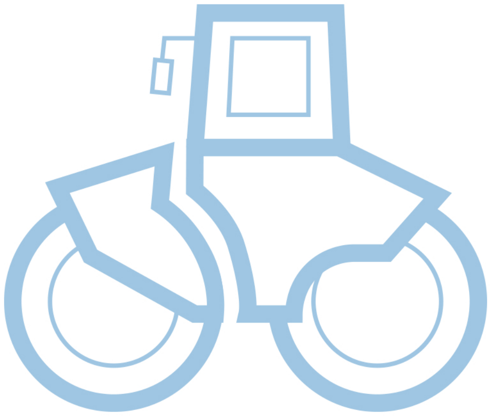


A methodology to design guided operational strategies for asphalt compaction

Priya Darshini Cheyyar Nageswaran

A methodology to design guided operational strategies for asphalt compaction

Final report

Priya Darshini Cheyyar Nageswaran

PDEng Trainee
ASPARi, Construction Management and Engineering
University of Twente
Enschede

November 2019

A methodology to design guided operational strategies for asphalt compaction

submitted in partial fulfilment of the requirements of the degree

Professional Doctorate in Engineering in Civil Engineering

by

Priya Darshini Cheyyar Nageswaran

ASPARi, Department of Construction Management & Engineering (CME)

Engineering technology (ET)

University of Twente

Examination Committee

Prof.dr.ir. A.G. (André) Dorée	Professor responsible chair, University of Twente
Dr. J.T. (Hans) Voordijk	Director PDEng program, University of Twente
Dr.ir. S. (Seirgei) Miller	Supervisor, University of Twente
Dr. ir. F. (Frank) Bijleveld	Committee chair (ASAPRi), Strukton Civiel
ir. N. (Natascha) Poeran	Committee member (ASPARi), Boskalis
Dr. ir. E. (Eyassu) Hagos	Committee member (ASPARi), KWS
ir. Michiel-Martijn Willemsen	Committee member (ASPARi), Heijmans
Dr. V (Vanessa). Magnanimo	External Chair, University of Twente

Acknowledgement

I would like to offer my deepest gratitude to the Ultimate consciousness (*Brahman*), which goes by several names and forms, through the Sanskrit verses below.

कृष्णाय वासुदेवाय, देवकी-नन्दनाय च ।
नंद-गोप-कुमाराय, गोविन्दाय नमो नमः ॥

To Krishna, to the son of Vasudeva, and to the [source of] joy of Devaki,
to the boy of the cowherd [chief] Nanda, to the benefactor of cattle, my humblest salutations.

I kept this chapter, probably like everyone else, to finish the last. I have thought of the names I have to add here over and over. To be honest, the list is too long. On realising this I was only quite overwhelmed and I am thankful for the same.

I would like to thank Prof.dr.ir André G. Dorée, Dr.ir. Seirgei Miller, Dr. Frank Bijleveld and ir. Natascha Poeran. My committee has been very kind and understanding in times of adversity. They always had the attitude of "How I can help you?". Although I am unsure if I had used this offer well, but I am quite thankful for this. This inspired me to also do the same to others. Also I would like to thank Rudi Dekkers, Peter van Hinthem, Eyassu Hagos, Michiel-Martijn Willemsen for your guidance.

Every person in the laboratories I visited right from the head of the laboratory to the lab technician who is not even directly involved in my project have helped me in one way or the other.

I would also like to acknowledge my colleagues Denis, Monik and Dieuwertje who helped me with my project, my draft and help me structure my presentations better.

I am very blessed to have met some amazing people in Enschede, a city which slowly grew on me. Thank you Elvia, Vignesh and Varun for supporting me through the tough times. Danny, you were too kind in helping me put this together.

My family even though far away have always showered their love, support and blessings for my well-being. Thank you *Amma* for motivating me always and Prasan for giving me my reality checks. Thank you *Athimber* and Kinu for going easy on me.

Executive Summary

The asphalt pavement construction process has been improving over the years with the advancing technology. Although new technologies are being used, the process of compaction still manages to be the "black-box" in the paving industry. Researchers publishing studies as recent as 2016, still call for more focus on understanding the same. It is hence quite a challenge that has been addressed in this design project to design guided operational strategies for asphalt compaction.

The project focuses on developing guided instructions for the roller operators and to simulate field compaction in the laboratory. A detailed study was made on the existing solutions in the industry, previous researches on making compaction explicit and laboratory simulation. On considering the requirements and stakeholder needs a methodology was designed to develop guided operational strategies for asphalt compaction.

The designed methodology covers the key aspects involved in asphalt compaction to develop guided instructions for the roller operators. These aspects are asphalt mixture, field compaction, laboratory compaction, and performance characteristics of asphalt mixture. When it comes to compaction, this is a wholesome approach in understanding the science behind the process. To have a set of guided instructions for the roller operators who work on the field it becomes very essential to use the already existing knowledge in field compaction which forms also an important basis in the project. In addition to this, using laboratory compaction not only helps understanding the compaction process in general but also adds value in the long run when new mixtures are prepared. Thus, with respect to compaction the field and the laboratory go hand-in-hand in helping the contractors realize the science behind it and in aid in developing guided instructions. Finally, as compaction directly affects pavement performance and durability, the understanding of the compaction behaviour is complete when the performance of the chosen mixture is tested for and analysed. This method was validated using an approach designed which includes all the above-mentioned aspects.

The tasks carried out to during the entire PDEng project is shown in Figure 1 also in Appendix D.

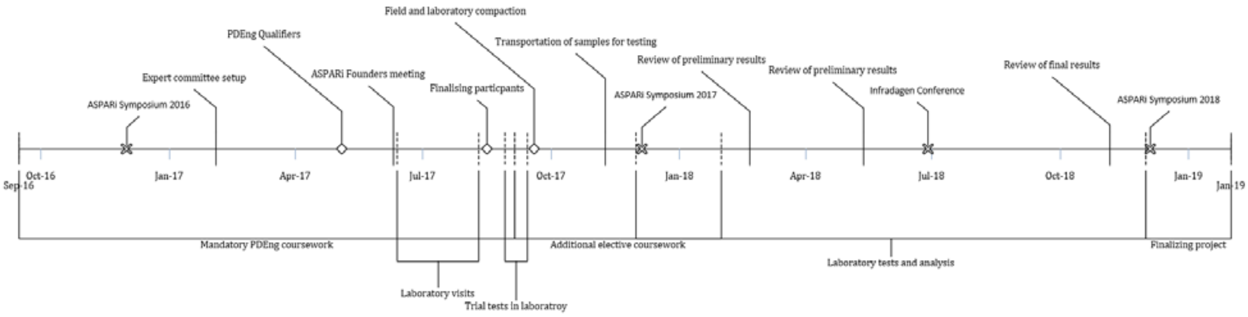


Figure 1 Timeline of the PDEng project

Apart from designing the methodology and an approach to validate the same, this project also gives insight into the practical aspects of the methodologies through the reflection and lessons learnt which adds value for the re-use of methodology itself.

The structure of the report is shown in

Table 1. Structure of the report

Design stages	Content	Chapter no.
Problem investigation	- Project context - Problem statement - Aim of the project - Introduction to design approach	**Chapter 1**
	- Studies on field and laboratory compaction - Requirements of the design	**Chapter 2**
Treatment design	- Designed artefact - Assumptions in the project - Designed approach to validate the artefact	
Treatment validation	- Validation of the methodology - Data collected from field and laboratory - Density - Indirect tensile strength ratio test - Triaxial cyclic compression test - Cyclic indirect tensile test - Compaction strategies	**Chapter 3**
	- An example of guided instruction	**Chapter 4**
	- Conclusions and recommendations - Reflection - Lessons learnt	**Chapter 5**

Methodology Summary

This is a comprehensive summary of the methodology designed in this PDEng project and how it meets the design criteria required for the PDEng design project. The criteria are: Functionality, Construction, Realisability and Impact. It is important to note here that the criteria mentioned in general considers an artefact which in general implies an 'object'. However, in this PDEng project it is not an object or product that was designed rather a methodology to design guided instructions or asphalt compaction.

1. Functionality

The functionality of the design project is described based on the aspects the satisfaction of requirements, its ease of use and repeatability.

The validation of the methodology designed was done based on an approach which resulted in guided instructions for roller operators and laboratory simulation. It meets the following requirements:

1. Utility: The compaction strategy for the chosen mixture was developed using the designed methodology. The strategies are clear, simple and technologically feasible. The design methodology itself is structured in such a way that it includes all aspects of laboratory, field and performance tests. Thus at the design level, a number of steps are involved in decision making, data collection and analysis. Thus, to come up with a clear strategy, these three aspects are to be matched well. The density outcome on the pavement and slab compactor can be evaluated only upon implementation of the strategy which is beyond the scope of the project.
2. Efficiency: The methodology incorporates two critical factors in this project and has the capability to include multiple factors in respect to compaction such as temperature, roller regime, compaction equipment, type of compaction and so on, to make the compaction process more explicit. The feedback system helps to incorporate new learnings upon the next use.
3. Reliability: The validation of the methodology shows that it can be used for a chosen asphalt mixture to develop compaction strategies. It is possible to define the type of mixture or mixtures. This methodology can thus be used to test a number of other mixtures.
4. Flexibility: The approach used in this project to implement this methodology is based on carefully chosen boundaries, the approach that needs to include the field, lab and test elements and assumptions. The same can be done by other contractors or researchers to develop compaction strategies.

The ease of use of methodology depends on the approach, mixture(s), and tests to be performed. The proposed methodology is easy to use as the contractors can choose their goals and set the approach accordingly involving the steps and components proposed in the methodology. As this methodology involves both field and laboratory compaction and is an iterative process, upon every use the knowledge on compaction and its effect on performance improves. All the contractor must do is to initially decide the asphalt mixture(s) and associated performance test. The contractors have lot of freedom with respect to the approach they follow to implement the methodology, to make choices whether the compaction is controlled in the field or in the laboratory and what are the important tests that validates the performance of the mixture in the field. This freedom is essential as there are a few decisions to be made in different stages of compaction. For example, to monitor compaction there are several options available. To simulate compaction in the laboratory the contractors can choose an equipment of their choice based on its availability and their experience. To monitor field compaction again, the contractors can use their available equipment. This way a contractor has freedom to choose from as they are already bound by a few limitations.

Repeatability of the methodology is feedback based. The domain here can be defined as compaction and the context as the asphalt mixture. In this case, the methodology can be used not only for one specific mixture but can also be extended to a family of mixtures under the same domain which is compaction.

2. Construction

The methodology is designed in a way to encompass the critical components to understand compaction in a step towards making the process more explicit. This was achieved through a series of discussions with the experts from the field, literature reviews and visits to pavement projects. The methodology has a clear hierarchy between different aspects such as field compaction, laboratory compaction and laboratory tests. Although including all three aspects might make the procedure complex, one can also see that the approach to implement this methodology is flexible. For example, the field and laboratory compaction can be done step-by-step process or simultaneously depending on the user. Even though there is freedom to choose the method of implementation, the methodology strongly binds the different aspects of compaction and has an iterative system in place for better learning on repetition. In addition to the designed methodology, the approach designed for validation deviates from the usual method of laboratory to field approach. Instead, in this design project the field compaction was monitored first and later was recreated in the laboratory. The methodology was tested using statistical difference making experiments on the approach designed.

3. Realisability

The methodology can be realised by making use of the already designed approach in this project or another user-defined approach to validate and implement the outcome of the methodology. The reflection and learning points from these projects can be used in the feedback loop of the methodology in order to choose for a new approach or design their own approach. Apart from the goals of the contractors with respect to compaction, the financial and practical aspects of monitoring projects, preparing slabs, testing samples play a major role in realising the artefact. The challenge here is availability of time and money. This project took at least one year with all the stakeholders involved. This way the resources were pooled together. To repeat the same in its entirety would require lot of resources in terms of man power and money.

4. Impact

The implementation of the compaction strategy itself on the field falls beyond the scope of the project. Although if implemented the industry is sure to be benefitted from learning the extent to which roller operators can use the guided instructions efficiently. This includes the learning about their ease of understanding and following the instructions, being able to adhere to the instructions and so on. It would also provide insights into the uniformity in density. The impact of the methodology itself with respect to understanding compaction and its effect on the performance characteristics and practical working has provided valuable lessons. The risk of combining the field and laboratory compaction along with testing of asphalt mixtures are:

a. Variability risks: With a proven existing variability in compaction in the field and amongst laboratory, trial tests were done prior to the actual data collection. Proper assumptions and boundaries were also set prior to the actual data collection, on choosing the reference for simulation in the laboratory, procedures to be followed in the laboratory and material and mixing procedure for the asphalt mixture chosen.

b. Time risks: To avoid running out of time there were always buffer time, especially for laboratory tests were planned-in. However, due to certain unfortunate series of events the final series of laboratory test still got delayed. It is also to be noted that in the very beginning proposal of this project, two sets of mixtures were planned to be tested. The initial committee meetings and trial tests, helped in understanding the time that would be taken to complete the analysis of one mixture. Thus, with due consideration it was then decided that only one asphalt mixture would be tested.
c. Non-availability of laboratories: With seven participants in the project and the plan to simulate the field compaction simultaneously in four different laboratories, the risk of non- availability of the laboratories were high for sample preparation and testing.
d. Budget risks: As the use of laboratories in the project were in-kind contribution amongst the ASPARi members, due diligence was done by visiting all the laboratories to take stock of the facilities available and costs each test incur. Despite this and because of the number of participants, budget problems still existed.

Contents

List of Figures

List of Tables

1 Introduction

Compaction is a critical and complex process (BOMAG GmbH 2009; Indian Roads Congress 2013; Nikolaides 2014; Thom 2014). The road-engineering world is aware of it and the scores of researches done on compaction and its various effects on pavements is a solid proof of the same. The compaction process being the final phase of road construction, when done properly, ensures good durability and service life of the roads. It is affected by a number of factors such as temperature of the asphalt layer, type of asphalt mixture, environmental conditions, compaction equipment and so on (BOMAG GmbH 2009; Lavin 2003; Miller 2010; Nikolaides 2014). Thus, different mixtures require different strategies for compaction.

Adding to this complexity, the practice of compaction is largely based on experience of the roller operators (Bijleveld 2015; Heurne 2004; Miller 2010; Vasenev 2015). This implicit knowledge makes it tough for the roller operators to help others understand the rolling pattern or roller regime adopted on the field. The knowledge transfer among the roller operators is limited as only few things are tangible and translatable through written instructions. This difficulty of having implicit knowledge and the importance of compaction for a durable pavement makes it essential to develop a methodology to design guided operational strategies resulting in consistent compaction.

In order to understand the compaction process and to predict field compaction of specific mixtures accurately, simulation of compaction is carried out in the laboratories. Design procedures and pavement specifications are also derived from laboratory compaction of asphalt mixtures (Muniandy et al. 2008). This is essential to aid the process of determining the pavement performance. Several compaction methods are used in the laboratory such as impact, gyratory, vibration, and rolling compaction. Various methods of compaction results in mechanically different specimens (Plati, Georgiou, & Loizos, 2016). These methods ultimately aim to simulate field conditions with respect to air voids, density, and mechanical properties.

The importance of the compaction process in the field and laboratory is a major driving factor in this PDEng design project. This project makes clear the need to make the compaction process explicit through monitoring existing compaction procedure used and simulating them in the laboratory. This project takes on the existing challenges in compaction and provides solution from a design perspective based on which this report is structured.

1.1 Background

ASPARi research group is a collaboration between researchers of the University of Twente and several road contractors in the Netherlands. These contractors include BAM Infra, Ballast Nedam, Boskalis, Dura Vermeer Infrastructuur, Heijmans Infra, KWS, Roelofs, Strabag, Strukton Civiel, and Twentse Weg –en Waterbouw. Of these 7 contractors – Ballast Nedam (DIBEC), Boskalis, Dura Vermeer Infrastructuur, Heijmans Infra, KWS (Infralinq), Roelofs (AKC) and Strukton Civiel – were part of this project. This research project covers two main aims of the Asphalt Paving Research and innovation (ASPARi) Roadmap 2020: to develop strategies that will support roller operators achieve a more consistent compaction product and strategies for achieving specified end-quality parameters (for specific asphalt mixes and circumstances) (ASPARi 2014). The project focusses on two major challenges involved in compaction – process variability including its effect on mechanical properties and laboratory simulation of compaction.

The variability in compaction process is one of the biggest challenges in pavement construction as it has direct effect on the serviceability of the pavements (Bijleveld 2015; Miller 2010). For a better understanding of the compaction process numerous technologies are being used (Ghafoori Roozbahany, Partl, and Guarin 2017; Inc 2018; Kassem et al. 2016; Miller 2010; Timm et al. 2001). Secondly, laboratory simulation of compaction is critical to understanding field compaction as this is used in predicting pavement performance based on compaction and setting target densities for mixtures. A number of studies (Airey and Collop 2016; Plati, Georgiou, and Loizos 2016; Wistuba 2015) explores the closeness of field compaction in the laboratory with specific properties such as stiffness, deformation, air void content, and so on as validation parameters.

1.2 Problem Statement

The road construction process is divided into the following four phases: production phase, transportation phase, laydown phase and the compaction phase. The final compaction is an important phase, where the roads are compacted to achieve stability and to avoid deformation under traffic loads. Compaction has a direct effect on the service life of the pavements (Dubois, Roche, and Burban 2010; Masad et al. 2016).

Significant changes are occurring in the pavement construction industry which encourages the contractors to adopt improved operational strategies. Increased guarantee period, new competitors and demand for better pavements have pushed contractors to focus on process improvement. There is a huge gap between the on-site construction process and laboratory practices in asphalt construction process because this is hugely based on implicit (tacit) knowledge (Bijleveld, 2015). Given that the compaction of asphalt roads (hereinafter referred to as road/pavement) relies more on experience of the roller operators which leads to great variability in the construction process, the need to come up with definitive guided strategies is high. This is true especially in the case of compaction process.

Although a lot of attention has been on intelligent compaction and analysing the output (Hu et al. 2017; Liu, Lin, and Li 2016; Neff 2013; Xu and Chang 2013; Xu, Chang, and Gallivan 2012) its impact on the instructions for the operators has been limited. The roller companies like BOMAG have their own compaction guides, which extensively talks about principles of compaction, machine technology, factors influencing compaction and so on (BOMAG GmbH 2009). These guides do not address any specific kind of asphalt mixtures and the strategies to be used for consistent compaction. A book in the series by VBW asphalt, (VBW Asfalt 1989), which addresses the issue of compaction in practice, again gives in detail mathematics and technicalities of compaction. This certainly helps to understand the basics of the working of compaction but fails to instruct the roller operators on how to move on with this information to implement it in practice.

