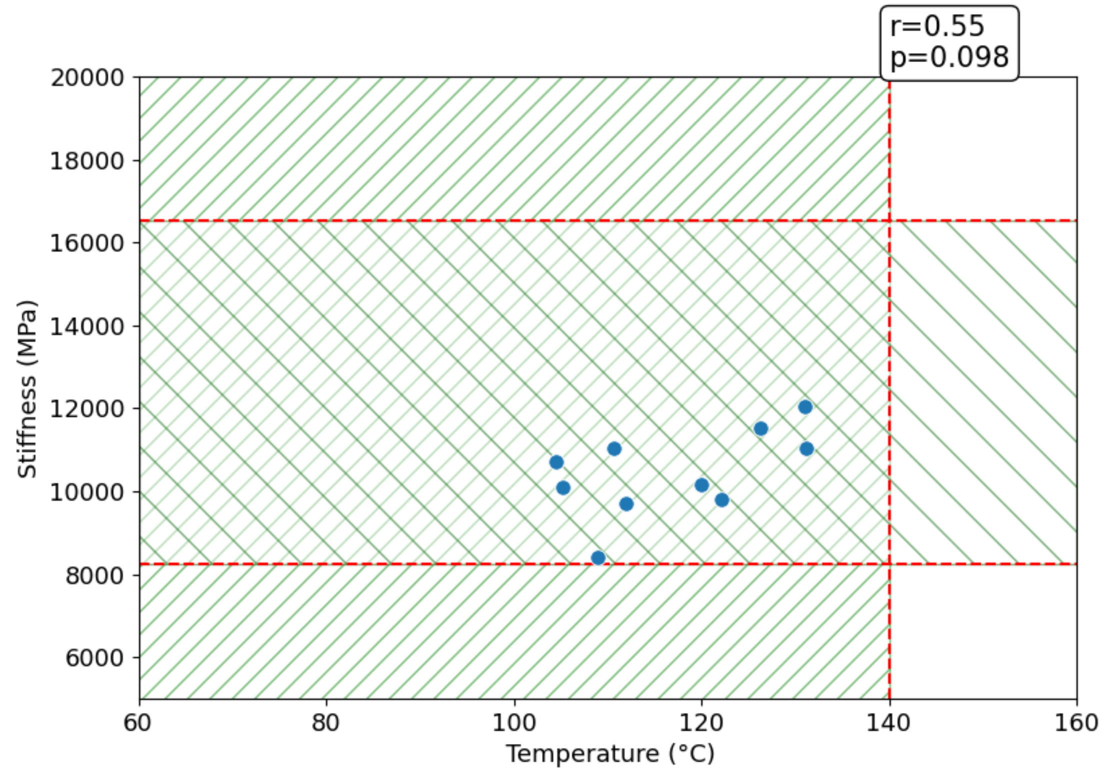

Figure 80: Scatterplot highest compaction temperature vs stiffness

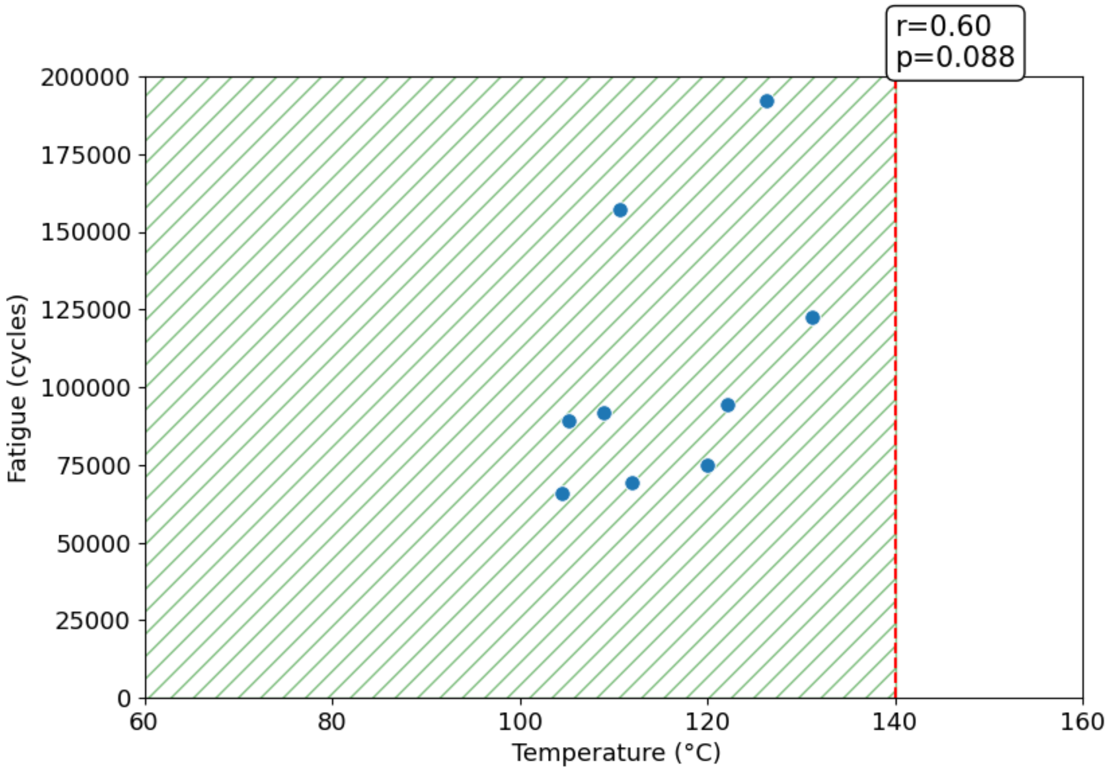

Figure 81: Scatterplot highest compaction temperature vs fatigue

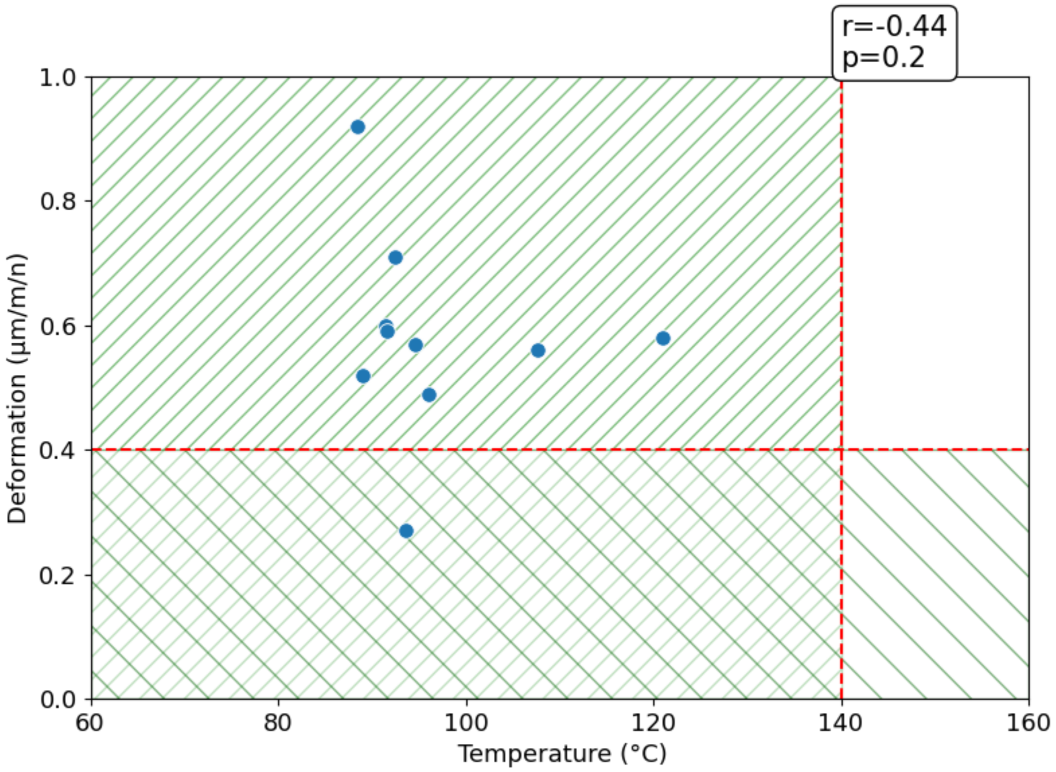

Figure 82: Scatterplot highest compaction temperature vs deformation

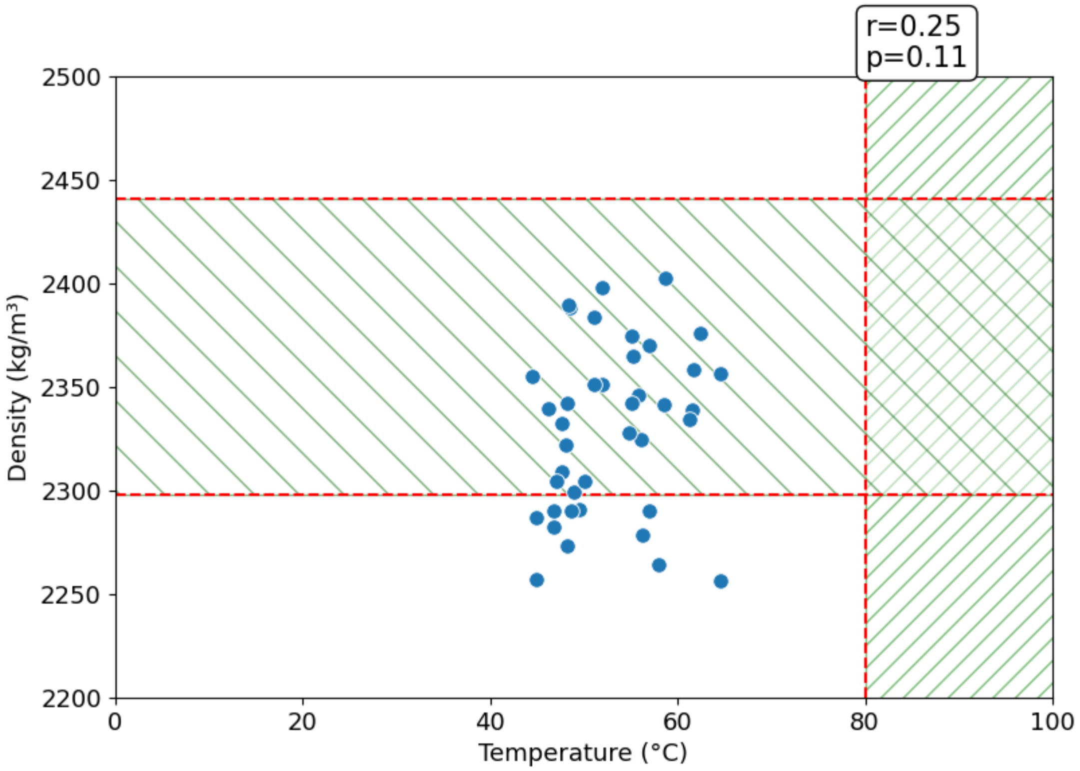

Figure 83: Scatterplot lowest compaction temperature vs density

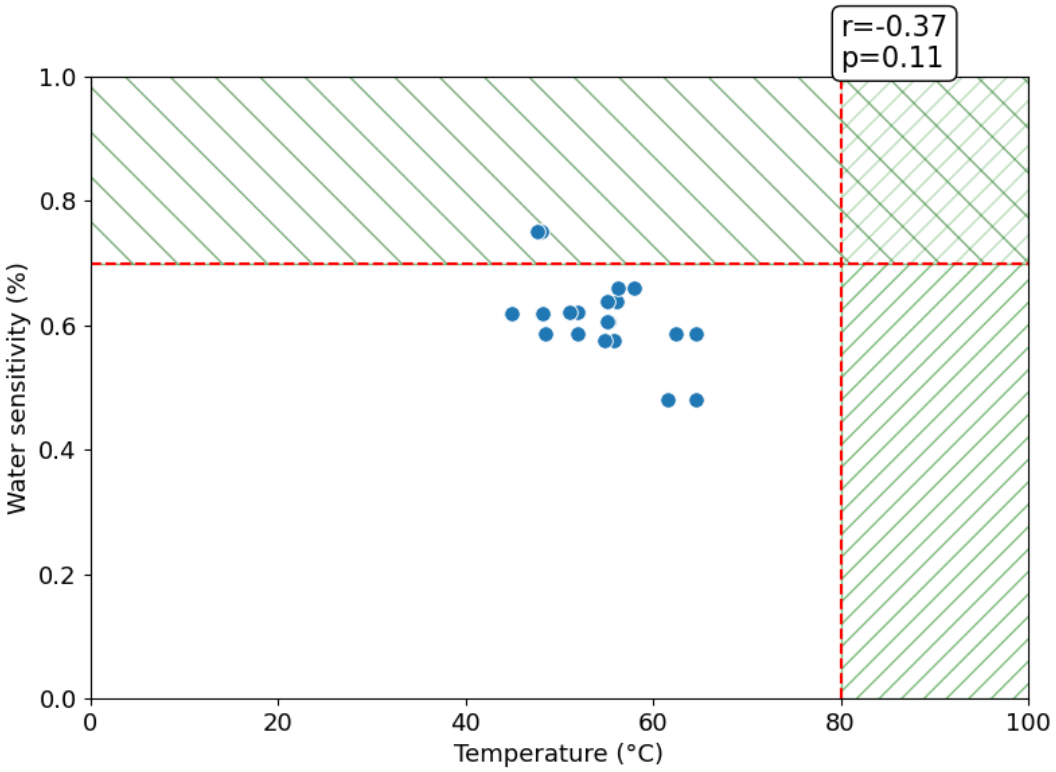