Countries like the USA and India which have very large road networks also lack the information. The book, Rolling and Compaction of HMA pavement, from a series on pavement construction published by National Asphalt Pavement Association has illustrated the rolling techniques clearly. This includes factors critical to compaction and rolling techniques. The downside is that this addresses a very wide range of mixtures and hence the temperature window of rolling is also wide which leads to the experienced operators to make the final decision on compaction. The guidelines on compaction equipment for road works which is commonly used in India (Indian Roads Congress 2013) gives information on starting and minimum temperature and the pattern of rolling but does not give additional information on the number of passes or time taken. Also, all these guidelines try to streamline the process itself, this information is already generally available as a thumb rule for hot mix asphalt or dense asphalt which includes many mixtures which have their own properties and target densities to meet.

Several factors must be considered for optimal pavement compaction such as temperature of the asphalt layer, number of roller passes, type of aggregate, environmental condition, etc. With hundreds of asphalt mixtures in use and many factors to be accounted for, the roller operators lack guided operational strategies for asphalt compaction. The operational strategies in a pavement construction involve selection of equipment and working methods that affect asphalt quality parameters.

Thus, this project takes a design approach to help in developing guided operational strategies for compaction. The designed methodology would aid in providing the roller operators a set of guided instructions for optimal compaction of asphalt pavement and understand the science behind the compaction process better.

1.3 Aim of the project

The aim of this project is to develop strategies that help to achieve consistent compaction and maintain the quality of the paving asphalt roads. Since there are hundreds of asphalt mixtures available, a specific mixture which fits in the timeline of the post-master project and that which is of high importance for roller operators and contractors was chosen. The mixture chosen for this project is $AC11_{surf}$. This decision was made based on the following factors: a surface mixture, commonly used in the Netherlands, challenging with respect to compaction (often under-compacted) and the time limitation of the project itself. Thus, the objectives of this project are to:

i. design guided compaction strategies for asphalt mixtures and;
ii. design laboratory protocol for simulating on-site compaction in the laboratory.

1.4 Outline

As a design project it becomes imperative to take an appropriate approach towards developing an artefact for the identified problem. In this case the artefact designed is for the contractors and the ASPARi researchers to have guided instructions for the roller operators. The solution provided to the problem posed is a methodology designed to obtain guided instructions for roller operators for a more consistent compaction. In order to design the same, the problem-solving approach used in the project is the use of a design cycle. The design cycle, as defined by (Wieringa 2014), is part of a larger cycle, in which the result of the design cycle—a validated treatment—is transferred to the real world, used, and evaluated. The constituents of a design cycle are shown in Figure 2.

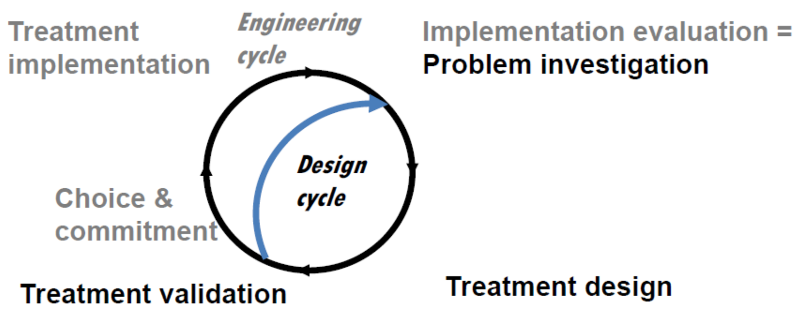


Figure 2 - Image highlighting the design cycle which forms a part of engineering cycle (after Wieringa 2016*).*

The chapters of this report answer the questions as shown in Table 2 which were framed based on the design cycle.

Table 2 - Outline of the report.

Design cycle	Questions answered	Chapter no.
Problem investigation	- What is the project context? - What is the problem context? - What needs to be improved? - What is the approach towards problem-solving?	**Chapter 1**
	- Who are the stakeholders? What are the stakeholder goals? - What are the phenomena? - What research has been done about this?	**Chapter 2**
Treatment design	- What is the new design? - What are the requirements of the design? - What are the context assumptions? - What is the approach to use the design?	
Treatment validation	- What is the evidence to show the proposed design would solve the problem? - How was the evidence evaluated?	**Chapter 3**
	- What is the outcome of the evaluation? - What are the learnings from the validation?	**Chapter 4**

2 Problem investigation and methodology design

In problem investigation, the aim is to identify, describe, explain and evaluate the problem to be treated (Wieringa 2014). From Chapter 1, it can be understood that the roller operators lack clear methodological instructions for optimal pavement compaction. Thus, the aim is to provide them with guided operational strategies for compaction. During the problem investigation step, the stakeholders are identified. The stakeholders involved in this project and their goals are listed in Table 3. The stakeholders were identified based on the list given by Ian Alexander as mentioned in (Wieringa 2014).

Table 3 - Stakeholders and their goals.

Stakeholders	Goals
System under Development 1. Roller operators 2. Paving team 3. Project managers at road construction companies 4. Quality control and assurance	1. Instructions that are simple, direct and non-intimidating 2. Same as 1. 3. Need clear strategies for optimal compaction 4. Consistent compaction
Immediate context 1. Road construction companies (ASPARi member companies)	1. Optimal compaction and long-lasting pavements; Successful strategy implementation; cost effective and safe practices
Wider context 1. Rijkswaterstaat 2. Competitors (non-members of ASPARi) 3. Environmentalists 4. Road maintenance personnel 5. Personnel from roller operator training institutes 6. Personnel from regulations department 7. Road users	1. Durable and long-lasting pavements 2. Failure of strategy 3. Sustainable practices needs to be implemented 4. Long maintenance intervals and reduced maintenance works 5. Easily trainable and understandable strategies 6. The standard rules and regulations for road construction is followed and not broken 7. Smooth roads with less disturbances (maintenance and otherwise)
Involved in development 1. ASPARi researchers 2. University of Twente 3. Select members of ASPARi directly involved in the project	1. Developing strategies that can be implemented; explicit strategies 2. Successful design project 3. Same as 2

With the stakeholder goals made clear, an overview of the recent field and laboratory researches on compaction is made. This, in combination with the current solutions identified in Chapter 1, was used to design an artefact for the problem.

2.1 Field and laboratory compaction studies

In asphalt pavement construction the final phase – compaction, is the given utmost importance. This is so because compaction influences the service life of the pavement. Several factors affect compaction. They are as follows (BOMAG GmbH 2009; Indian Roads Congress 2013; Nikolaides 2014):

1. Aggregate material: The size, shape, and texture of the aggregates directly influence the ease with which the asphalt mixture can be compacted.
2. Bitumen grade and compaction temperature: Each type of bitumen used in the asphalt mixture has different hardness and viscosity. The harder the bitumen used, the more difficult it is to compact. Thus, such bitumen containing asphalt mixtures need to be compacted at higher temperatures.
3. Environmental conditions: The ambient temperature, wind speed, possibility of rain/snow during compaction affects the process of compacting. High wind speed and low ambient temperature shorten the time available for compaction.
4. Layer thickness: It affects the ease of attaining the desired degree of compaction. The thicker the layer, the easier it is to attain the desired degree of compaction.
5. Compaction equipment: The type of rollers used for compaction also affects the amount of compaction. The number of roller passes and the type of roller pass (static or dynamic) depends on the type of asphalt mix, the thickness of the layer, type of roller, weight of the roller, temperature of the asphalt layer and ambient temperature.
6. Compaction procedure: The way the roller operates also influences compaction. Rolling procedure includes the number of passes, speed of the roller, time between passes, roller type and so on.

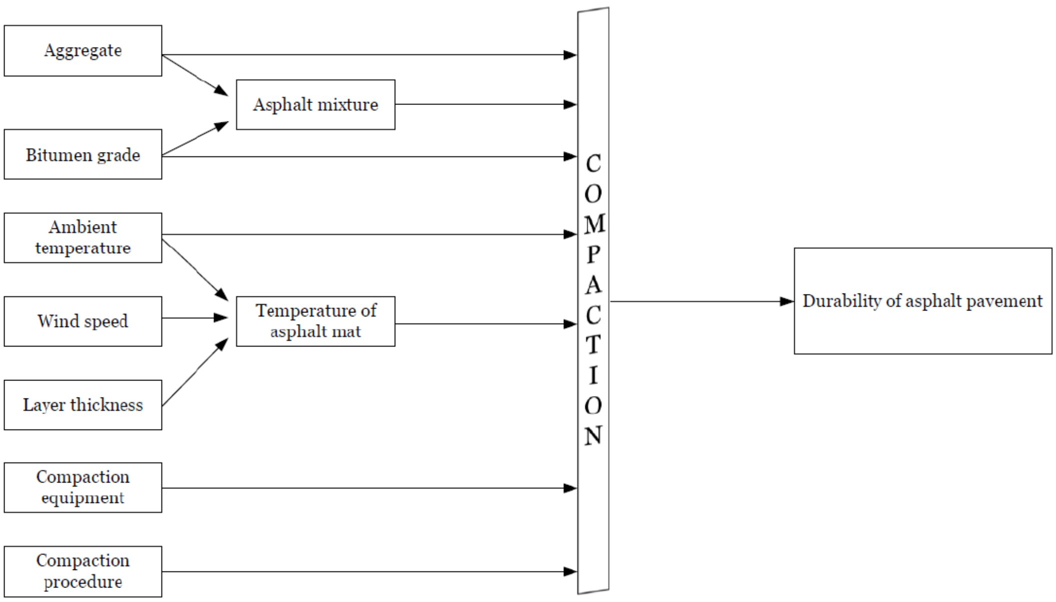


Figure 3 - Factors influencing compaction process (based on Nikolaides, 2014*).*

The influencing factors shown in Figure 3 are the textbook factors which are known to affect compaction. Although what the roller operators face during everyday compaction of the pavements is more, such as last-minute planning mishaps which could be carried over from the previous construction phases and others. A very critical factor that affect uniformity of compaction is implicit knowledge. It is critical because, a number roller operators working on a general thumb rule as mentioned in the introduction, directly affects the uniformity of the pavement.

In a workshop conducted during the research by (Heurne, 2004) a key problem identified while developing a model that shows undertaking roadwork under severe weather conditions was knowledge problem. As the final compaction level was identified as the key factor determining the quality of the paved road, it was also acknowledged by the participants that there were insufficient procedures for roller operators. These studies thus clearly show the implicit nature of compaction and the steps being taken towards making the same explicit. In addition, this emphasises the need for having instructions for roller operators in order to minimize the variabilities observed during the compaction process.

Through the research conducted by (Miller 2010), the significant variability in the HMA construction process was made evident through diligent monitoring of temperature of the asphalt layer, movement of the pavers and rollers, density a number of pavement projects. The visualisation such as those shown in Figure 4 of monitored data made the behaviour of the operators more explicit.

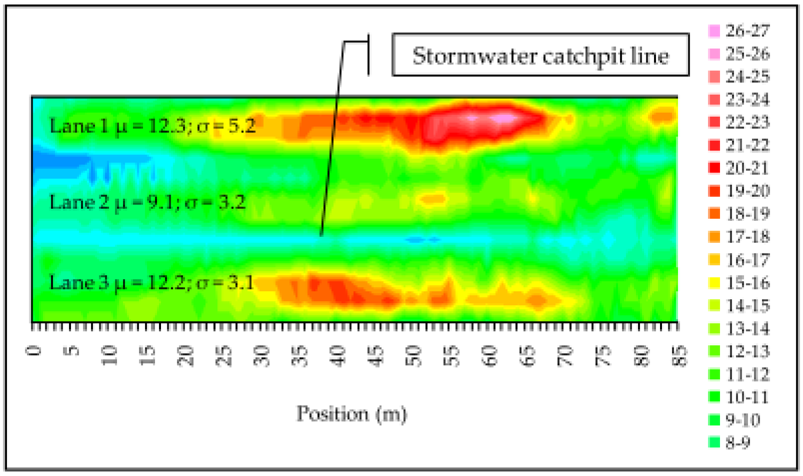


Figure 5.18 - Compaction Contour Plots for Project 2 (2nd Phase Study)

Figure 4 - Image of Compaction Contour Plot (after Miller 2010*).*

Monitoring and visualization of these data, especially with respect to compaction process, revealed a number of variabilities taking place during the compaction process of which the variation in compacting temperature and rolling pattern across the pavement are important. This is so because it affects the roller operator's attempt to reach the target density which are usually spot measurements using nuclear density gauges.

The Process Quality improvement (PQi) cycle (Miller 2010),used by ASPARi, helps to observe, record and reflect on the asphalt pavement construction process. This in turn helps in controlling the variability and improve the pavement construction process. Although the PQi cycle makes the construction process explicit it still does not completely explain the reasons for certain practices carried out on-site or the performance of the pavement thereafter. To completely understand this, it becomes necessary to combine the monitored data with the performance characteristics of the asphalt mixtures upon compaction.

Another key research that addressed the need to making the pavement construction process more explicit is that by (Bijleveld 2015). This research approaches the issue from technological, laboratory and operator perspective. Upon implementing the PQi method in order to improve the construction process, not only was the variability during the construction process re-established but also the need to implement the essential monitoring process to understand these variations. This research also goes a step ahead to link the field and laboratory methods with the final mechanical properties of the asphalt mixtures. From this it was determined that the current procedures undertaken in the laboratory to set the compaction temperature affects the performance of the pavement. This is mainly due to the difference in approach towards the compaction process in the field and the laboratory. This reiterates the need for proper simulation of compaction in the laboratory.

The importance of laboratory simulation of compaction process and the need for making the compaction process explicit has resulted in several studies in this direction. The need to predict pavement performance of specific mixtures in a controlled and less time consuming (Muniandy et al. 2008) environment is also one of the key reasons for this. For laboratory simulation of compaction, gyratory, vibration or slab compactor (also known as roller segmented compactor) are commonly used. A number of studies have been made to understand the influence of laboratory and field compaction on performance characteristics of the asphalt mixture using the above mentioned compaction machines (Airey & Collop, 2016; Mollenhauer & Wistuba, 2016; Plati, Georgiou, & Loizos, 2014). Apart from the differences in the performance characteristics of the field and laboratory compacted specimens, these researches also show that there are differences within the various methods of the laboratory compaction methods itself.

In the study conducted by (Mollenhauer & Wistuba, 2016) on determining the influence of asphalt compaction procedure on 3D deformation properties, the laboratory compaction was conducted using different procedures namely, impact compaction, gyratory compaction, pneumatic tyre, and smooth steel roller compaction. It was found that the 3D deformation properties of field compacted samples were better represented by roller-compacted specimens.

In a study conducted by (Plati et al., 2016) the influence of different roller compaction modes on the performance of asphalt concrete (AC) mixtures was investigated. A new asphalt construction project was monitored. A laboratory simulation of the monitored compaction was aimed at using different compaction modes by a steel roller (slab) compactor. The roller compaction modes were, static, vibratory and a combination of both. Asphalt cores from the field and laboratory were extracted and their air void content and stiffness were compared. These comparisons were made based on the compaction temperature, effort (number of passes) and compaction mode. Upon comparing the field and laboratory cores on the air void content and stiffness of open graded mixture it was found that the compaction modes were statistically identical to the field cores.

In the report by (Wistuba, 2015) on the German segmented steel roller compaction method the segmented roller compaction method represents the best the engineering properties of the field cores. This method closely represents the air void distribution, particle distribution, particle orientation, and performance properties. The author concludes that this is the most appropriate method to simulate field compaction.

In the study by (Airey & Collop, 2016) the influence of laboratory compaction methods on the aggregate orientation, segregation, stiffness modulus, permanent deformation, and fatigue was analysed. Four types of asphalt mixtures were tested and three methods of laboratory compaction – gyratory, vibratory and slab (roller) compactor were compared to the results of field compaction. The author concludes that in terms of particle arrangement and mechanical properties, slab compacted specimens tend to show close correlation with field cores.

The field compaction studies clearly highlight the variation in field compaction due to the implicit nature of compaction thus far. Similarly, the laboratory studies highlight the variation between different compaction methods and that the roller compaction tends to represent the field compaction the most in the laboratory.

2.2 Requirements

The designed artefact, methodology, has certain requirements based on the goals of the design project and stakeholders involved. These requirements are:

1. Utility: The designed methodology should be able to provide develop compaction strategy for specific mixture or family of mixtures chosen. This strategy should include the following:
    a. Consistency in compaction (uniform density): The compacted roads shall have a uniform specific density for the chosen mixture.
    b. Easily trainable/understandable: The new operational strategies shall be easily understandable by roller operators and easily implementable. The strategies are clear for the roller operators thus reducing intuitive construction process. The strategies adhere to the existing rules and regulations in terms of safety, construction and environment requirements.
    c. Simulate compaction in laboratory: The strategies shall enable the on-site construction process to be imitated in the laboratories with ease.
    d. Technologically feasible: The roller operators and the laboratory should be able to use and implement the technological aspects if any.
2. Efficiency: The methodology must be able to incorporate multiple factors (or a few in specific) with respect to compaction such as temperature, roller regime, compaction equipment, type of compaction and so on to make the compaction process more explicit.
3. Reliability: The results of the methodology should be reliable to be used for compaction of different asphalt mixtures and in making compaction process explicit upon its usage.
4. Flexibility: The stakeholders must be able to implement the methodology at their own pace based on the goals set for their vision for compaction.

2.3 Designed methodology

To meet the challenges, requirements and stakeholder goals with respect to compaction, a methodology was designed, shown in Figure 5. The design was developed keeping in mind the number of challenges faced during the pavement construction process. A holistic approach was attempted by addressing the key elements such as being specific about the asphalt mixture. As different mixtures are compacted differently, the first step would be to choose a specific asphalt mixture. Then the critical proposal here is to start from the field and then to take it to the laboratory. The reason for this is to monitor the actual practice that takes place outside to keep it close to reality. This process is then simulated in the laboratory to identify where more elements can be controlled. It is important to note that it is also possible to start from the laboratory and later monitor in the field. These two actions are placed on the same level to imply that one can choose either to start in the field or in the laboratory. It can be done simultaneously or in steps based on the requirements of the contractors. The samples from the field and the laboratory can then be tested for their mechanical properties. The tests depend on the type of asphalt mixture chosen.