Figure 84: Scatterplot lowest compaction temperature vs water sensitivity

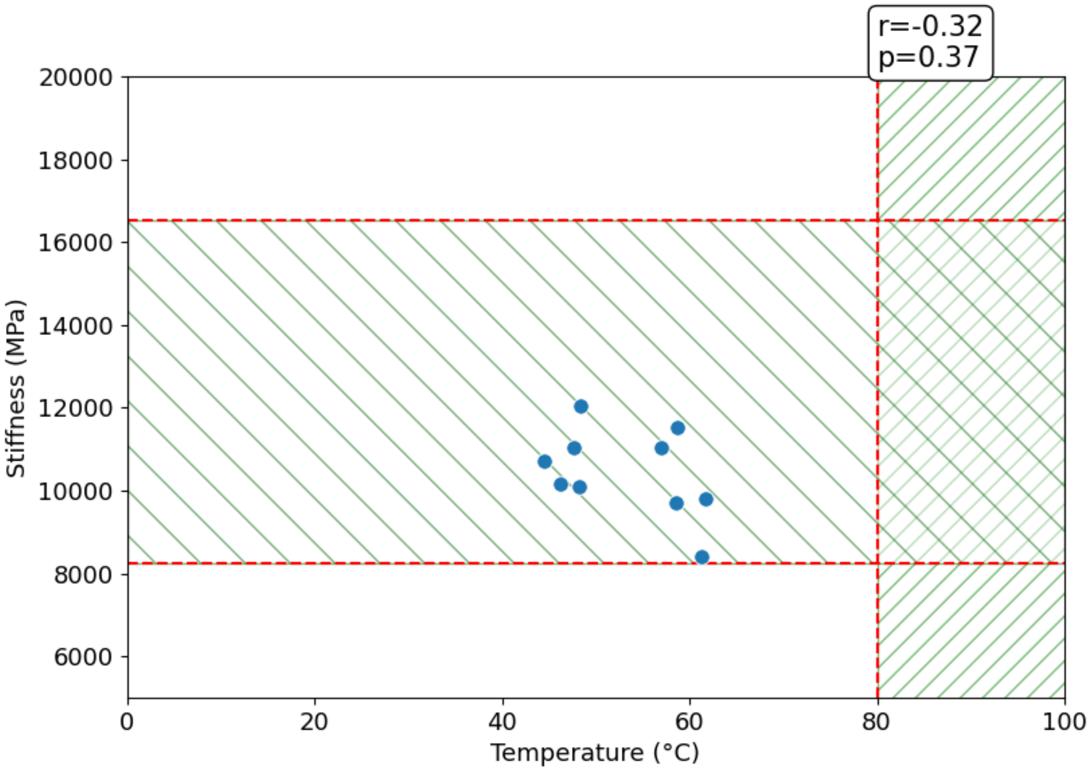

Figure 85: Scatterplot lowest compaction temperature vs stiffness

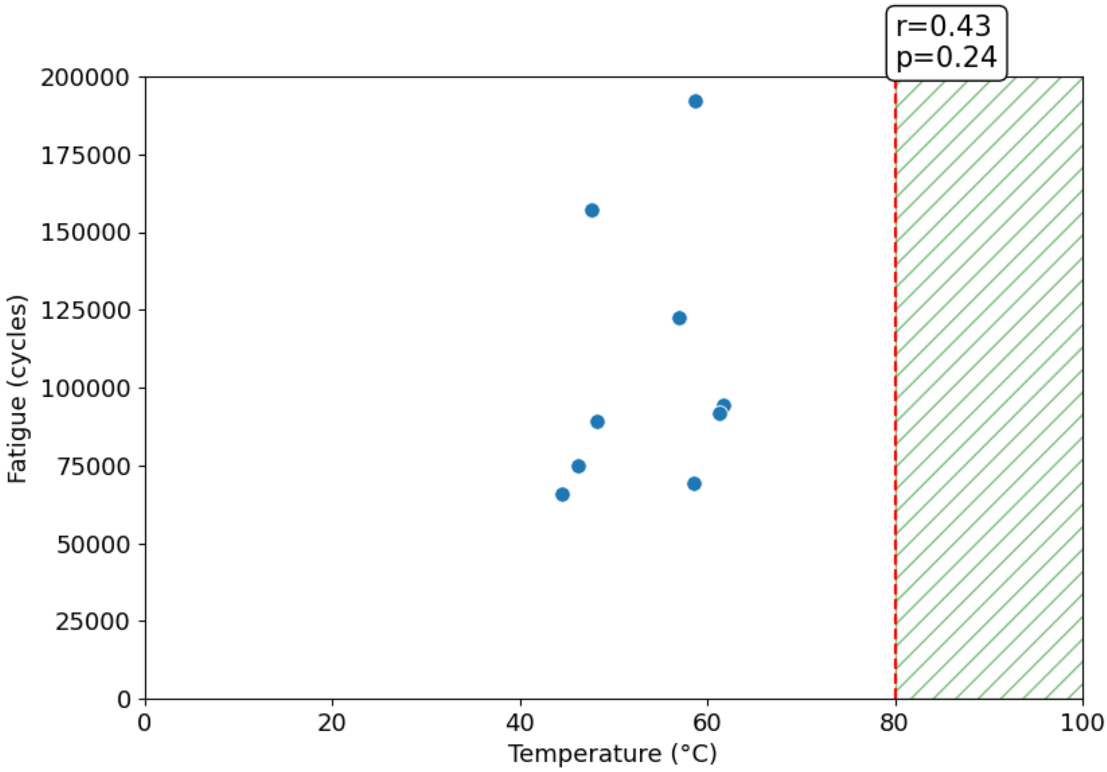

Figure 86: Scatterplot lowest compaction temperature vs fatigue

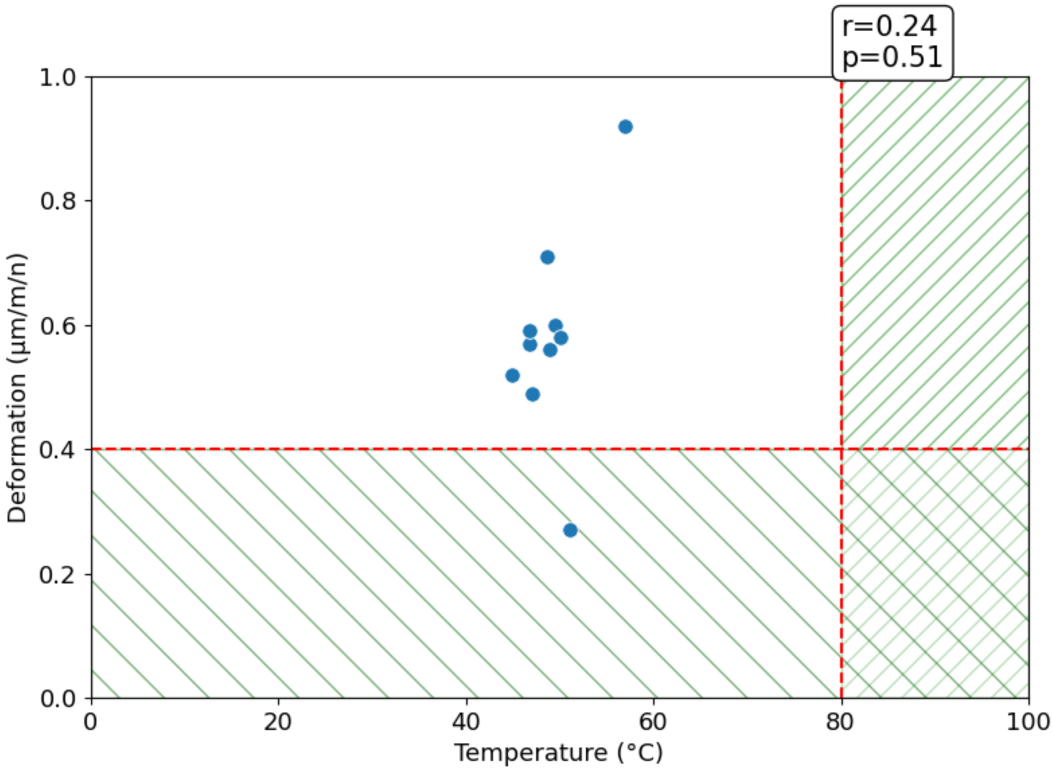

Figure 87: Scatterplot lowest compaction temperature vs deformation

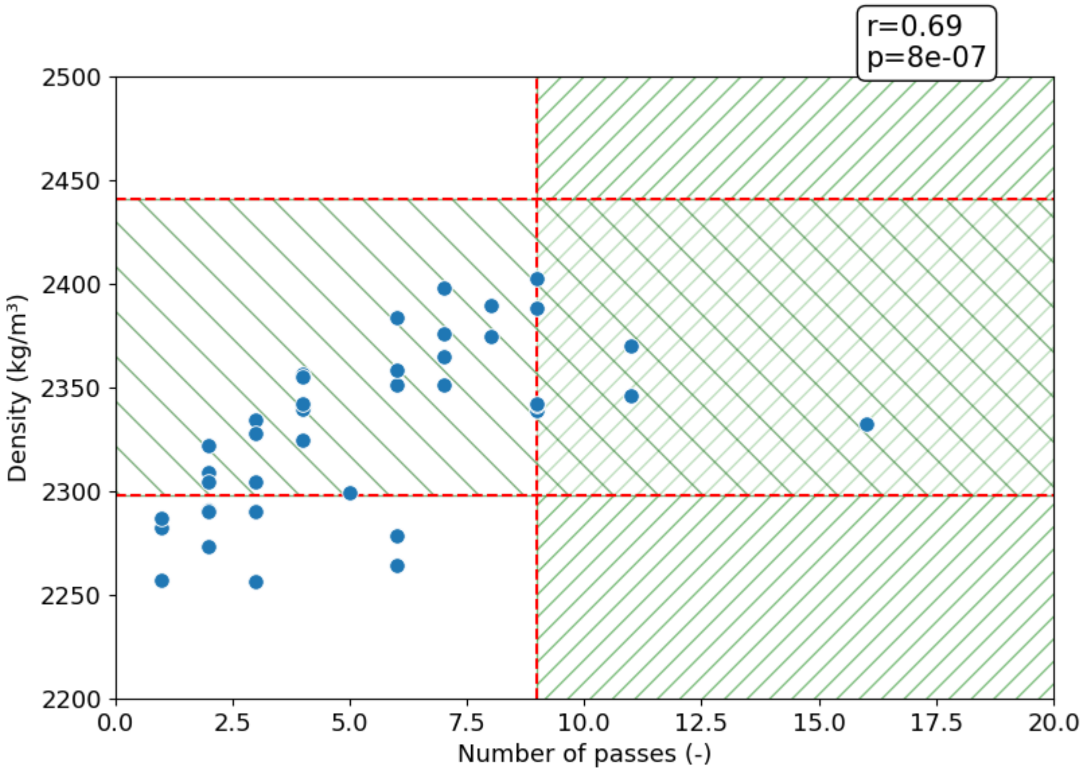

Figure 88: Scatterplot number of passes in TCW vs density

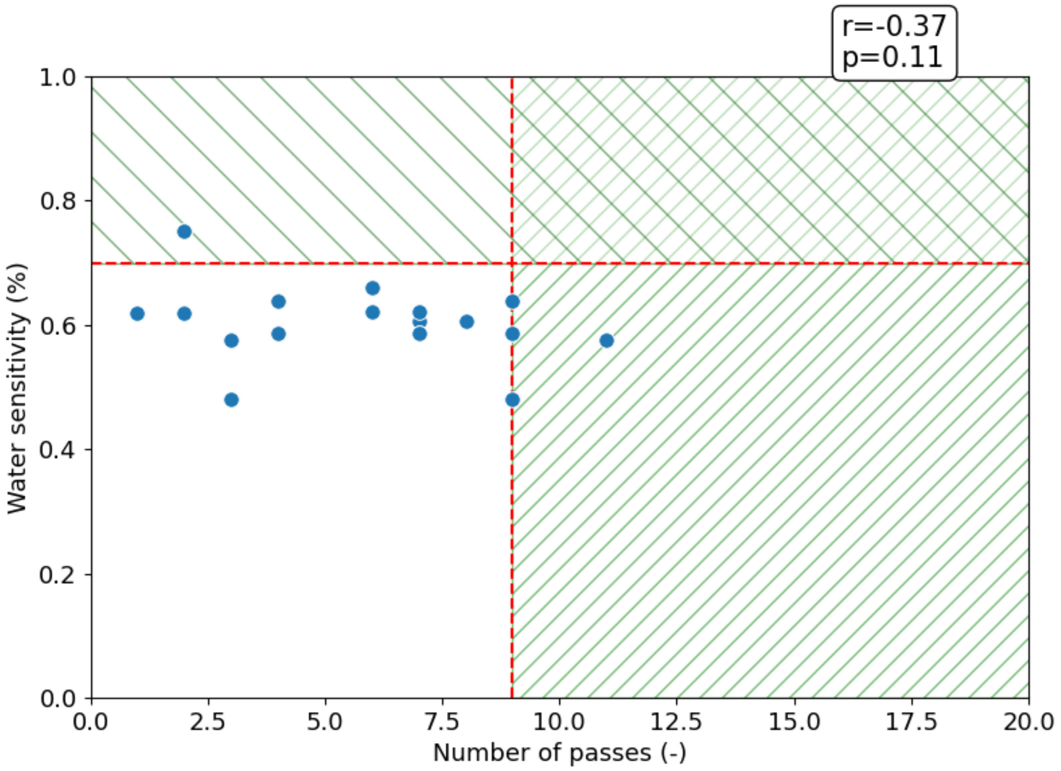