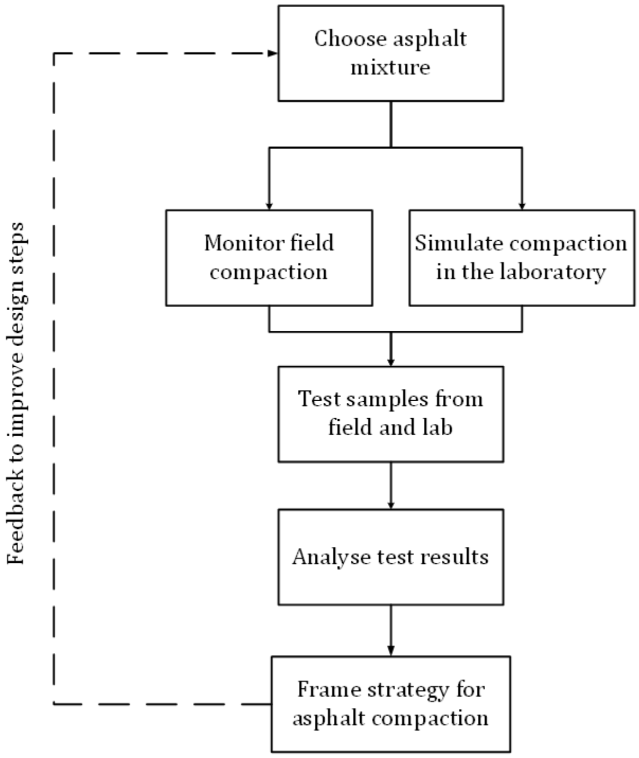


Figure 5 - Methodology designed to develop guided strategies for asphalt compaction.

The test results could then be analysed to understand the best practices in the field based on the performance characteristics. Similarly, a comparison between the field and laboratory can be made based on procedural and performance results, which would give insight into the effect to which simulation can be done. The results of the analyses will help in developing strategies for guided instructions and simulations in the laboratory. The design is developed in such a way that there is scope for improvement through feedback.

2.4 Assumptions and approach

2.4.1 Assumptions and boundaries in the project

In order to validate the designed methodology an approach to use the methodology was developed. This was done based on advice from the experts and trial tests made in the laboratory, the details of which can be seen in Appendix B. The attempt to make the compaction process explicit is a very big gap to bridge and this project is only the first step towards it. Thus, there are few points that are to be realised in case of this project.

1. The mixture that will be tested in this project – $AC11_{surf}$. The premises on which these were chosen were based several factors and consciously set limitations:
    a. It was decided to test the surface mixtures.
    b. It was decided to test dense mixture.
    c. Mixture that is commonly used in the Netherlands.
    d. Mixture that pose challenges with respect to compaction, here, being under-compacted.
    e. Mixture that does not include polymer modified bitumen.
    f. The entire time allotted for the project itself is 2 years thus limiting the amount of work that can be done to reach the goals of the project.

It can still be argued that there are other mixtures which would fit these framework or those which could be more important for certain contractors/researchers for several reasons. But it is more important to start the project based on availability of the mixture.

2. The most critical factors for the chosen mixtures were identified as temperature and energy input.
    a. **Temperature:** For any given asphalt mixture, it is known that temperature plays an important role for compaction because of the behaviour of the materials in the mixture on change in temperature.
    b. **Energy input:** The compaction process also highly relies on the energy input on the mixtures by the roller. This can further be divided into three criterion – type of energy, magnitude and time.
        i. The type of energy input, static or dynamic, is important. In this project, for $AC11_{surf}$ dynamic compaction is generally done to reach the target density.
        ii. The amount (magnitude) of energy input which also depends on the type of roller used is important.
        iii. The type and amount of energy must be put in at the right time on the mixture without any time lag between the rollers thus making time also a critical factor.
3. During the execution of the road construction project outside, there are few factors which cannot be influenced such as weather condition.
4. It is also known that with the roller compactor that is designed to be used in the laboratory, the magnitude can be influenced to a very limited extent and that there will be edge effects on the slabs made. In addition, in this project a freely moving 2.2-ton roller was used in order to have the same movement of roller on the mixture as on the field.
5. The slab compactors from different participating contractors are to be used in the project. It was consciously chosen to repeat one procedure in one laboratory instead of all procedures in all laboratories. This was made so to have consistent test samples from each procedure instead of also introducing another level of inter-lab variability on samples. This would then also affect the final test results.
6. Target density is one of the major criteria that is looked for on the constructions on-site to validate proper compaction. However, the direct relation of this to the mechanical properties of mixtures are not clear. Thus, this project also considers this factor and the influence of density on the mechanical properties will be studied.
7. This project aims to design a laboratory protocol for simulating on-site compaction in the lab and compaction strategies for asphalt mixtures. However, it is important to note that there are several less explored terrains such as recreating a temperature range similar to the on-site conditions, input of energy at the right temperature and so on which is included in this project.
8. The methods suggested in this project are different from the regular type-testing. This means using different compaction methods, temperature range in the lab, different sample sizes and so on. The advantages of this are that the comparison of the on-site and lab compaction will be on the same level as the procedures are similar and thus the outcome will be more concrete. The major disadvantage is the lack of experience with such conditions and thus the outcome of these tests is also highly subject to interpretation based on experience.

2.4.2 Approach

This project combines the much-required monitoring of the compaction process in the field, simulation of compaction and the evaluation of the performance of the asphalt mixtures. As the research covers on-site and laboratory compaction, the samples of asphalt mixtures from both these locations were studied. The approach followed to implement the methodology designed in this project is shown in Figure 6.

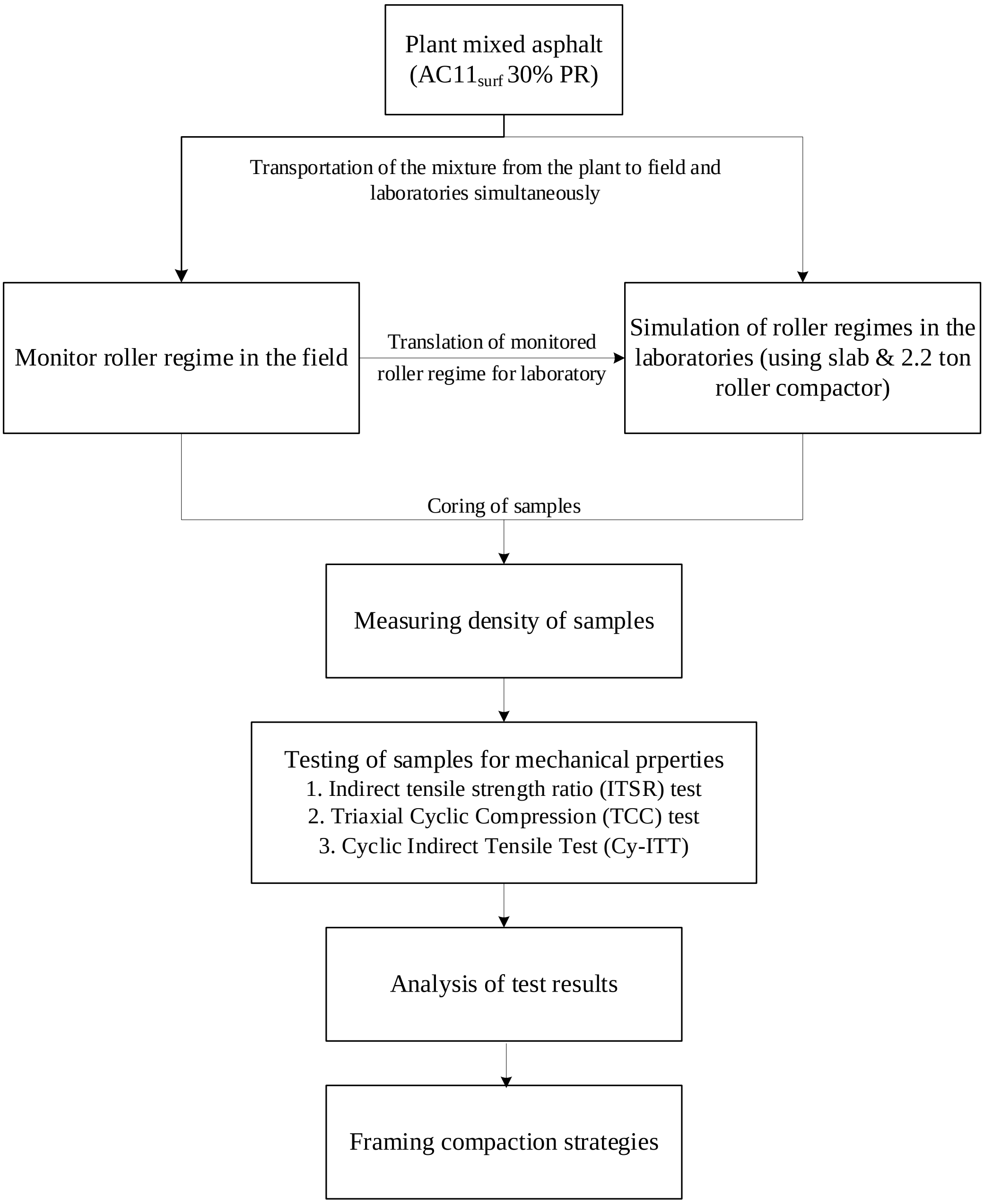


Figure 6 - Approach used to implement proposed methodology.

The chosen mixture was transported to the site and laboratories simultaneously from an asphalt plant. The mixture was plant-mixed, from the same plant and batch. The roller regime on the site was monitored and then translated to that which can be used in the laboratory based on the type of compactor used. This translation was based on calculations made (similar to, 2015) prior to the monitoring with the information available regarding the type of rollers used by the compaction crew of the contractor, working of slab compactor and the 2.2-ton roller compactor. The details of the filed roller regime and its translation to laboratory regime is given in detail in Chapter 3. The core samples for testing were then taken from the site and the slabs that were prepared at the laboratories. The density of these samples was measured. The samples were then tested for their mechanical properties such as stiffness, fatigue, cracking and rutting resistance.

The most critical factors considered in this project for the chosen mixture ($AC11_{surf}$ 30% PR) are the temperature of the mixture and the energy input (number of roller passes, type of roller and static or dynamic pass). For any given asphalt mixture, it is known that temperature plays an important role for compaction because of the behaviour of the materials in the mixture upon change in temperature. The compaction process also highly relies on the energy input on the mixtures by the roller. The energy input can further be divided into three criterions: the type of energy, the magnitude and time. The type of energy input, static or dynamic passes, is important. In this project, for $AC11_{surf}$ dynamic compaction is commonly performed to reach the target density. The amount (magnitude) of energy input which also depends on the type of roller used is also important. The type and amount of energy must be put in at the right time/temperature on the mixture without any time lag between the roller passes for effective compaction. It should also be noted that the time and temperature are coupled here. As the time goes by the asphalt layer starts cooling down.

To achieve the two-pronged goals of this project, the approach undertaken was to use the data obtained from the site to simulate the same in the laboratories. That is, to monitor the compaction strategies that are currently taking place, try to simulate the same in the laboratory and compare both.

The implementation of the approach is further explained in detail. An $AC11_{surf}$ 30% PR pavement project carried out by one of the contractors who is part of this research was identified for PQi monitoring. Three consecutive locations, *M1*[1], *M2* and *M3*, were identified on this site for monitoring the roller regime and density. As temperature and energy input were identified as the critical factors, the core temperature of the asphalt layer, number of roller passes, type of roller pass (static or dynamic), type of roller and the density after each pass were recorded at these locations. The roller regime adopted by the asphalt crew, measured at location 1 (*M1*) was chosen as the reference procedure for simulation in the laboratories. The laboratory compaction also had to take place simultaneously with the same asphalt mixture. This means the compaction regime for laboratories should also reach them in time for the compactors at laboratories to start preparing the slabs. Therefore, the first measurement at location 1 (*M1*) was chosen to be used for the project. The measurements from locations 2 (*M2*) and 3 (*M3*) were later recorded and used for analysis of the variation (if observed) in the roller regime in the field.

[1] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

3 Methodology validation

In this section, the methodology developed is put to the test to identify the contribution made by it to the stakeholder goals, if it is being implemented. To develop guided operational strategies for $AC11_{surf}$ 30%PR, the methodology developed is put to the test based on the measurements made at each step. The results from these tests are statistically analysed using tools such as SPSS and MS Excel to validate the performance of the asphalt mixture tested. This validates the compaction strategies that would be implemented, resulting in an optimally compacted pavement.

The research methods used for treatment validation are as follows:

1. Expert opinion: Expert opinion is a research method that helps to collect assessments of experts who have experience in the area of system under development. It helps to identify the possible problems faced, probable solution framework regarding the problem context. The asphalt contractor companies (members of ASPARi) were involved for their guidance in identifying current trends and difficulties faced, outcomes desired, implementation procedure, their suggestions on area of concern helping and set boundaries for the project. Thus, the input from the contractors reveal various development issues and relevant feedback. The experts in this project are the steering committee from Strukton Civiel, Boskalis, Heijmans and KWS.
2. Statistical difference making experiment: The compaction procedures were tested on various asphalt mixtures chosen and the results will be further analysed using Analysis of Variance (ANOVA) and regression analysis to validate the compaction procedures. With statistical difference making experiment the difference in treatments in a sample population was identified. The result analysis were made based on the level of significance set at 5%. Thus, in this document, the word significance implies the statistical significance of the tests performed until and otherwise mentioned.

The following sections gives the test details and results of each step measured during the testing of the methodology designed.

3.1 Roller regime

3.1.1 Field compaction

Roller regime in this study includes the number of passes made by the roller, type of roller, time of roller pass, temperature at which the pass was made and the type of pass (dynamic or static) at the location of measurement. A pavement project undertaken by Heijmans was used for monitoring field compaction. The mixture used was $AC11_{surf}$ 30%PR surface layer with a target thickness of 35mm. The roller regime was monitored at three different locations *M1*[2], *M2* and *M3* on-site[3]. The density and the temperature of the asphalt layer were measured at these locations using nuclear gauge and thermocouples respectively. Figure 7 shows the image captured during the density measurement on-site.

[2] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

[3] The words on-site and field are used interchangeably in this report

Figure 7 - Picture while measuring the density after the paver on-site.

The density progression and cooling curve were then plotted from the measurements and are shown in Figure 8 and Figure 9 respectively. The number of roller passes and the type of the pass measured on-site is shown in Table 4. From each measurement location on-site 12 cores were drilled. The density of all these cores were then measured in the laboratory.

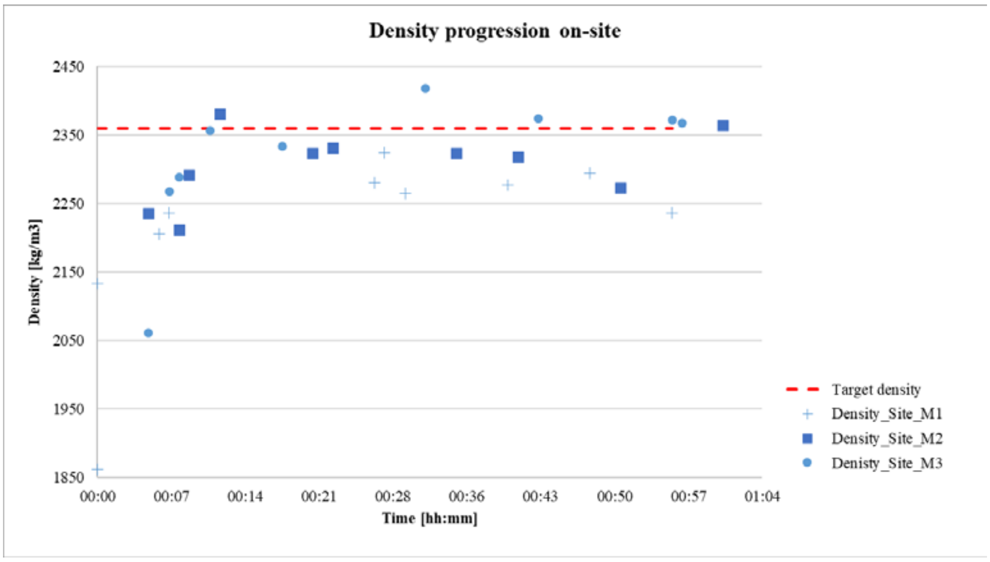


Figure 8 - Density progression measured at the three locations on-site.

It can be seen from Figure 8 that the target density has been reached at measurement locations *M2*[4] and *M3* whereas the same is not true at location *M1*. At location *M1* after the first four roller passes[5], there is a gap of 20 minutes before the next pass. The maximum time gap between passes at location *M2* and *M3* are 12 and 14 minutes respectively. The target density was reached in the

[4] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

[5] A roller pass here is the movement of the roller drums (front and back) over the density measurement location in one direction, once.

first 15 minutes at locations *M2* and *M3*. At location *M1* the target density was not reached at any point in time. At location *M2*, the target density has been reached twice and for the rest of the time the density remains very close the target density. At location *M3*, the target density has been reached and stays over the density for the rest of the time. This shows that the roller passes made in the initial phase is critical and that there must be successive roller passes at least in the first 15 minutes.

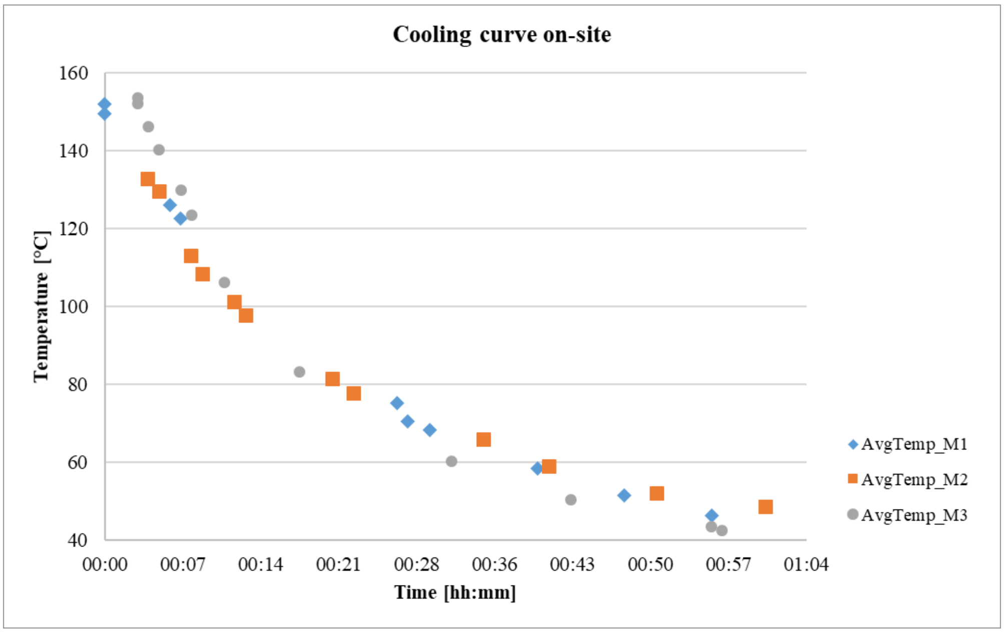


Figure 9 - Cooling curve measured at the three locations on-site.