Figure 89: Scatterplot number of passes in TCW vs water sensitivity

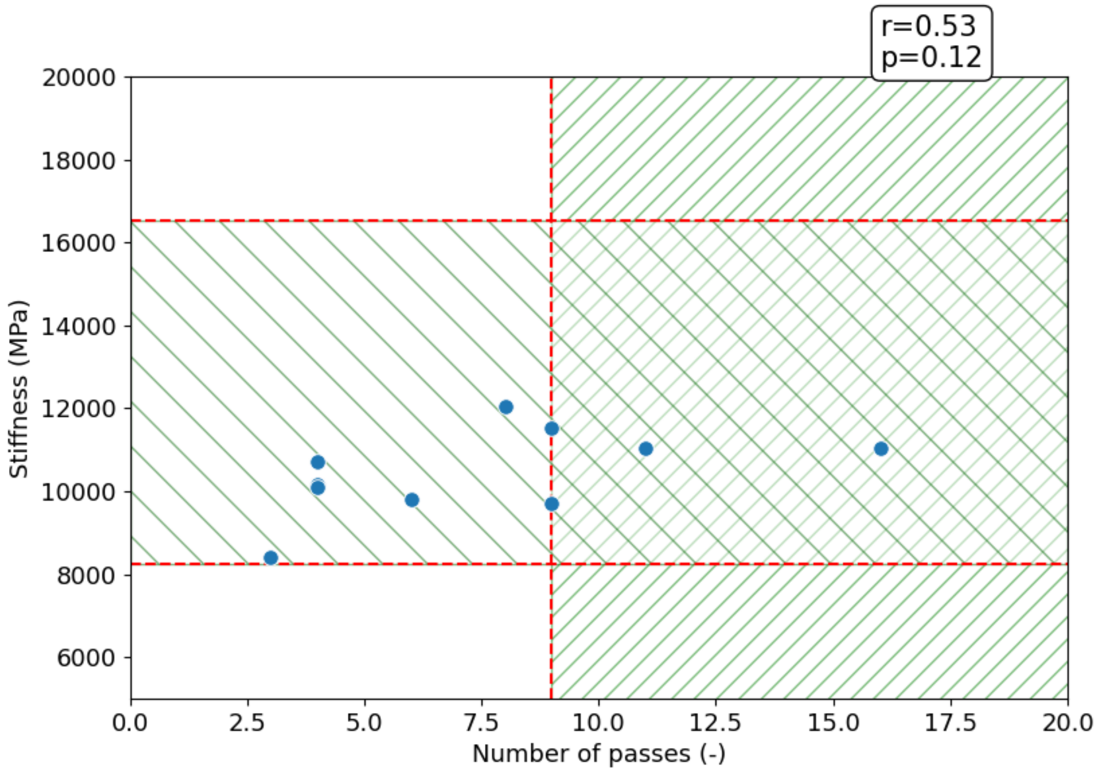

Figure 90: Scatterplot number of passes in TCW vs stiffness

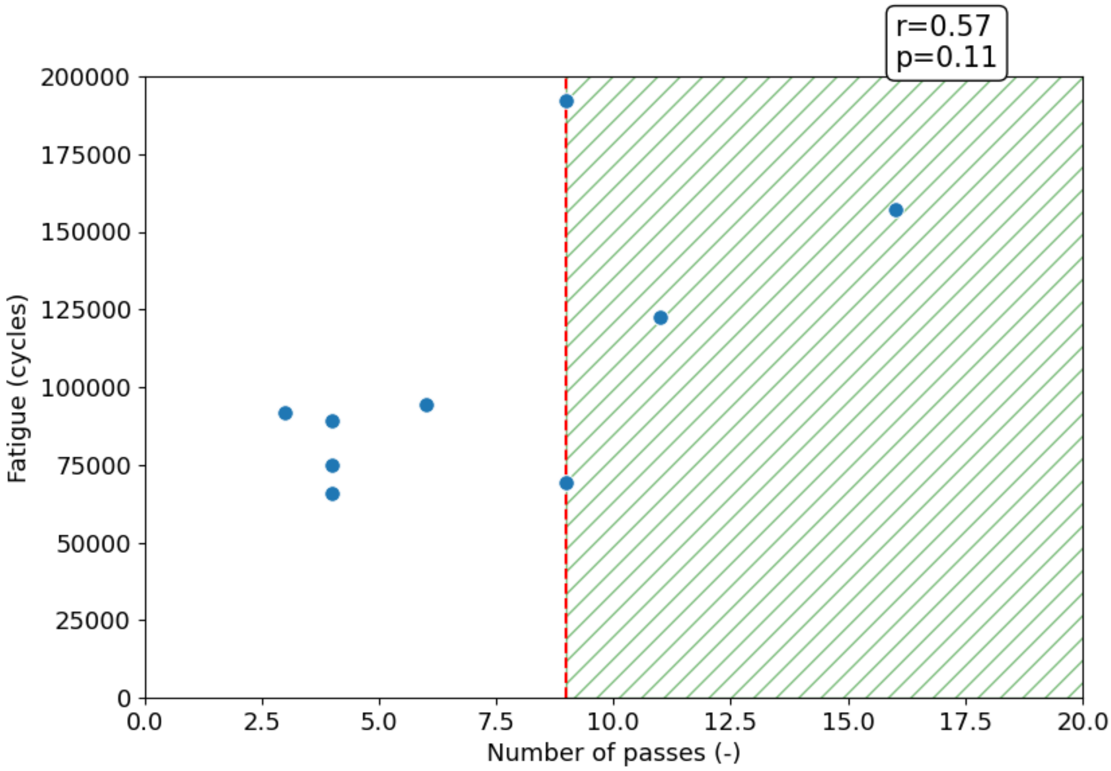

Figure 91: Scatterplot number of passes in TCW vs fatigue