Figure 9 shows the cooling rate of the asphalt layer at all three locations measured. It shows that a greater number of passes were made in the first 8 minutes and between 160°C and 120°C at location *M3*[6] compared to *M1* and *M2*. The number of roller passes before reaching 90°C is greater at locations *M2* and *M3* compared to *M1*. This in combination with Figure 8 implies that target density could be reached with successive passes at a temperature higher than 90°C within the first 15 minutes of laying of the asphalt layer.

The number and type of roller passes made at the locations *M1, M2* and *M3* were measured and are shown in Table 4. The tandem and the three drum rollers used at the site weighed 7 and 10 tonnes respectively.

[6] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

Table 4 - Number and type of roller passes measured on-site.

Roller pass	*M1*		*M2*		*M3*	
	Type of roller	Dynamic roller pass [Yes/No]	Type of roller	Dynamic roller pass [Yes/No]	Type of roller	Dynamic roller pass [Yes/No]
0	Paver	N	Paver	N	Paver	N
1	Tandem	N	Tandem	Y	3 drum	N
2	Tandem	Y	Tandem	Y	3 drum	N
3	Tandem	N	Tandem	Y	3 drum	N
4	Tandem	Y	Tandem	Y	3 drum	N
5	3 drum	N	3 drum	N	3 drum	N
6	3 drum	N	3 drum	N	3 drum	N
7	3 drum	N	3 drum	N	3 drum	N
8	3 drum	N	3 drum	N	3 drum	N
9	3 drum	N	3 drum	N	3 drum	N
10	3 drum	N	3 drum	N	3 drum	N
11	-	-	3 drum	N	3 drum	N
12	-	-	3 drum	N	3 drum	N

Table 4 shows that the total number of passes made at locations *M2* and *M3* is higher than that at location *M1*. The initial compaction phase at locations *M1* and *M2* had dynamic passes. At *M1* these were alternating dynamic and static passes and at *M2* the dynamic passes were continuous. However, at *M3*[7] all the roller passes were static. There is also a difference in the type of roller used. At locations *M1* and *M2* the tandem rollers were used in the initial phase and later the three-drum rollers were used. At location *M3* only the three-drum roller was used.

Thus from the density progression in Figure 8, cooling curve in Figure 9 and the number and type of roller passes from Table 4 a clear difference in the roller regime in terms of time gap between passes, number and type of roller is evident. This difference implies that there is variability in the roller regimes followed by the operators between locations on-site. It can also be concluded that irrespective of the type of roller and roller passes (static or dynamic) the target density can be achieved. This can be done by performing more number (6 – 7) of successive passes at higher temperatures (160 - 90°C) for $AC11_{surf}$ 30%PR.

3.1.2 Laboratory compaction

In order to simulate the roller regime that was carried out on-site, in the laboratory, three different compaction procedures were devised. The procedures were executed in the laboratory using the slab compactor and the 2.2 ton roller compactor. The measurement made at location *M1* on-site was translated to a regime that can be implemented by the slab compactor and the 2.2 ton compactor based on (Bijleveld, 2015). The location *M1* was chosen because the plan was to compact the asphalt in the laboratories simultaneously in order to use the same plant-mixture from the same batch to avoid variability in the mixture.

In addition to the original rolling regime at *M1* two more rolling procedures were developed for laboratory compaction based on that at *M1* by varying the temperature and energy input. This was to identify the effect of variation in temperature and energy input (in terms of roller passes) on compaction of asphalt in the laboratory. The temperature monitored on-site was lowered by

[7] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

20°C and the number of roller passes was increased by 50%. The procedure followed in the laboratory including their names is detailed in Table 5. The exact rolling procedures of those mentioned in Table 5 are shown in Appendix C.

Table 5 - Compaction procedure adopted in the laboratories based on site measurements.

Procedure Code	Procedure	Type of compactor	Company
P1_Ref_SC	Same roller regime as measured at M1	Slab compactor	Strukton Civiel
P2_LowT_SC	Same energy input as measured at M1 at a lower temperature (↓ 20°C)		Dura Vermeer
P3_HighE_SC	Higher energy input (↑50%) at same temperature as measured at M1		KWS
P1_Ref_RC	Same roller regime as measured at M1	2.2-ton roller compactor	Boskalis
P2_LowT_RC	Same energy input as measured at M1 at a lower temperature (↓ 20°C)		
P3_HighE_RC	Higher energy input (↑50%) at same temperature as measured at M1		

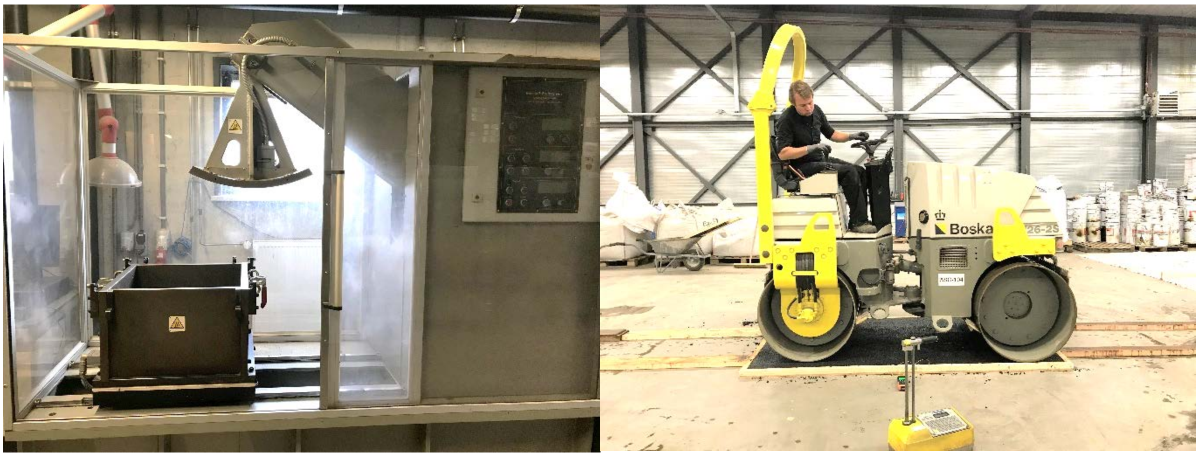


Figure 10 - Image of slab compactor (left) and 2.2 ton roller compactor (right) used in slab preparation.

Figure 10 shows the slab compactor and 2.2 ton roller compactor used for preparing the asphalt slabs. Using a slab compactor[8], three slabs were prepared for each compaction procedure and 16 cores were made from each slab. The size of the slab and cores are shown in Figure 11, in the Appendix C. Thus, for each procedure a total of 48 cores were obtained. The procedure followed can be seen in Table 2 and Table 3 of Appendix C. The densities of the cores from each of these slabs were measured. The variation in density among the slabs was found to be non-significant. A thickness progression plot was made for each slab made using a slab compactor. This showed that the variation was least in the slabs made for P3_HighE_SC. For the other two procedures the

[8] Roller pass in slab compactor: 1 roll in a slab compactor is equal to 1 pass made by one drum of the roller in one direction. It is assumed that 1 dynamic pass by tandem roller is equal to 2 static passes by the tandem roller.

variation in slab thickness was minimum but still obvious. This means that the accuracy of the compactor used for P3_HighE_SC was the highest.

Using a 2.2 ton roller compactor[9] one slab was prepared for each compaction procedure and 48 cores were made from each slab. The procedure followed can be seen in Table 4 and Table 5 of Appendix C. A variation in temperature existed when the compaction of the first slab was started and thus the procedure then had to be adapted to this. The size of the slab and cores are shown in Figure 12 of Appendix C. Thus, for each procedure a total of 48 cores were obtained. The densities of the cores from each of these slabs were measured and their variation was found to be non-significant. An attempt was made to measure the density progression during rolling, but the results showed that the layer was too thin for the density gauges to give accurate measurements of the density. Thus, these values were not considered.

3.1.3 Density

The bulk density of cores prepared at the laboratories and those from the site were measured according to the standard NEN-EN12697-6. The average density of all the cores from each procedure is shown in Figure 11. Traditionally, achieving the target density of asphalt materials has been used as the acceptance criteria for pavement construction (Xu and Chang 2013).

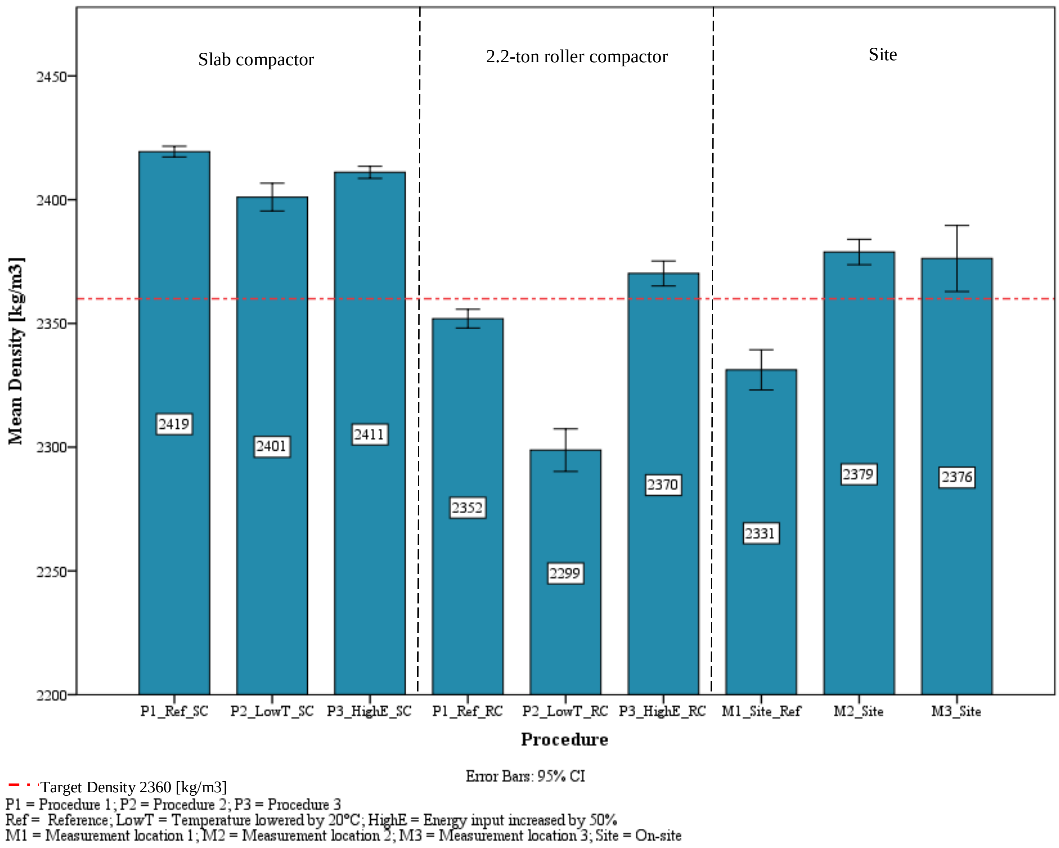


Figure 11 - Average density of samples from all procedures.

3.1.3.1 Comparison between compaction procedures

Figure 11 clearly shows that the average densities of the cores that were made by the slab compactor are higher than the target density of 2360 kg/m³. Of these cores, the maximum density

[9]Roller pass in 2.2 ton roller compactor: It is assumed that 1 pass by 3 drum roller (10 ton) is equal to 1.5 from the 2.2 ton roller at the laboratory and 1 pass by a 7-ton tandem roller (static or dynamic) is effectively the same.

has been attained by those made using procedure *P1_Ref_SC*[10] followed by *P3_HighE_SC* and finally *P2_LowT_SC*. This means that the cores made using the same roller regime (temperature and energy) as measured at *M1* on-site have the highest density. The cores prepared under a lower temperature range, but same amount of energy compared to *P1_Ref_SC,* have the lowest density. The difference in density between *P1_Ref_SC* and *P2_LowT_SC* is 0.74% and shows the effect of temperature change on density. The density of cores prepared using higher energy and same temperature range as *P1_Ref_SC* differs by 0.33%. This implies that there is a dependence on temperature and energy input. However, the significance of this change in the slab compactor is not clear.

From Figure 11 we can also see that with the cores made using 2.2 ton roller compactor the target density has been exceeded (0.42%) in the case of *P3_HighE_RC* and is close to reaching target density value (0.34%) in the case of *P1_Ref_RC*. This means when the same roller regime (temperature and energy) as measured at *M1* on-site was used, the target density could not be reached by the 2.2-ton roller compactor. The density achieved is higher than the target density when additional energy is used. The density in case of *P2_LowT_RC* is lower (2.58%) than the target density. The average density of these cores is highest in case of *P3_HighE_RC* closely followed by *P1_Ref_RC* and lowest in case of *P2_LowT_RC*. The density of cores prepared using higher energy and same temperature range as *P1_Ref_RC* differs by 0.77%. The difference in density between *P1_Ref_RC*[11] and *P2_LowT_RC* is 2.25%. When the same energy as *P1_Ref_RC* is used at a lower temperature, the average density is not only lower compared to the other two roller regimes, it is also lower than the target density. This shows that there is an effect of temperature and energy input on the density achieved using a 2.2 ton roller compactor. The significance of this change in the slab compactor is not clear.

The target density has been reached on-site at measurement locations *M2* and *M3* and not at location *M1*. The average density of the cores from the site is the highest in case of *M2_Site* very closely followed by *M3_Site* and is least in case of *M1_Site_Ref*. On comparing Figure 8 and Figure 9, we can see that the average density values of the cores from the site are considerably close to what the density progression plot shows. The difference in the final average density between *M1*, *M2* and *M3* shows the effect of compacting less (at *M1*) and more (at *M2* and *M3*), respectively, at higher temperatures. This shows that irrespective of the type of compaction (static or dynamic) the target density can be achieved given there are more roller passes at higher temperatures. It also shows that the nuclear gauges could be relied on in density prediction.

Thus, we see that among the three procedures, the average density is lower when the mixture is compacted at a lower temperature with slab and 2.2 ton roller compactor (*P2_LowT_SC* and *P2_LowT_RC*) compared to the other two procedures in the laboratory. The effect of temperature and energy input change in 2.2 ton roller compactor is more pronounced compared to slab compactor which can be seen from the percentage difference in the densities among the procedures.

3.1.3.2 Comparison of laboratory and field compaction

On comparing the densities of cores from *M1* with those from other procedures, Figure 11 clearly shows that *P1_Ref_SC* is the highest followed by *P1_Ref_RC*. It must be noted that the target density was not reached at *M1* as shown by the nuclear density gauge and bulk density measured. Similarly target density was not reached with *P1_Ref_RC*. The density was 2.5% and 0.34% higher

[10] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

[11] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

with slab and 2.2 ton roller compactor, respectively, with respect to the target density. Similarly, the density was 3.7% and 0.90% higher with slab and 2.2 ton roller compactor, respectively, with respect to the *M1*.

Similarly, on comparing the densities from *M1* with remaining laboratory procedures it can be seen that their average densities are not comparable. This means that although temperature and energy variation in the laboratory influences the density of the mixture, these procedures did not simulate the on-site procedure with respect to the density values.

This implies that the roller regimes used for the slab compactor and 2.2 ton roller compactor did not simulate the roller regime outside with respect to density. It suggests that with the laboratory roller regime that was used leads to over-compaction of the mixture. As all (three procedures) the results of slab compactor show densities higher than the target density (2.13%), it can be concluded that with the used translation of the site to slab compactor roller regime, the force used was higher than what was required to meet the density measured on-site. This could have been caused due to the confinement of the asphalt mixture within the mould and a better temperature control in compactor.

3.1.4 Conclusions

The conclusions below were made based only on the observations strictly in terms of density as the result. The conclusions are:

1. There is variability in the roller regime followed on-site which was monitored at locations *M1*, *M2* and *M3*.
2. The target density can be achieved when more successive roller passes (6 – 7) are made at temperatures higher than 90°C irrespective of the type of roller pass (static or dynamic).
3. Assuming the same procedure on-site was followed in the laboratory, it can be concluded that the type of compaction performed that is, using a slab compactor, roller compactor or field compaction has a clear influence on the resulting density.
4. The amount of energy used in the slab compactor is higher (density variation of 3.6% compared to the site) than that used on-site which implies that there is a need to recalculate the translation of roller regime adopted on-site to that for the slab compactor to avoid over-compaction.
5. The amount of energy used in the 2.2 roller compactor is higher (density variation of 0.9% compared to the site) than that used on-site which implies that a there is a need to change the translation of roller regime adopted on-site to that for the 2.2 ton roller compactor.
6. The 2.2 ton roller compactor can simulate the site roller regime better than a slab compactor with the force translation used in this project.
7. Temperature influences the final density achieved using slab compactor and roller compactor. The significance of this was not verifiable.
8. The slab compactor and 2.2 ton roller compactor roller regime does not exactly simulate the roller regime on-site with respect to density. The energy input calculated in this project for slab and 2.2 ton roller compactors results are higher by 3.7% and 0.9% respectively.

3.2 Indirect tensile strength ratio (ITSR) test

The samples cored from the site and slab compactor were tested for their moisture sensitivity and indirect tensile strength. The Indirect Tensile Strength Ratio (ITSR) test was performed according to the NEN EN 12697-12 with the Indirect Tensile strength (ITS) test performed in accordance to

NEN EN 12697-23 for the samples from the laboratory. The samples from the field were lower than the ideal number prescribed in the standards. The test setup used is shown in Figure 12.

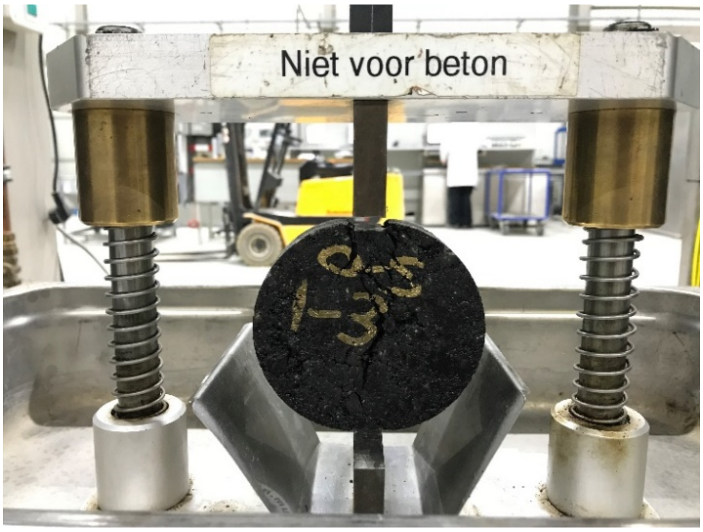


Figure 12 - One of the samples being tested in a ITS test setup.

3.2.1 Indirect tensile strength ratio (ITSR)

The minimum ITSR value as prescribed by Dutch pavement specifications – Standaard RAW bepalingen 2015 (CROW 2015) in Table 81.2.7 is 80% for the asphalt mixtures belonging to the class DL-IB.