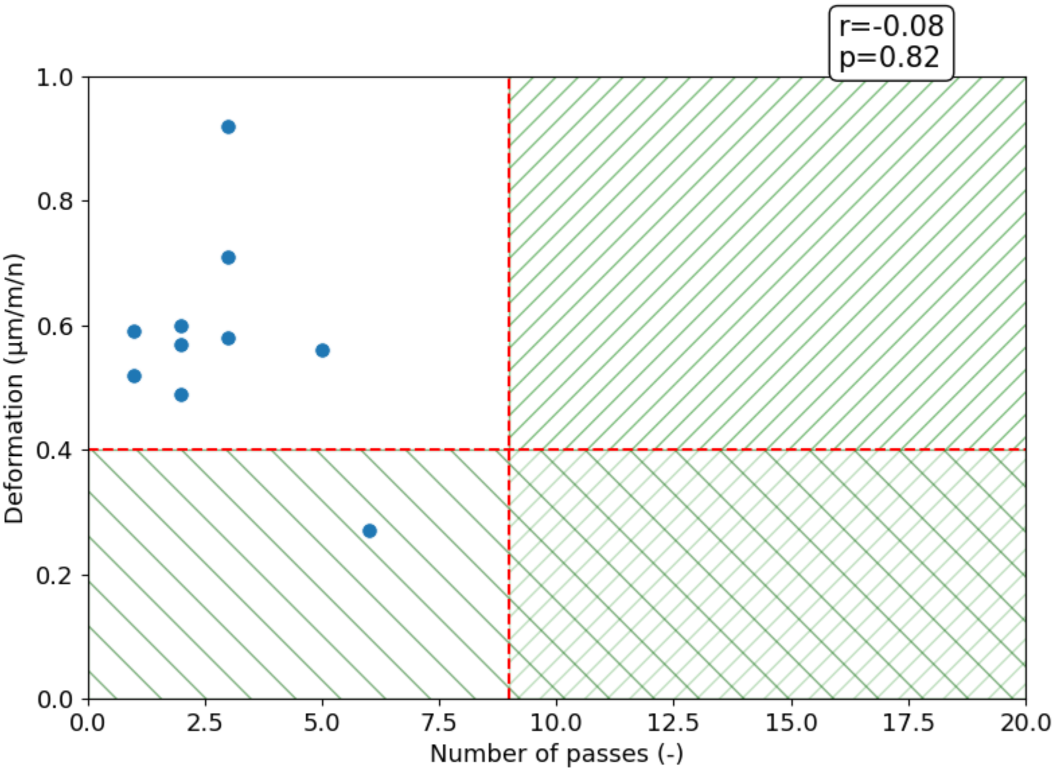

Figure 92: Scatterplot number of passes in TCW vs deformation

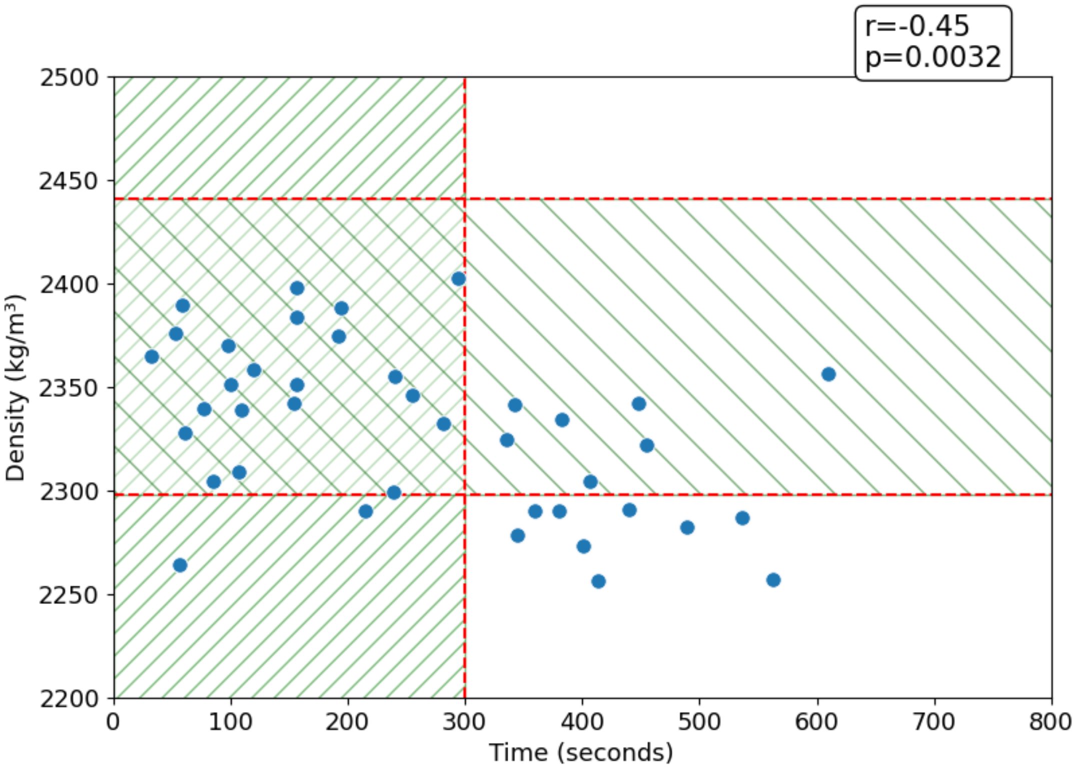

Figure 93: Scatterplot time between paving and first compaction pass vs density