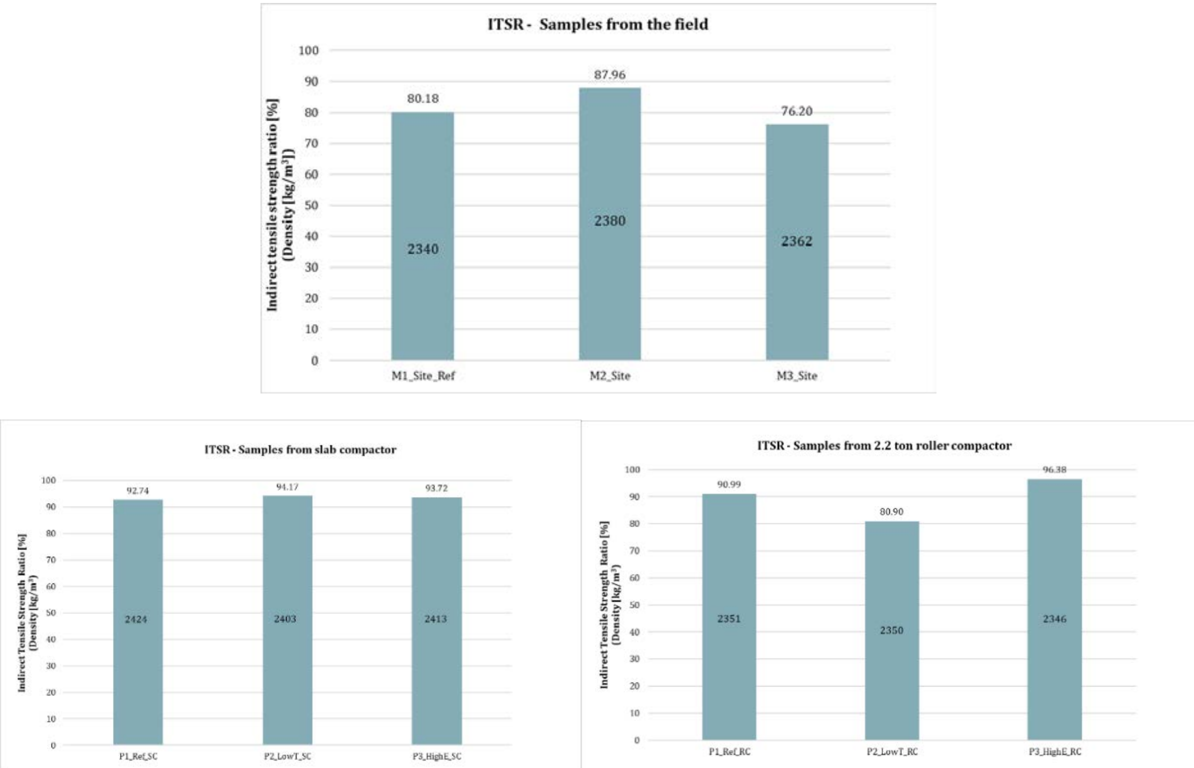


Figure 13 - ITSR of samples from the field (top), slab compactor (bottom left) and 2.2 ton roller (bottom right).

Figure 13 shows that the ITSR for samples from the field differ and this difference was found to be non-significant. This implies that the variation in the roller regime does not affect the ITSR values of the samples. From the type test, the ITSR value is 82%, which meets the minimum requirement by the Dutch standards and has been met by samples from location *M1* and *M2*. The samples from the location *M3* is lower than the requirement prescribed by RAW. This implies that this procedure is not ideal to be followed on-site.

The ITSR values of the samples from the slab compactor do not differ significantly. Compared to the ITSR of the reference procedure, *P1_Ref_SC*[12], those of *P2_LowT_SC* and *P3_HighE_SC* are higher by 2% and 1% respectively. This means that with the change in rolling procedure there is no change in the resulting ITSR values. The ITSR values of the samples from the 2.2 ton roller compactor do not vary significantly. Compared to the ITSR of the reference procedure, *P1_Ref_RC,* those of *P2_LowT_RC* and *P3_HighE_RC is 12*% lower and 6% higher respectively. This means that with the change in rolling procedure there is no significant change in the resulting ITSR values.

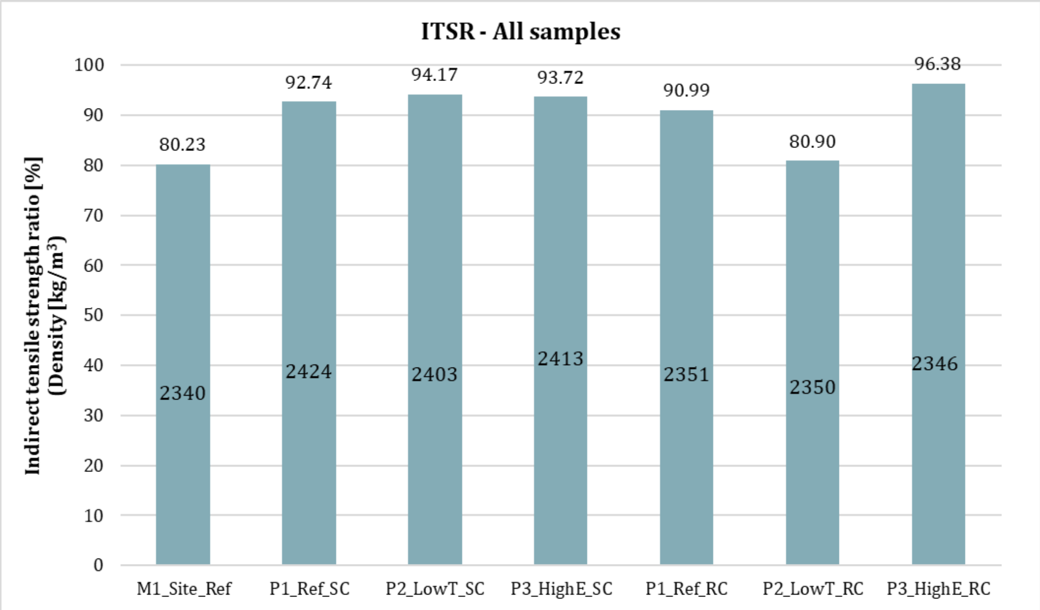


Figure 14 - ITSR of samples from field (reference location) and laboratories.

Figure 14 shows the ITSR value of the samples compacted in the field at reference location *M1_Site_Ref* and those compacted using the slab and the 2.2 ton roller compactors. To compare the procedure that best represents the field roller regime a tolerance an arbitrary value of 11% was used. Any value that falls in the 11% range of the ITSR values from field is then considered to represent the field compaction. On comparing the laboratory ITSR of samples to that of the field *P2_LowT_RC* represents the field regime.

[12] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

3.2.2 Indirect tensile strength (ITS)

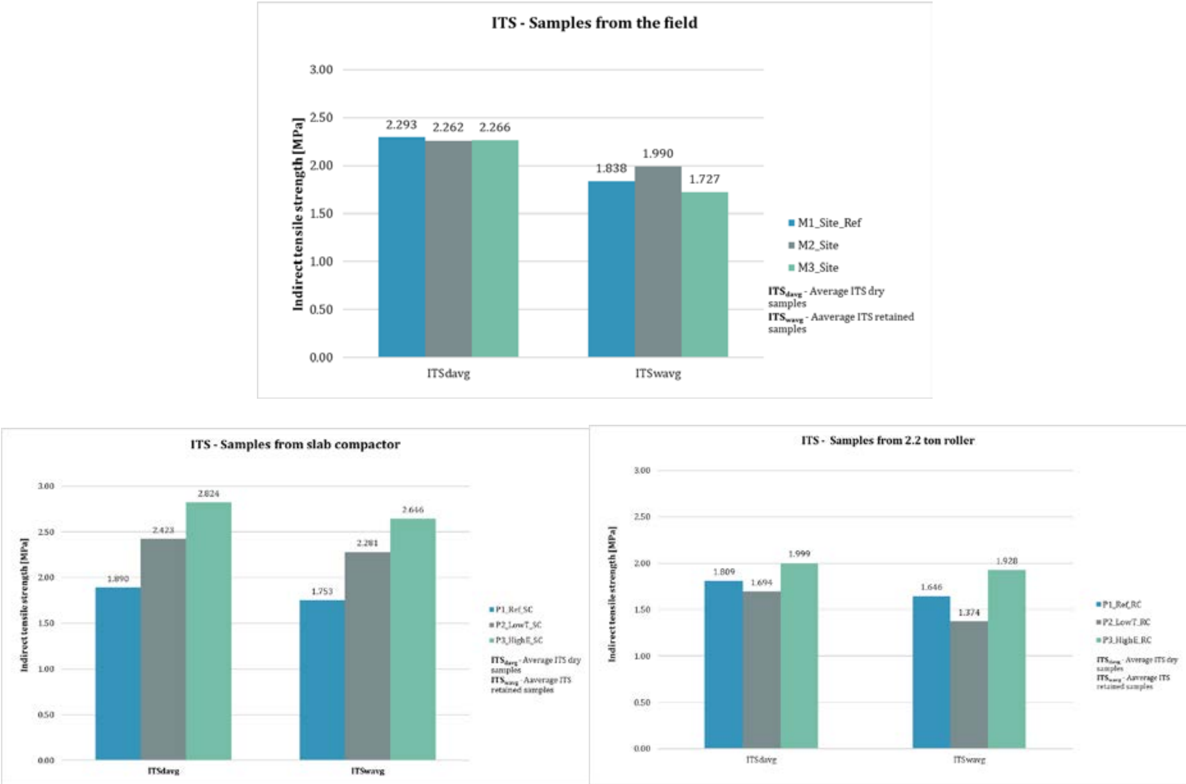


Figure 15 - ITS of samples from the field (top), slab compactor (bottom left) and 2.2 ton roller (bottom right).

Figure 15 shows ITS values of dry and retained samples from the field. It was found that the differences in these values are not significant. This implies that the variation that occurred in the roller regime on-site does not affect the ITS values of the samples. From the type test, the ITS value dry and retained samples are 3.09 MPa and 2.53 MPa, respectively. On comparing the ITS values of site and type test, the difference between the two is significant. This means that the observed ITS values for the samples from the site do not match the type test.

The ITS values of the dry and retained samples from the slab compactor vary significantly for each of the procedures followed. Compared to the ITS of the reference procedure, *P1_Ref_SC*[13], those of *P2_LowT_SC* and *P3_HighE_SC* are higher by 32% and 33%, respectively, on average for the dry and retained samples. This means that with change in rolling procedure there is a change in the resulting ITS values. The ITS values of the dry and retained samples from the 2.2 ton roller compactor varies significantly for each of the procedure followed. Compared to the ITS of the reference procedure, *P1_Ref_RC*, those of *P2_LowT_RC* and *P3_HighE_RC* are 12% lower and 13% higher respectively on average for the dry and retained samples. This means that with the change in rolling procedure there is a change in the resulting ITS values.

[13] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

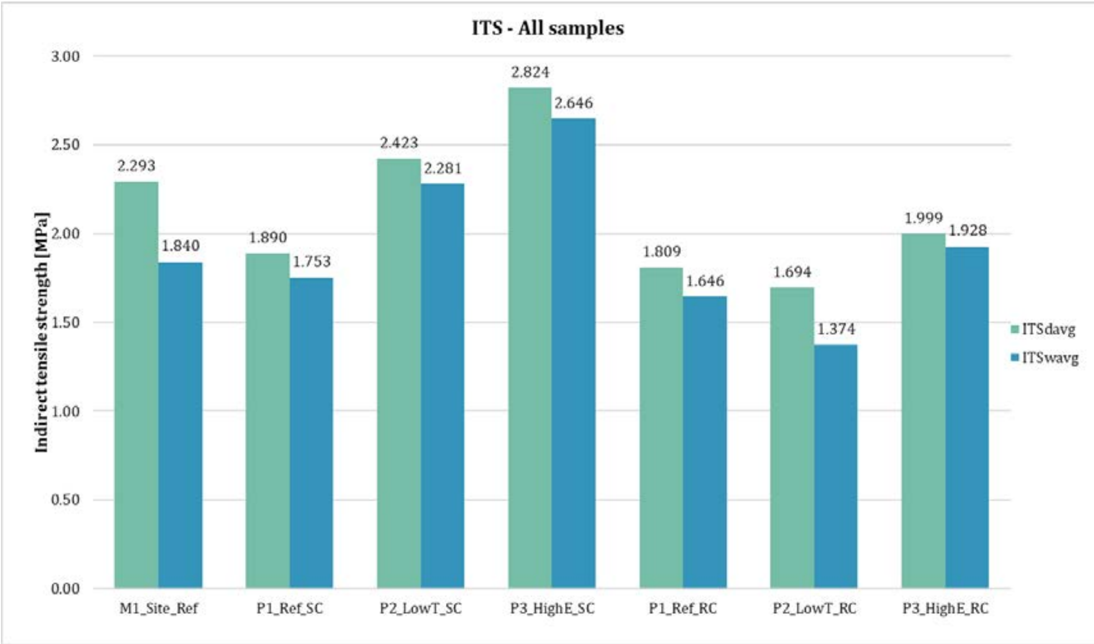


Figure 16 - ITS of samples from field (reference location) and laboratories.

Figure 16 shows the ITS value of the samples compacted in the field at reference location *M1_Site_Ref* and those compacted using the slab and the 2.2 ton roller compactors. To compare the procedure that best represents the field roller regime a tolerance of 11% was used. Any value that falls in the 11% range of the ITS values from field is then considered to represent the field compaction. On comparing the laboratory ITS of dry samples to that of the field *P2_LowT_SC* represents the field regime. On comparing the laboratory ITS of retained samples to that of the field *P1_Ref_SC* and *P3_HighE_RC* represents the field regime.

3.2.3 Fracture energy

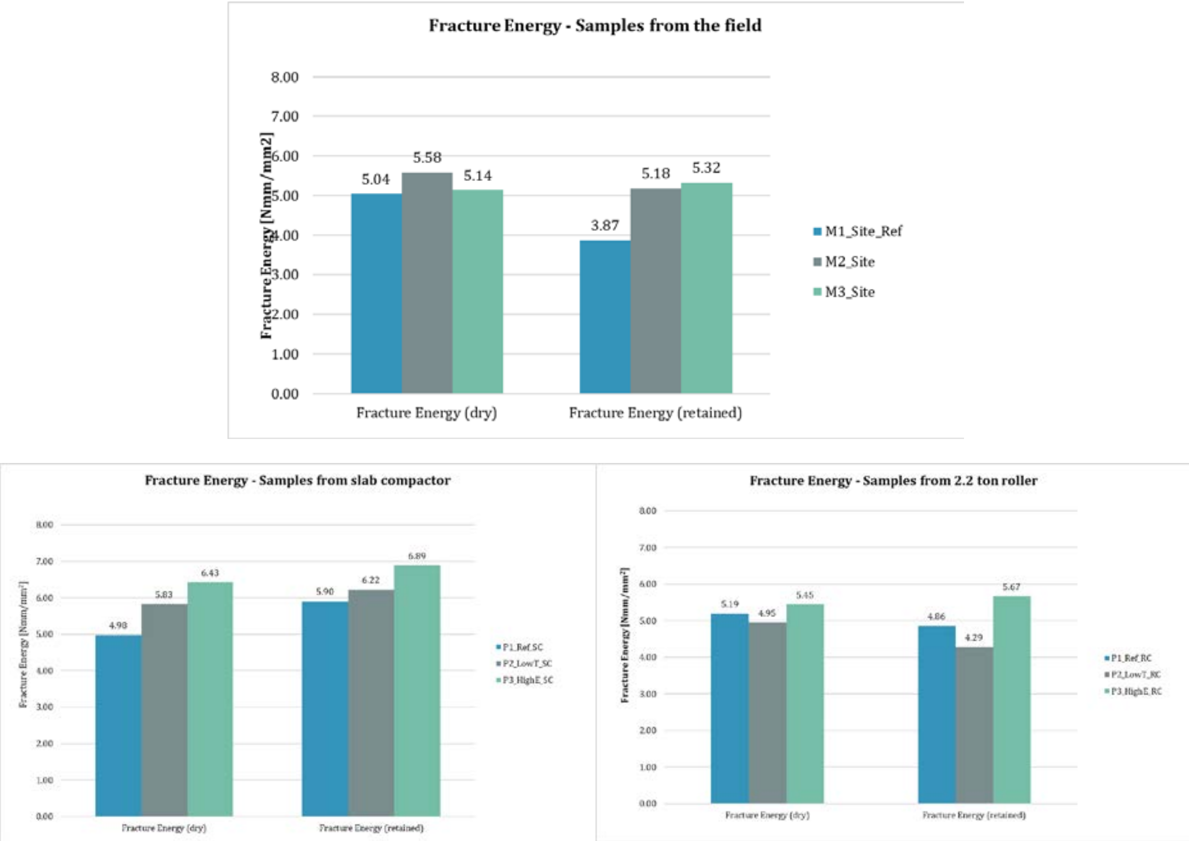


Figure 17 - Fracture energy of samples from the field (top), slab compactor (bottom left) and 2.2 ton roller (bottom right).

Figure 17 shows that the site values of fracture energy (FE) for dry and retained samples do not vary significantly. This implies that the variation that occurred in the roller regime does not affect the FE values of the samples.

The FE values of the dry and retained samples from the slab compactor do not vary significantly. This is not true only in the case of dry samples from *P3_HighE_SC* where there is a significant difference. Compared to the FE of the reference procedure, *P1_Ref_SC*[14], those of *P2_LowT_SC* and *P3_HighE_SC* are higher by 11% and 20%, respectively, on average for the dry and retained samples. This means that the change in rolling procedure there is no change in the resulting FE values except in the case of *P3_HighE_SC*. The FE values of the dry and retained samples from the 2.2 ton roller compactor do not vary significantly for each of the procedure followed. Compared to the FE of the reference procedure, *P1_Ref_RC*, those of *P2_LowT_RC* and *P3_HighE_RC* are 9% lower and 10% higher, respectively, on an average for the dry and retained samples. This means that with the change in rolling procedure using 2.2 ton there is no change in the resulting FE values.

[14] P1 = Procedure 1; P2 = Procedure 2; P3 = Procedure 3; Ref = Reference; LowT = Temperature lowered by 20°C; HighE = Energy input increased by 50%; M1 = Measurement location 1; M2 = Measurement location 2; M3 = Measurement location 3; Site = On-site

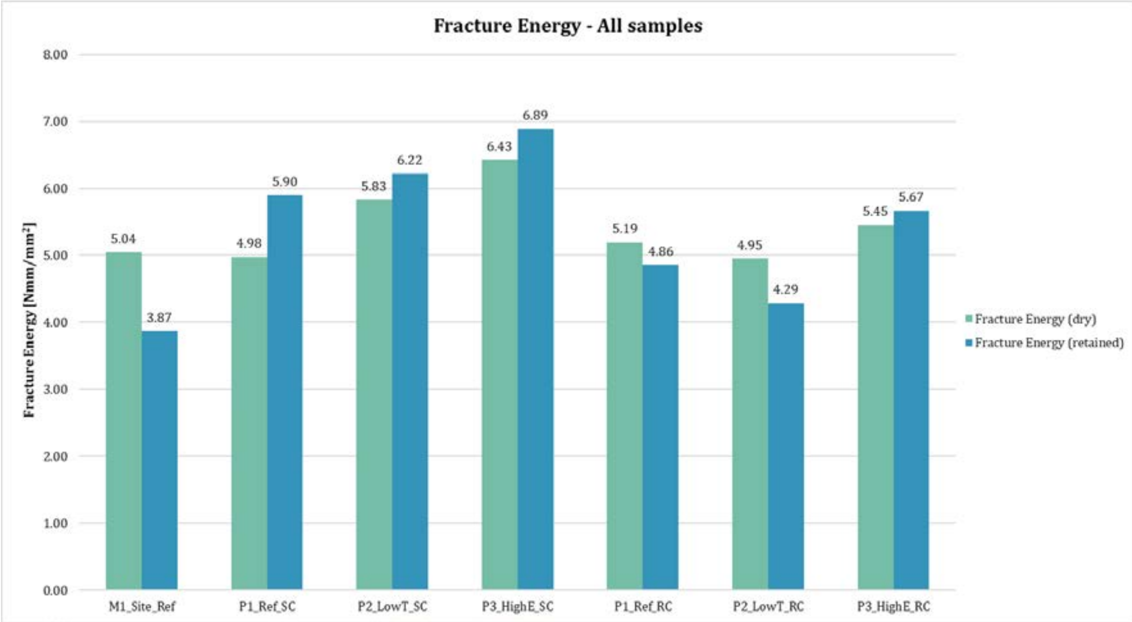


Figure 18 - Fracture energy of samples from reference location at field and laboratories.

Figure 18 shows the FE value of the samples compacted in the field at reference location *M1_Site_Ref* and those compacted using the slab and the 2.2 ton roller compactors. To compare the procedure that closely represents the field roller regime a tolerance of 11% was used. Any value that falls in the 11% range of the FE values from field is then considered to represent the field compaction closely. On comparing the FE of dry laboratory samples to that of the field *P1_Ref_SC* and all three procedures of 2.2 ton roller compactor represents the field regime. On comparing the FE of retained laboratory samples to that of the field only *P2_LowT_RC* represents the field regime.

In addition, regression analysis was performed on ITSR, ITS and FE values with density and it was found to have a moderate-strong correlation between the chosen parameters. This means that within the used range of density values, it is a good predictor of ITSR, ITS and FE values.

3.2.4 Conclusions

From the results of the density and the ITSR tests, the following conclusions can be made:

1. ITSR:
    a. The change in roller regimes on-site, in the slab compactor or 2.2 ton roller compactor does not significantly influence the ITSR values.
    b. Although point 1.a holds good statistically, the difference in the ITSR values is more pronounced in the 2.2 ton roller than the slab compactor. One of the major reasons for this could be the controlled way in which the samples are prepared using the slab compactor.
    c. The roller regime with lower temperature than the reference temperature monitored simulates the field regime the closest with respect to the ITSR value.
2. ITS:
    a. Although the three roller regimes monitored on-site are different, this doesn't influence the ITS of the samples.
    b. Compacting the mixture on a lower temperature or higher energy compared to the original roller regime for the slab compactor input the value of ITS increases by 25% and 40%, respectively.

c. Compacting the mixture on a lower temperature compared to the original roller regime for 2.2 ton roller the ITS value decreases by 12%. On using higher energy compared to the original roller regime for the 2.2 ton roller compactor ITS increases by 13%.
d. The roller regime with lower temperature than the reference regime of slab compactor simulates the field regime close with respect to the ITS dry value. The reference slab compactor roller regime and regime with higher energy input using a 2.2 ton roller compactor simulates the retained ITS value from the field.

3. FE:
   a. The three roller regimes monitored on-site do not influence the FE of the samples.
   b. Compacting the mixture on a lower temperature or higher energy compared to the original roller regime for the slab compactor input the value of ITS increases by 11% and 20%, respectively. This change however is not significant.
   c. Compacting the mixture on a lower temperature compared to the original roller regime for 2.2 ton roller the FE value decreases by 9%. On using higher energy compared to the original roller regime for the 2.2-ton roller compactor FE increases by 10%. This change however is not significant.
   d. The reference roller regime of slab compactor and all three regimes using 2.2 ton roller simulates the field regime close with respect to the FE dry value. The regime with lower temperature using a 2.2 ton roller compactor simulates the retained FE value from the field.
4. Density is a good predictor of ITSR, ITS and FE values for the used range of 2236 and 2432 kg/m^3.

3.3 Triaxial cyclic compression (TCC) test

The triaxial cyclic compression test on the samples were performed based on NEN-EN 12697-25. However, the sample height is different from what is generally used for type test that is 35mm instead of 60mm. The friction reduction system used to test the sample is shown in Figure 19 Schematic diagram of the friction reduction system and test setup used in the TCC test.

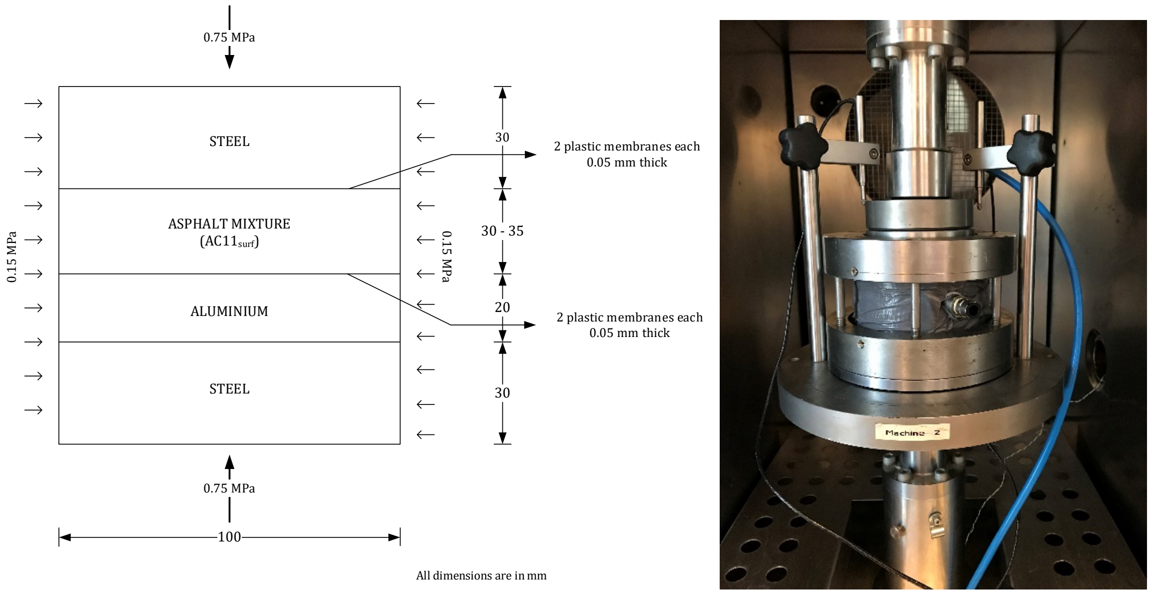


Figure 19 - Schematic diagram of the friction reduction system and test setup used in the TCC test.

The samples from the field, slab compactor and the 2.2 ton roller compactor were tested for permanent deformation. The major difference with the standard tests, also followed in the type test, is that the sample size is shorter than prescribed. The prescribed sample size has a height of 60mm. The friction reduction system used during the type test is shown in Appendix E.

The triaxial test gives information on the sensitivity of the samples to deformation due to loading. The number of samples tested were three per procedure. There are no criteria given in the standards or the codes regarding the variability between the samples and its resulting effect.

3.3.1 Creep rate

The maximum creep rate (f_c ten hoogste) value as prescribed by Dutch pavement specifications (CROW 2015) in Table 81.2.7 is 0.2 for the asphalt mixtures belonging to the class DL-IB. This value is based on the standard sample size mentioned in NEN-EN 12697-25.

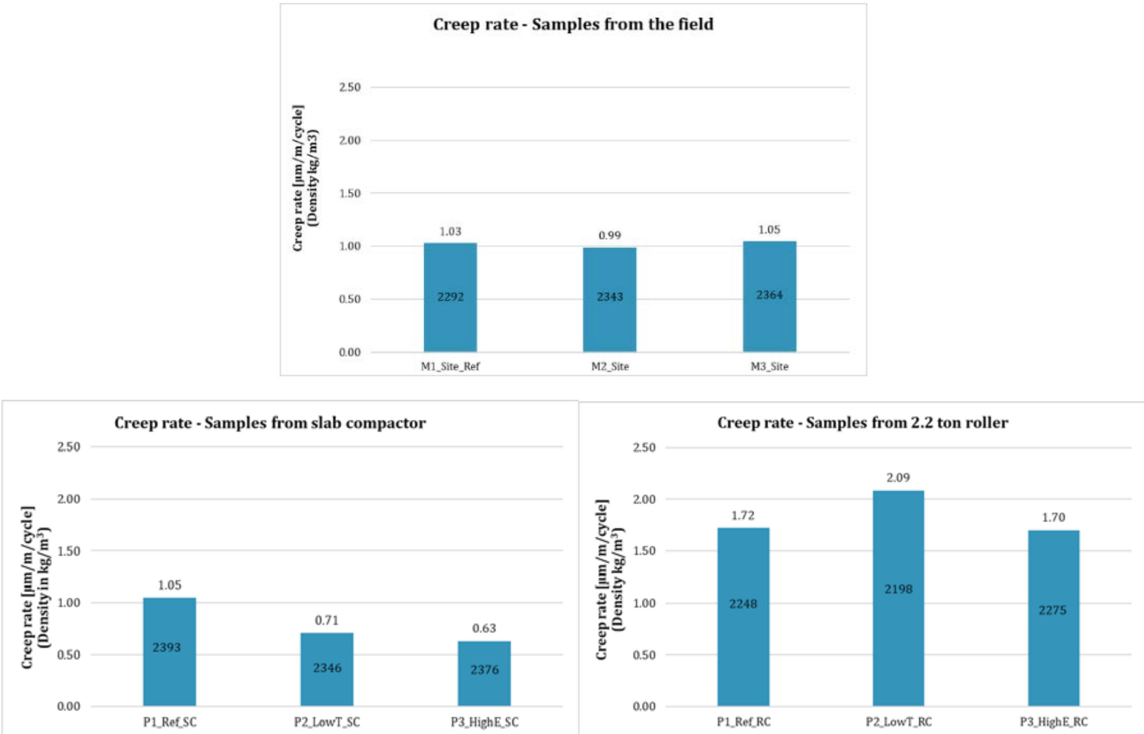


Figure 20 - Creep rate of samples from the field (top), slab compactor (bottom left) and 2.2 ton roller (bottom right).

Figure 20 shows the creep rate of all the samples from the field are similar. The difference between these values were found to be statistically insignificant. This means that the change in the variability between roller regime on the field does not influence the creep rate. On comparing this to the average creep rate from the type test, 0.1 µm/m/cycle, we can see that the values of this test are on an average 10 times higher (1.02 µm/m/cycle). From this observation, for the reasons of comparison between the compaction procedures the maximum creep rate was assumed to be 2 µm/m/cycle which is 10 times the value suggested by the Dutch pavement standards (CROW 2015). Based on this, it can be interpreted that the samples from the site meets the requirements as their values are well below 2 µm/m/cycle.

The creep rate of *P1_Ref_SC* is the highest among the samples from slab compactors followed by *P2_LowT_SC* and *P3_HighE_SC*. The differences amongst these samples were also found to be statistically insignificant. The creep rate of *P2_LowT_RC* is the highest among the samples from slab compactors followed by *P1_Ref_RC* and *P3_HighE_RC*. The differences amongst the 2.2 ton roller samples were also found to be statistically insignificant. This means that the change in the procedure amongst slab or 2.2 ton roller compactor does not influence the creep rate. Although the creep rate lower by 44% for samples from *P2_LowT_SC* and *P3_HighE_SC* compared to *P1_Ref_SC.* The amount of influence the change of procedures have on the creep rate could not be accounted for. Thus, we go by the statistical data even though it is for a limited number of samples.

With the limits between the variability not prescribed by the Dutch standards, the knowledge of the effect of such variability unavailable, and statistically the differences are insignificant, it becomes difficult to infer the effect of the variability. Since the project concentrates on the simulation of the compaction, procedure it becomes essential to have a threshold values to say the difference. Thus, an arbitrary value of 33% was assumed to identify the procedures that closely simulate the site.

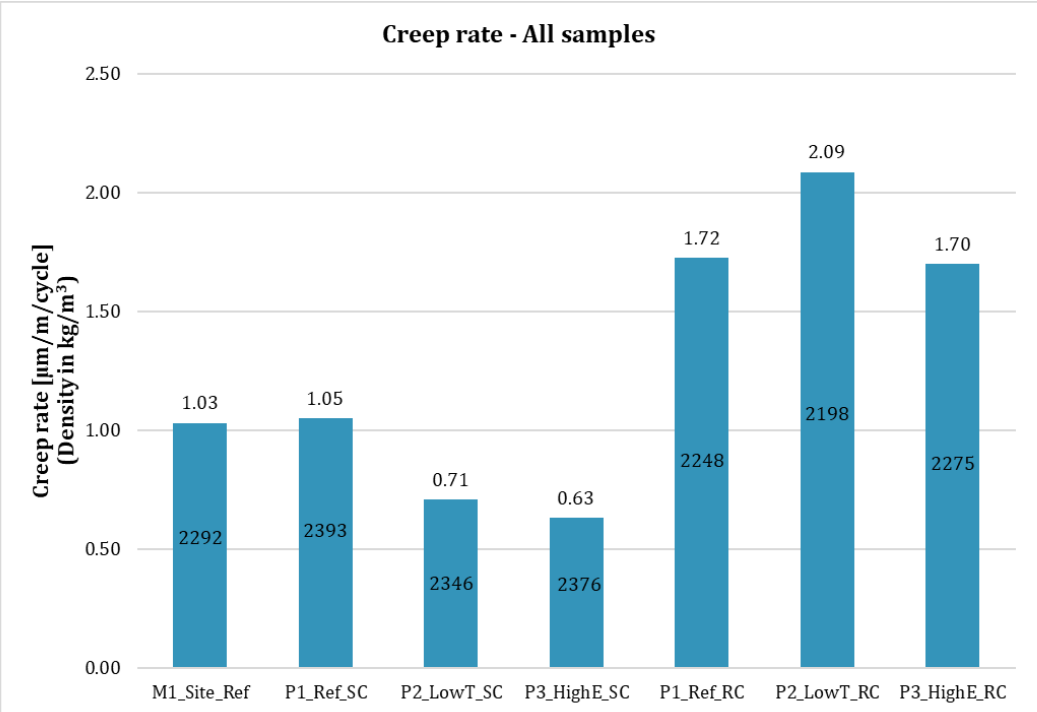


Figure 21 - Creep rate of samples from reference location at field and laboratories.

Figure 21 shows the creep rate of the samples from the reference location from the field and that of the various procedures from the laboratories. It can be seen that the creep rate of the samples from the slab compactor are closer to the field than those from 2.2 ton roller. The values from the roller are 48% higher on average compared to those from the field. This means that samples from slab compactor represent the field roller regime better with respect to creep rate especially the reference procedure, *P1_Ref_SC*.

Figure 20 and Figure 21 also shows the average density of the samples tested. It was found that the density and creep rate had a strong negative correlation. The trend observed was that with the decrease in density, the creep rate value increases. On performing a regression analysis, details of which can be found in the Appendix D, it was found that the density was a good predictor of creep rate.

3.3.2 Permanent deformation

The permanent deformation of the samples at the end of 10000 cycles is analysed in this section.

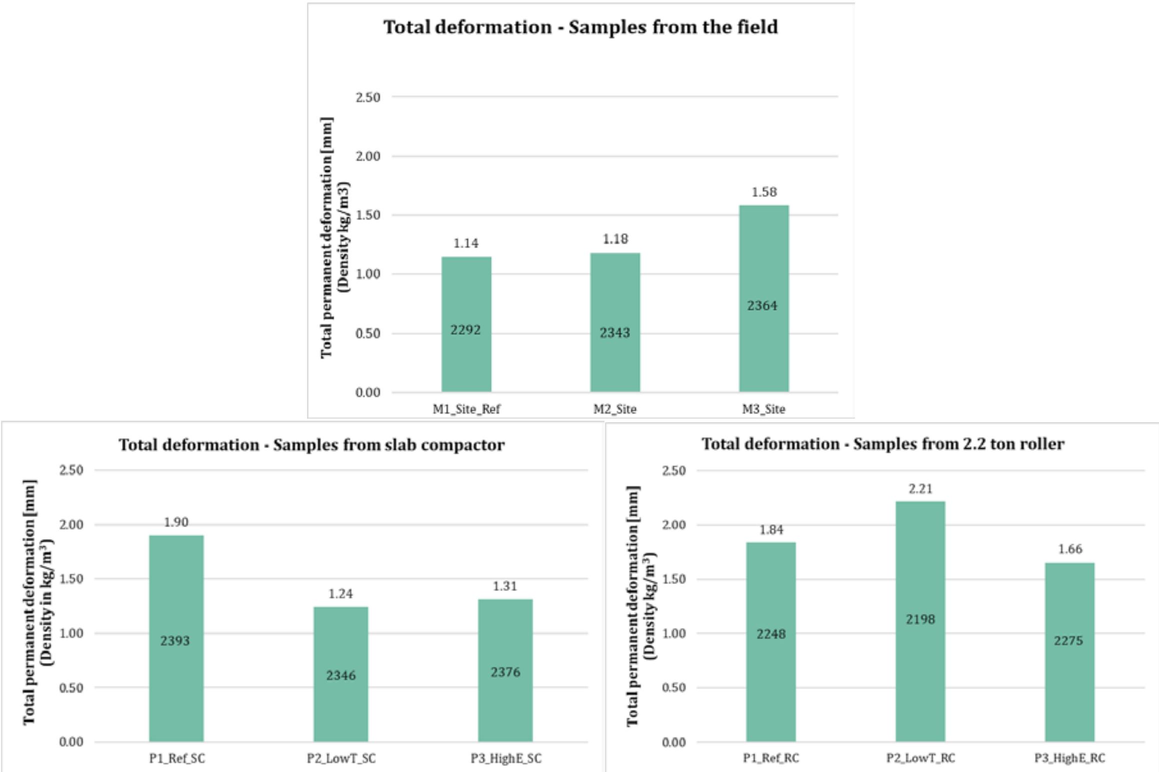


Figure 22 - Permanent deformation of samples from the field (top), slab compactor (bottom left) and the 2.2 ton roller (bottom right).