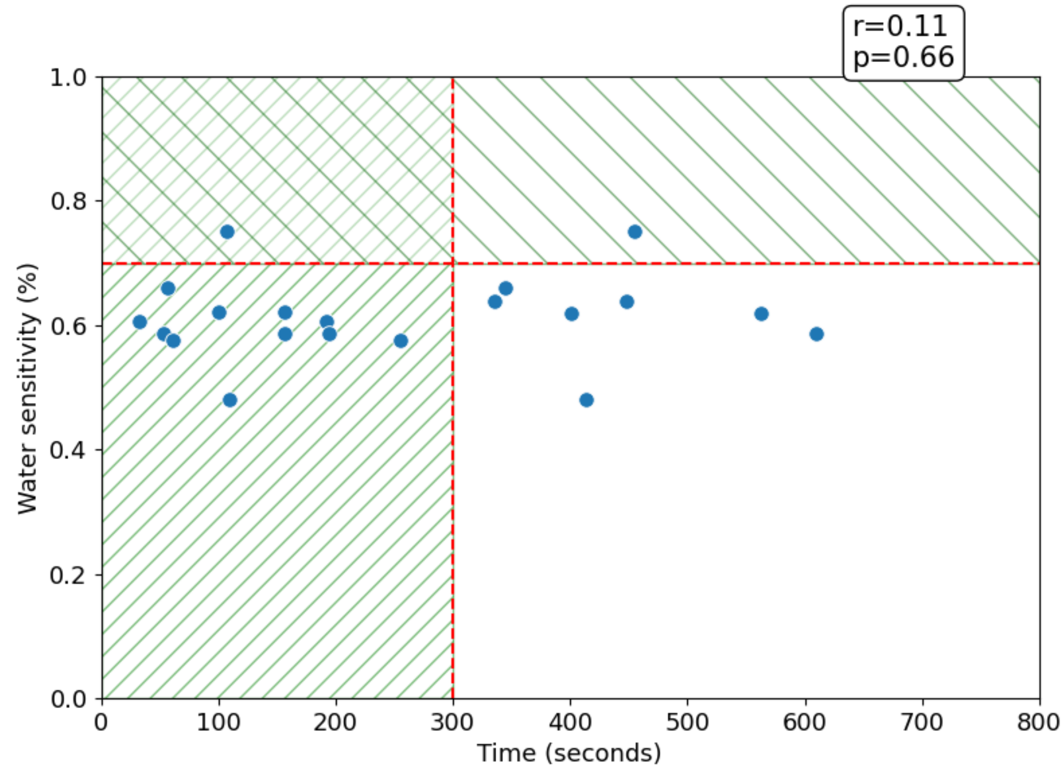

Figure 94: Scatterplot time between paving and first compaction pass vs water sensitivity

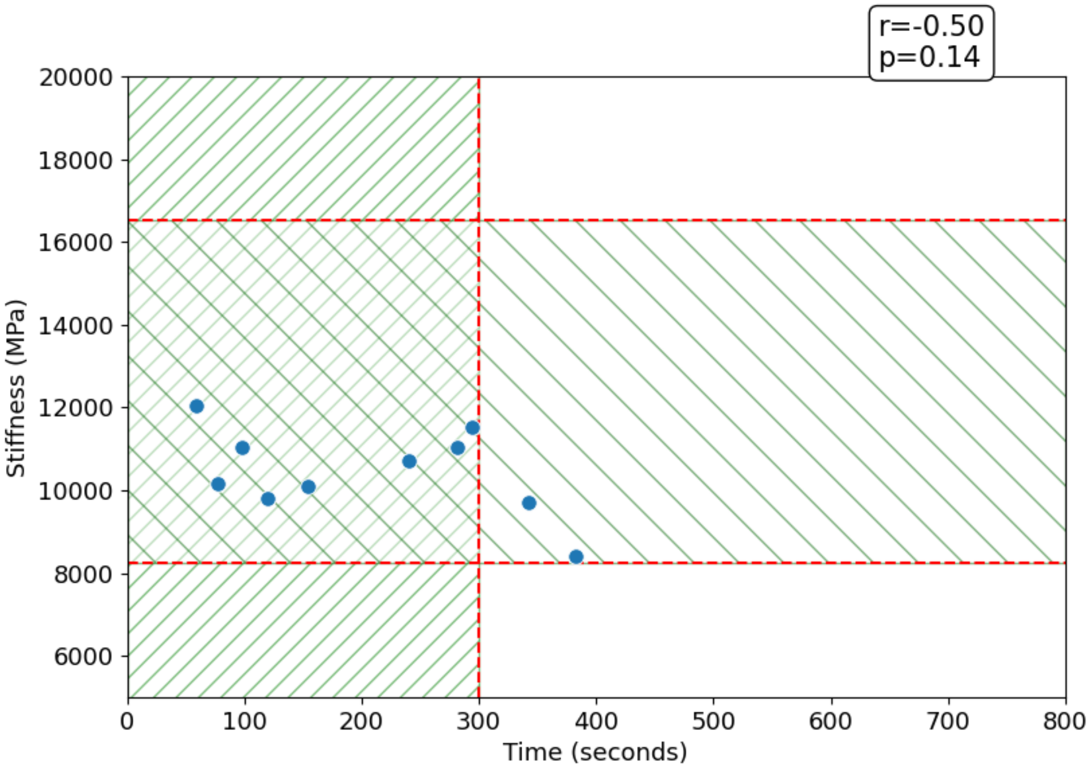

Figure 95: Scatterplot time between paving and first compaction pass vs stiffness