Figure 22 shows the permanent deformation of the samples from the field and laboratories. The difference in deformations of those from site were found to be non-significant. Although this is statistically true, it can also be seen that the permanent deformation of samples from location *M1_Site_Ref* and *M2_Site* are closer (3% difference) compared to *M3_Site* (32%). This means that there is indeed a clear influence of the roller regime on permanent deformation in site. Similarly, the difference in permanent deformation among the slab and roller compactors were found to be statistically non-significant. From the figure above it can be seen that the permanent deformation clearly varies for the slab and the roller compactor. Just as in the creep rate, the limited number of samples and effect of the variation in these numbers are hard to interpret in terms of influence of procedures on the result.

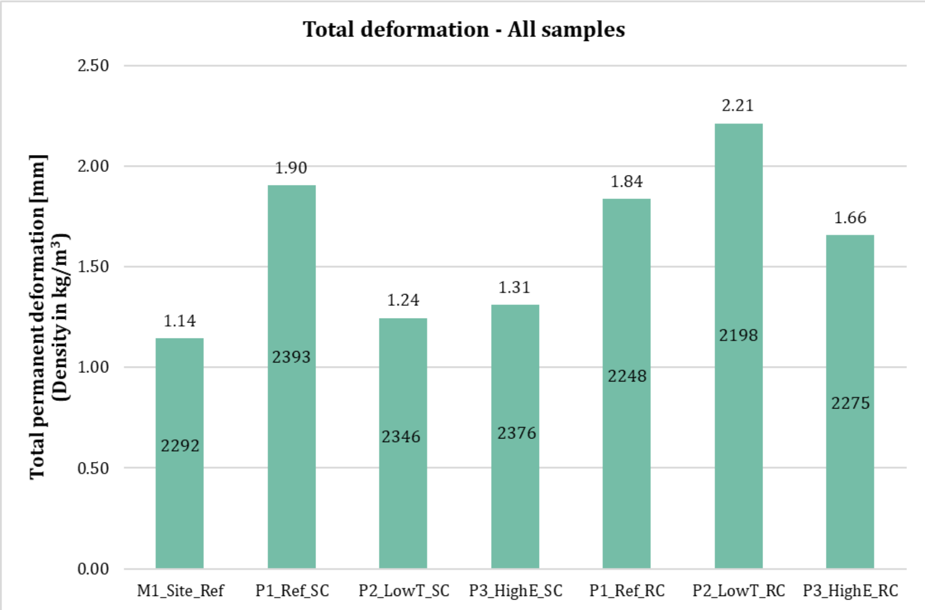


Figure 23 - Permanent deformation of samples from reference location at field and laboratories.

Applying the same tolerance value of 33%, it can be seen from Figure 23 that the procedures *P2_LowT_SC* and *P3_HighE_SC* are closer in value to the reference *M1_Site_Ref*. The other procedures in the laboratory have much higher values than that from the *M1_Site_Ref* samples. This means that the slab compacted specimens show more similarity to the field samples than the 2.2 ton roller compacted specimens. The details of the statistical analysis of the influence of density on permanent deformation are available in the Appendices.

Figure 22 and Figure 23 also shows the average density of the samples tested. It was found that the density and permanent deformation had a moderate negative correlation. The trend observed was that with the decrease in density, the permanent deformation value increases. On performing a regression analysis, details of which can be found in the Appendix E, it was found that the density was a good predictor of permanent deformation.

3.3.3 Conclusions

From the results of the density and the TCC tests, the following conclusions can be made:

1. Creep rate:
    a. The change in roller regime on-site or in the laboratory does not influence the creep rate values of the samples.
    b. The reference procedure used in the slab compactor, *P1_Ref_SC* represents the field samples the closest with respect to creep rate.
    c. The roller compactor does not represent the field samples respect to creep rate.
2. Permanent deformation:
    a. The change in roller regime on-site or in the laboratory does not influence the creep rate values of the samples.
    b. The procedure that uses lower temperature and that using higher energy input compared to the reference procedure in the slab compactor represents the field samples the closest with respect to permanent deformation.
    c. The roller compactor does not represent the field samples respect to creep rate.
3. Density is a good predictor for creep rate and permanent deformation when the range of density is between 2166 and 2405 kg/m^3.

3.4 Cyclic indirect tensile test (Cy-ITT)

The Cy-ITT tests were carried out based on the protocol developed by Boskalis which has its base in NEN-EN 12597-26 & AL Sp-Asphalt 09 (DE). The test setup used is shown in Figure 24. This is not a standard test as prescribed by the Dutch pavement standards and hence there is no reference value to compare the results to.

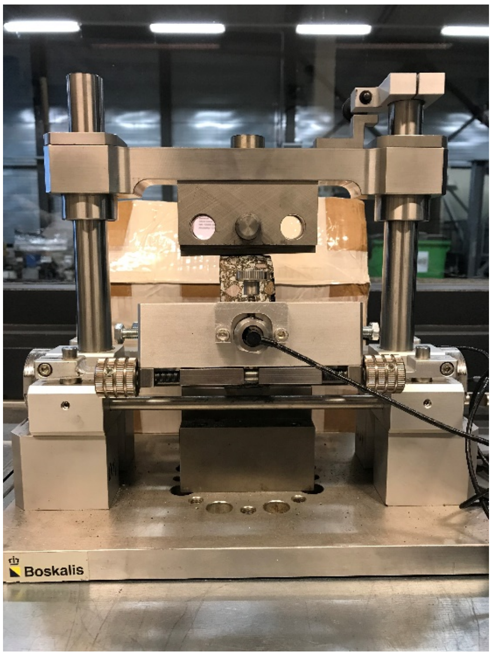


Figure 24 - Test setup used for performing Cy-ITT.

3.4.1 Stiffness

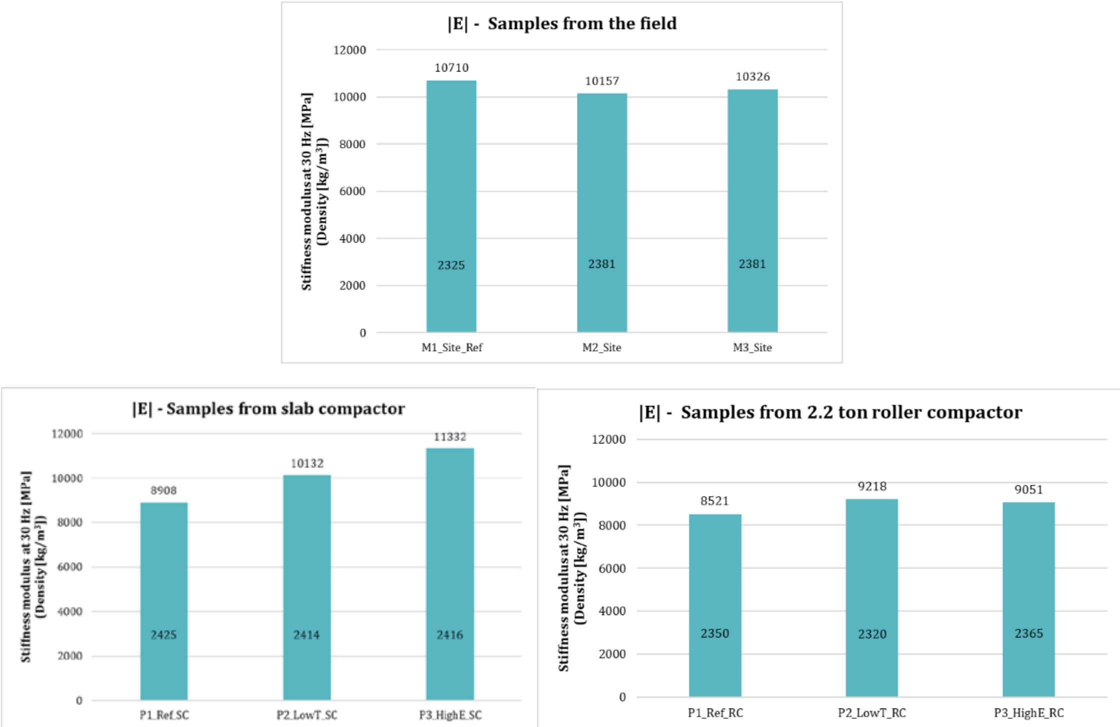


Figure 25 - Stiffness modulus of samples from the field (top), slab compactor (bottom left) and 2.2 ton roller (bottom right) measured at 30 Hz.

Figure 25 shows the stiffness modulus of samples from the field, slab compactor and 2.2 ton roller compactor at 30 Hz. The difference between stiffness of the samples from the site were found to be non-significant. This means that the variation in the roller regime that took place on-site is not significant enough to influence the stiffness. The difference between the stiffness of the samples from the slab compactor was found to be significant. The stiffness of samples from *P2_LowT_SC* and *P3_HighE_SC* are higher than that of *P1_Ref_SC*. This increase is significant. Thus, with change in the roller regime the stiffness increases. The difference between the stiffness of the samples from the 2.2 ton roller compactor was found to be non-significant. This implies that with change in the roller regime of 2.2 ton roller compactor does not influence the stiffness of the samples.

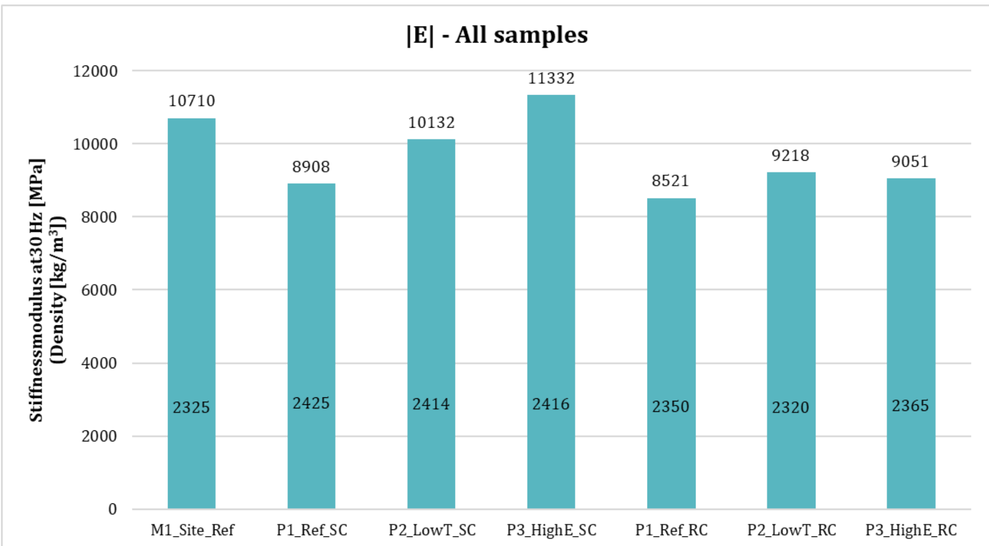


Figure 26 - Stiffness modulus of samples from reference location at field and laboratories measured at 30 Hz.

To compare the procedure that best represents the field roller regime an arbitrary tolerance value of 10% was used. Any value that falls in the 10% range of the stiffness values from field is then considered to represent the field compaction. On comparing the laboratory stiffness samples at 30 Hz to that of the field *P2_LowT_SC* and *P3_HighE_SC* represents the field regime.

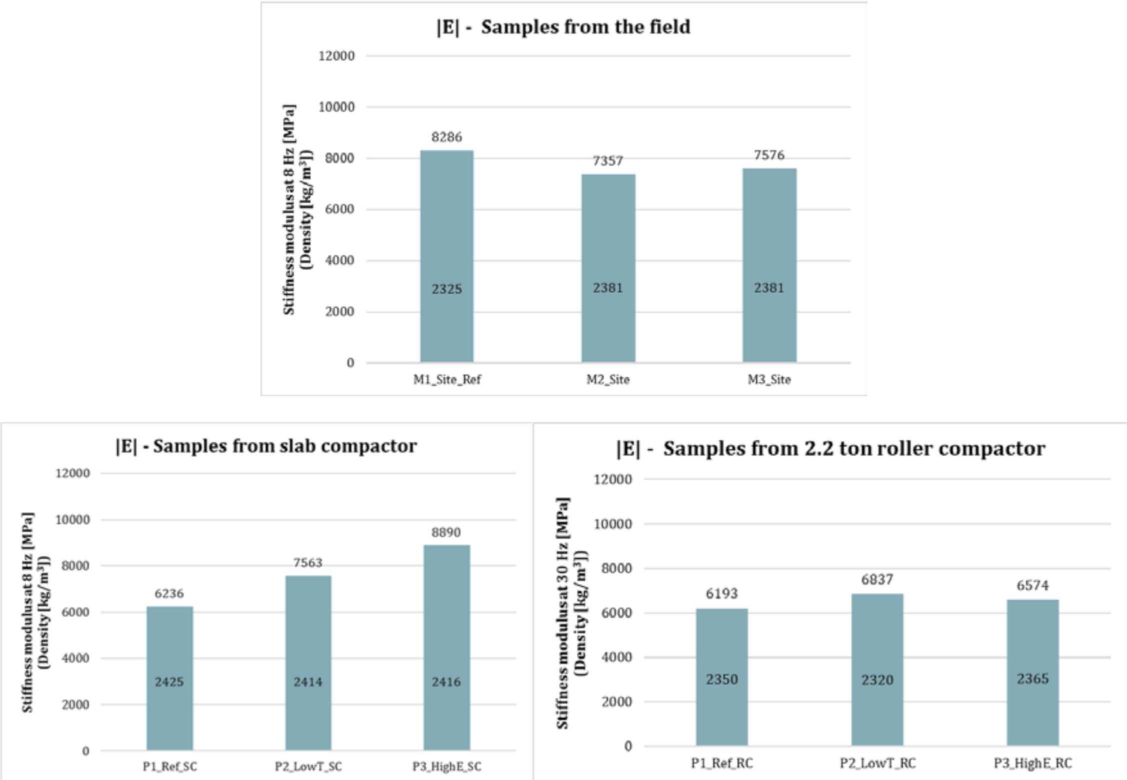


Figure 27 - Stiffness modulus of samples from the field (top), slab compactor (bottom left) and 2.2 ton roller (bottom right) measured at 8 Hz.

Figure 27 shows the stiffness modulus of samples from the field, slab compactor and 2.2 ton roller compactor at 8 Hz. The variation in the roller regime that took place on-site is not significant enough to influence the stiffness. The difference between the stiffness of the samples from the slab compactor was found to be significant. The stiffness of samples from *P2_LowT_SC* and *P3_HighE_SC* are higher than that of *P1_Ref_SC*. This increase is significant. Thus, with change in the roller regime the stiffness increases. The difference between the stiffness of the samples from the 2.2 ton roller compactor was found to be non-significant. This implies that with change in the roller regime of 2.2 ton roller compactor does not influence the stiffness of the samples.

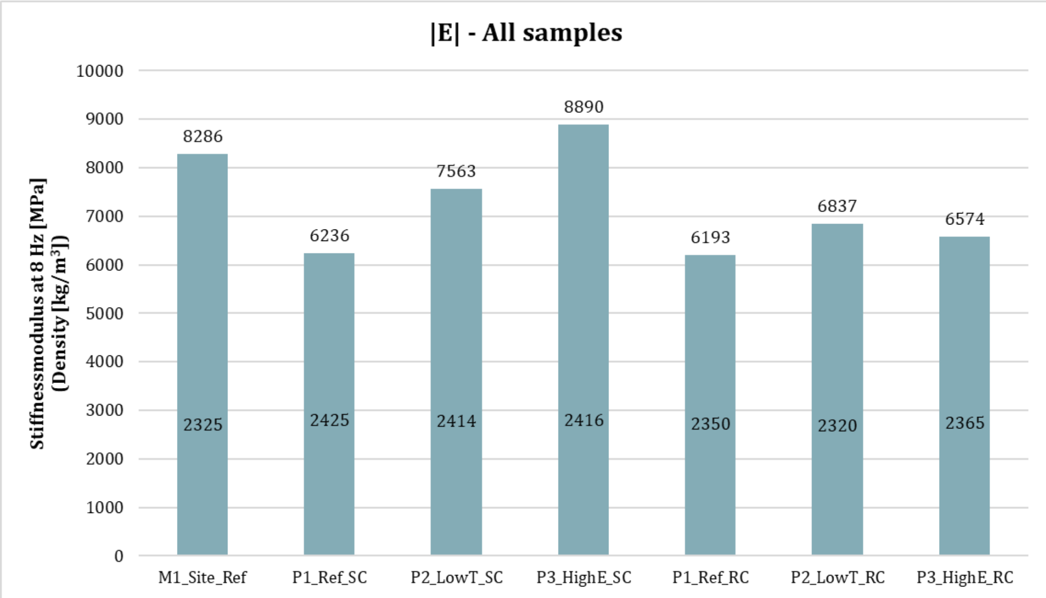


Figure 28 - Stiffness modulus of samples from reference location at field and laboratories measured at 8 Hz.

To compare the procedure that best represents the field roller regime a tolerance of 10% was used. Any value that falls in the 10% range of the stiffness values from field is then considered to represent the field compaction. On comparing the laboratory stiffness samples at 8 Hz to that of the field *P2_LowT_SC* and *P3_HighE_SC* represents the field regime.

The figures above also show the average density of the samples tested. It was found that the density and stiffness had no correlation. The change in density does not influence the stiffness modulus. On performing a regression analysis, details of which can be found in the Appendix D, it was found that the density was not a good predictor of stiffness.

3.4.2 Fatigue

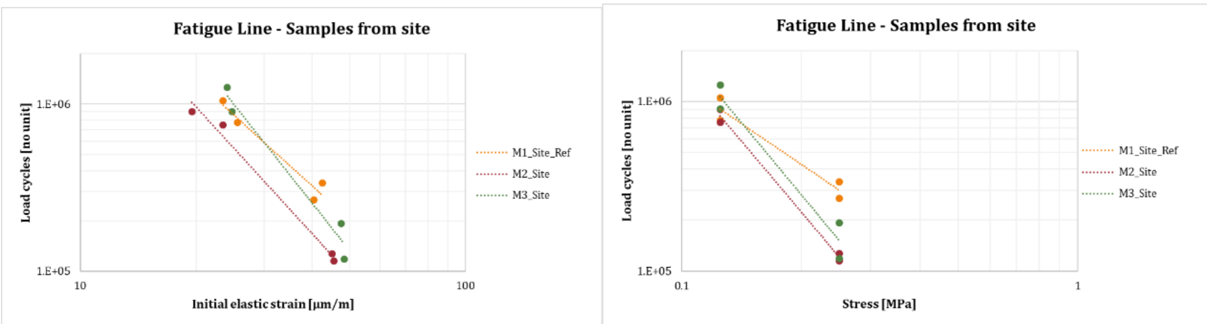


Figure 29 - Fatigue plots of samples from site.