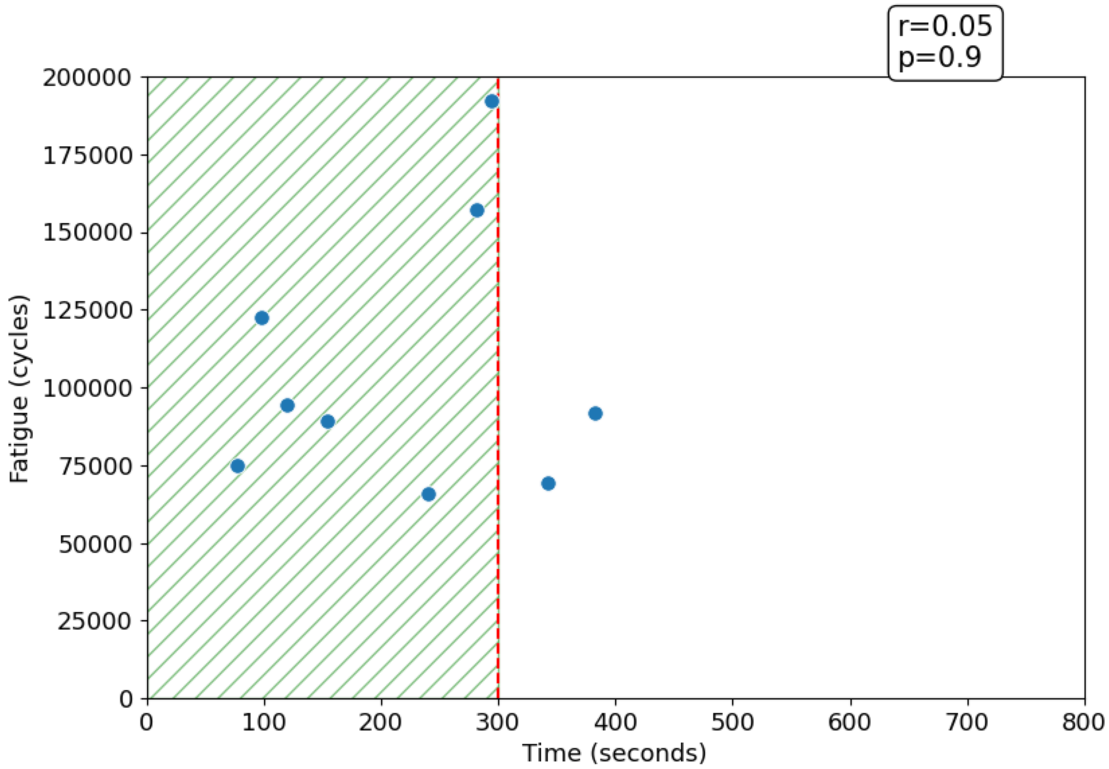

Figure 96: Scatterplot time between paving and first compaction pass vs fatigue

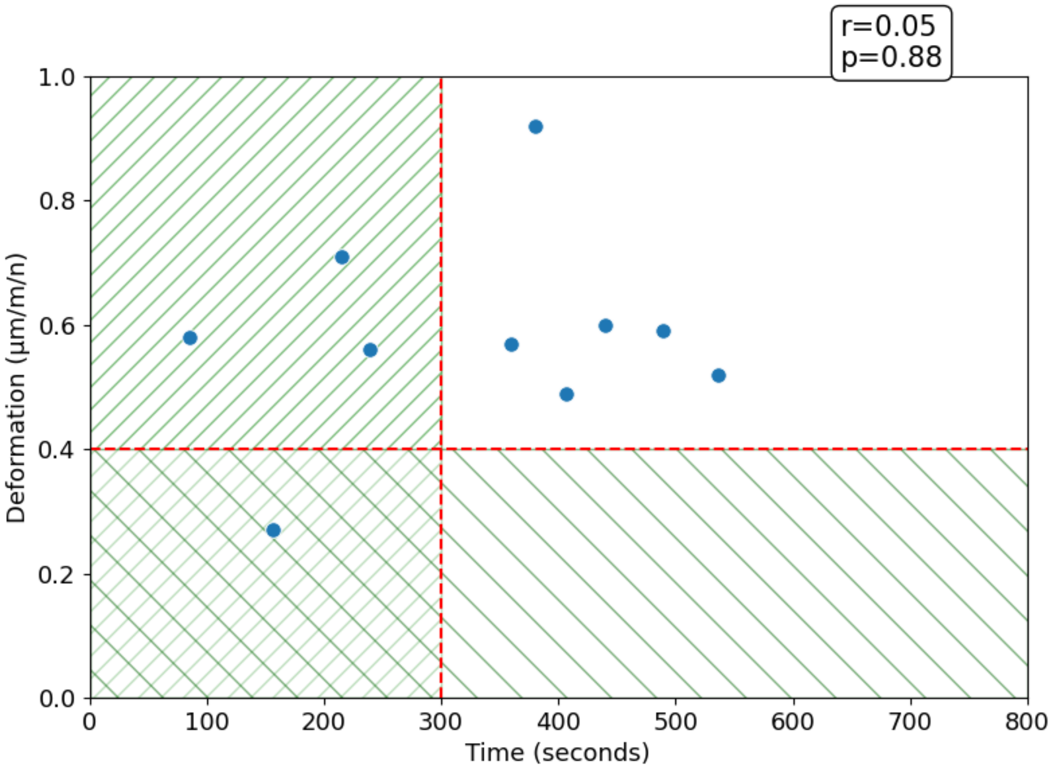

Figure 97: Scatterplot time between paving and first compaction pass vs deformation