Figure 29 shows the fatigue plots of the samples from site. It can be seen that the slopes *M2_Site* and *M3_Site* are similar compared to that of *M1_Site_Ref.* This means that there is a clear influence of the roller regime adopted on-site. On considering the slope of the stress plot of the samples, the samples from *M1_Site_Ref* is less sensitive to loading compared to those from *M2_Site* and *M3_Site.*

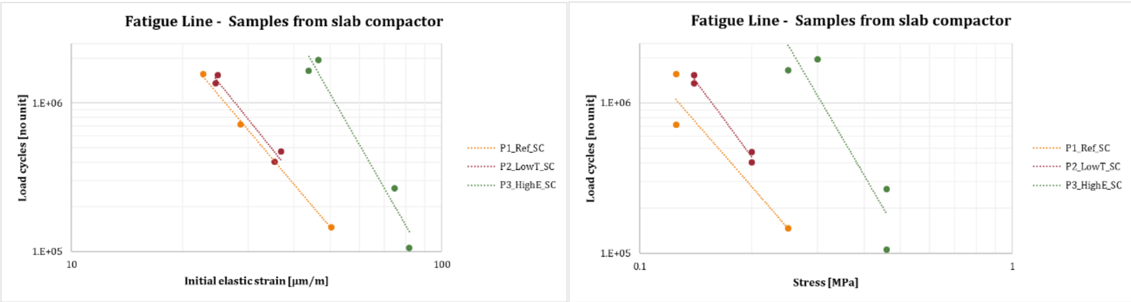


Figure 30 - Fatigue plots of samples from slab compactor.

Figure 30 shows the fatigue plots of the samples from slab compactor. The slopes of all three procedures vary and these lines would intersect each other at some point. This means that there is a clear influence of the procedures used in the slab compactor. On considering the slope of stress plots of the samples, the samples from *P1_Ref_SC* is the least sensitive to loading followed by *P2_LowT_SC* and *P3_HighE_SC.*

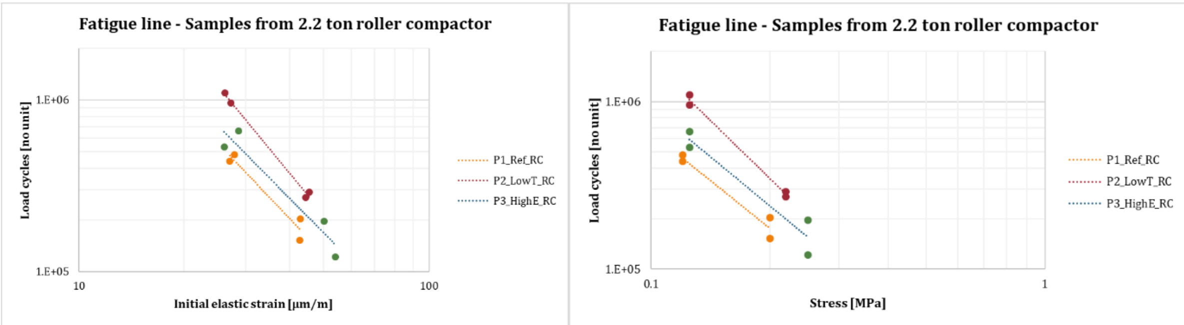


Figure 31 - Fatigue plots of samples from 2.2 ton roller compactor.

Figure 31 shows the fatigue plots of the samples from 2.2 ton roller compactor. It can be seen that the slopes of procedures *P1_Ref_RC* is similar to *P3_HighE_RC* compared to *P1_Ref_RC.* This means that there is a clear influence of the procedures used in the 2.2 ton roller compactor. On considering the slope of stress plots of the samples, the samples from *P1_Ref_RC* is the least sensitive to loading followed by *P3_HighE_RC* and *P2_LowT_RC.*

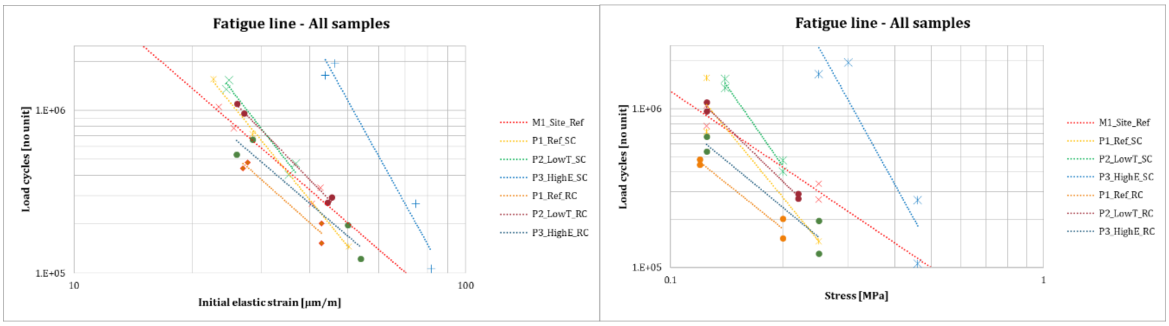


Figure 32 - Fatigue plots of samples from site (reference location), slab and 2.2 ton roller compactor.

Figure 32 shows the fatigue plots of the samples from *M1_Site_Ref*, slab and 2.2 ton roller compactor. The slopes of the samples from the slab compactor are much steeper compared to the samples from the field or 2.2 ton roller compactor. This means that the samples from slab compactor are more sensitive to loading compared to those from site or 2.2 ton roller compactor. The slopes of *P1_Ref_RC* and *P3_HighE_RC* are closer to that of *M1_Site_Ref.*

3.4.3 Conclusions

The conclusions from the Cy-ITT are as follows:

1. Stiffness:
   a. The stiffness modulus at 30 Hz is not influenced by the variation in roller regime on-site or from the 2.2 ton roller compactor. However, it is influenced by the variation in the roller regime in the slab compactor.
   b. The stiffness modulus at 8 Hz is not influenced by the variation in roller regime on-site or from the 2.2 ton roller compactor. However, it is influenced by the variation in the roller regime in the slab compactor.
   c. The procedure using lower temperature and that using higher energy input compared to the reference procedure in a slab compactor represents the field regime at 30 and 8 Hz.
2. Fatigue:
   a. The change in roller regime on-site or difference in the procedure in the slab or 2.2 ton roller compactor, influences the fatigue life of the samples.
   b. The reference procedure using 2.2 ton roller compactor and that with higher energy input represents the field regime.
3. Density is not a good predictor of stiffness between the range of 2308 and 2458 kg/m^3.

3.5 Overview of results

The overview of the results individually analysed and reported in the previous sections of this chapter is given in Table 6, Table 7 and Table 8.

Table 6 - Overview of the measurements and results from the field.

	M1	M2	M3
Was the target density reached on-site?	No	Yes	Yes
Compaction temperature range	155 – 40°C	160 – 44°C	155 – 40°C
Total number of roller passes	10	12	12
Type of passes (Static/Dynamic/Combination)	Combination	Combination	Static
Type of rollers used	Tandem & 3drum	Tandem & 3drum	3drum
Does field density and measured density match?	Yes	Yes	Yes
Does the tested samples match the Dutch pavement standards and type test with respect to ITSR?	Yes	Yes	No
Does the tested samples for ITS match the type test	No	No	No
Does the tested samples match the Dutch pavement standards and type test with respect to creep rate?	Yes	Yes	Yes

The details from Table 6 are used to develop compaction strategies for AC11$_{surf}$ 30%PR. The strategies will be respect to the temperature and the energy input which are the two key factors considered in this project. Even though there are a lot of questions around target density being a key indicating factor for optimum compaction, the suggested strategies also do the same. This is because it is the best available indicator for optimum compaction available at this point in practice.

Table 7 - Influence of variability of field roller regime on tested performance characteristics.

Was the influence of the observed variability in roller regime on the properties significant?	ITSR	ITS	Fracture Energy	Creep rate	Permanent deformation	Stiffness	Fatigue
Field roller regime	No	No	No	No	No	No	Yes
Slab compactor	No	Yes	No	No	No	Yes	Yes
2.2 ton roller compactor	No	Yes	No	No	No	No	Yes

Table 7 shows the significant variability statistically except for fatigue. It is important to remember that the number of samples were limited although the analysis presented that the effect size was significant to reliably interpret the results. Thus, it is acceptable to retain the inference made statistically.

Table 8 - Table showing the laboratory procedure that closely represents the field samples from M1.

Laboratory procedures	ITSR	ITS	Fracture Energy	Creep rate	Permanent deformation	Stiffness	Fatigue	Density
P1_Ref_SC			×	×				
P2_LowT_SC		×			×	×		
P3_HighE_SC					×	×		
P1_Ref_RC			×				×	×
P2_LowT_RC	×		×					
P3_HighE_RC							×	

Table 8 shows the laboratory procedure that closely corresponds to the performance characteristics of the mixture from the field. Although the 2.2-ton roller compactor meets the density of that measured in the field, it is the samples from slab compactor that meets most of the other properties. It is important to note here that the density of the samples from the slab compactor were higher (3.3%) than that from the site. The roller compactor regime simulates the field the closest with respect to density yet fails to match the other characteristics. The slab compactor takes much higher value in terms of density yet simulates the site with respect to most of the procedures.

3.6 Compaction strategies

Using the overview of results from Section 3.5, the compaction strategies for the rollers on the field and those for simulation in the laboratory could be developed.

With the temperature and energy input considered as key elements in this project the following strategies can be determined for field compaction:

1. The critical zone for reaching target density for $AC11_{surf}$ 30%PR is shown in Figure 33.
2. The type of rollers used could be 3drum or tandem rollers. In case of tandem rollers, the use of dynamic passes is recommended.
3. The number of passes made in the initial phase that is, between 160 – 90°C, should be around 6 to 7 passes.

4. The passes have to be made successively so that the total time taken for the passes is on an average 15 minutes.

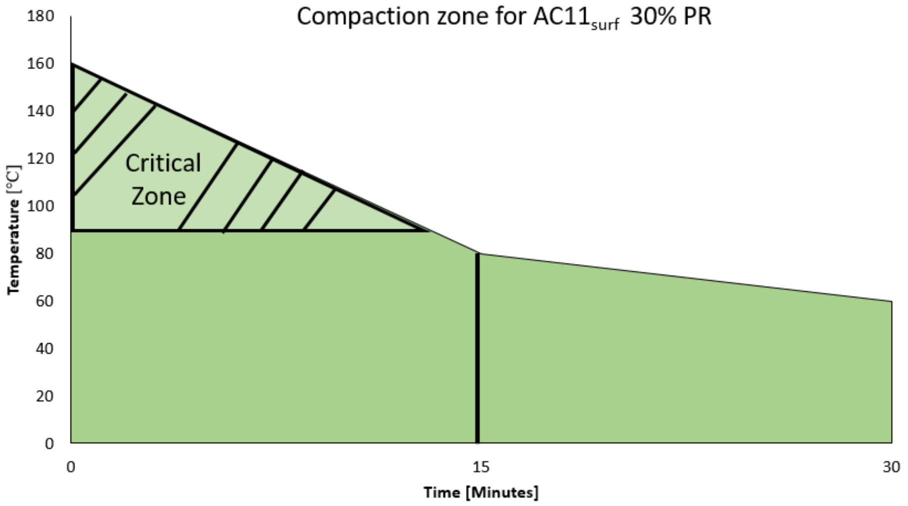


Figure 33 - Compaction zone for AC11surf 30%PR

5. The number of passes made following the initial phase, between 90 – 60°C should be around 3 to 4 static passes.

The strategies for simulation of field compaction in the laboratory was made based on (Bijleveld 2015) for slab compactor and 'walskarakteristiek' for 2.2 ton roller compactor.

To simulate the roller regime that takes place in the field using a 2.2 ton roller compactor on a freely moving slab, the following procedure must be followed to achieve the same density as on-site:

1. Use the same number and type of passes effectively with the assumption that 1 pass by three-drum roller (10 ton) is equal to 1.5 from the 2.2 ton roller at the laboratory and 1 pass by a 7-ton tandem roller (static or dynamic) is effectively the same.
2. The temperature monitored outside and the starting temperature can have a difference of 30°C in the initial phase that is, the same amount of passes can occur as long the temperature window is between 120 and 80°C.

To simulate the roller regime that takes place in the field using a slab roller compactor the following procedure must be followed to achieve specific end-quality parameters:

1. Density: Either of the three procedures used in the laboratories as shown in the Appendix can be used keeping in mind the force calculations, assumptions and the percentage difference of 3.3%.
2. ITSR, Creep rate and permanent deformation: Either of the three procedures used in the laboratories as shown in the Appendix C can be used keeping in mind the force calculations and assumptions made.
3. Stiffness: The procedures similar to procedure 2 and 3 shown in Table 2 and Table 3 respectively, in Appendix B can be used.

4 Guided instructions for roller operators

From the compaction strategies obtained in Section 3.6 an example of the instructions to the roller operators can be given as follows. The assumptions are made in case of surrounding temperatures, breadth of the road and so on are shown in Table 9.

Table 9 - Table showing the assumed conditions for the paving.

Conditions	Value	Units
Breadth of road	5	m
Length of road	2000	m
Temperature	9	°C
Wind speed	10	km/h
Target density	2360	kg/m3
Number of rollers	3	
Type of rollers	Tandem or 3 drum	
Mixture	$AC11_{surf}$	

From the assumptions above, an example of rolling instructions in simple and direct sentences is shown below. The start and stop of the rolling time was derived based on PaveCool.

Rolling instructions

Conditions

breadth 5m

length 2000m

9°C

10 km/h

Target density: 2360 kg/m³

Number of rollers: 3

Type of rollers: Tandem or 3 drum

Mixture: $AC11_{surf}$

	min	ideal	max
Mixture arrival temperature:	170°C	180°C	190°C
Layer thickness:	30mm	35mm	40mm

Initial phase

MIN 120°C

MAX 160°C

6 min — **Start rolling** within 6 minutes after the paver

Tandem roller: perform two alternating static and dynamic rolling. **2x**

OR

Three drum roller: perform three static passes. **3x**

Breakdown phase

90°C

120°C

Use tandem roller

3-4

Perform three to four **static passes**

Do not take more than 2 minutes between each pass.

Finishing phase

60°C

90°C

3-4

Perform three to four **static passes**

Stop rolling after 26min

5 Conclusions and recommendations

In this project, an attempt was made to provide better instructions to the roller operators, and to be able to simulate the field compaction in the laboratory. This way, one of the most complex process in pavement construction could be understood better. A design approach was undertaken to achieve the same. A methodology was designed based on the goals of the project and the stakeholders. This methodology included monitoring field compaction, simulating the same in the laboratory and testing performance characteristics of the chosen asphalt mixture – $AC11_{surf}$. In order to validate the methodology, an approach was adopted based on the requirements of the methodology and goals of the project. Upon completion of investigating the problem, designing the methodology and validating the same, the conclusions of this design project, reflection on various elements of the project, critical lessons learnt, and some recommendations are given in this chapter.

5.1 Conclusions

The designed methodology had some key requirements to be met in order to develop guided compaction strategies. On exploring these requirements, it can be concluded that all those mentioned in Chapter 2 are met, based on the following reasons.

1. Utility: The compaction strategy for the chosen mixture was developed using the designed methodology. The strategies are clear, simple and technologically feasible. The density outcome on the pavement and slab compactor can be evaluated only upon implementation of the strategy which is beyond the scope of the project.
2. Efficiency: The methodology incorporates two critical factors in this project and has the capability to include multiple factors respect to compaction such as temperature, roller regime, compaction equipment, type of compaction and so on, to make the compaction process more explicit. The feedback system helps to incorporate new learnings upon the next use.
3. Reliability: The validation of the methodology shows that it can be used for a chosen asphalt mixture to develop compaction strategies. It is possible to define the type of mixture or mixtures. This methodology can thus be used to test different mixtures depending on the need of the hour.
4. Flexibility: The approach used in this project to implement this methodology is based on carefully chosen boundaries, the approach that needs to include the field, lab and test elements and assumptions. The same can be done by other contractors or researchers to develop compaction strategies.

The major advantage of the methodology is that it can be adapted to the type of asphalt mixture that is chosen. This helps decide the critical factors to be considered and the tests to be accounted for the chosen mixture. This means that the approach used in this project is just one of the many approaches that can be used. Based on the contractors or researchers needs, the approach can be modified.

Although the requirements of this designed artefact are met, it is important to remember that the outcome – compaction strategies – are limited to the temperature and energy input as they were identified as the key factors influencing compaction. The implementation of the strategies on-site for evaluation lies beyond the scope of this project, as implementation and evaluation belong to the engineering cycle and not the design cycle.

5.2 Reflection

Designed methodology

There is a lot of scope and flexibility for the methodology to be used efficiently. With the freedom to choose the mixture type or types, customised goals, boundaries, choices made with respect to the field and laboratory compaction, and the tests to be made, it makes it a highly flexible design to use. This is very important and essential for the industry, especially for the contractors as it can be personalised to their needs at any point in time.

Assumptions made

A lot of assumptions had to be made and boundaries to be set to develop an approach to use the methodology. This is something I believe is going to recur in the future because there are a lot of variabilities with respect to compaction. This includes variability in process, mixtures, place where it is commonly used, tests, place of test type of laboratory, etc. In the beginning of the project, this was difficult to narrow down as there was always an alternative approach and no definitive right or wrong. Time played an important factor in setting strict boundaries for the project. This includes time available for the design project, time at which laboratory machines were available and time at which the paving projects took place.

Approach (Field and laboratory)

In this project, to validate the methodology the approach used field monitoring first to simulate it in the laboratory. This follows the idea of going from the least controlled environment (actual practice) to the most controlled environment (laboratory). The simultaneous approach towards this is not a necessity, such a choice made it possible to compare the 'same' mixture used in the field. Another key discussion was performing three procedures in three different laboratories versus all three procedures in each laboratory. In order to have a consistent samples, which was the priority in this case, it is better to have followed this approach.

Practicalities of field and lab compaction

The field and laboratory compaction took place on the same evening/night simultaneously. This was a consciously made choice to avoid the difference in the mixture that would be received. The sample from the plant had to be sent to three different laboratories across the Netherlands. The driver of the asphalt truck had to be informed. The laboratories had to be informed of what needs to be done starting from tentative time of receiving the material to the last information that needs to be reported back. The slab compactors at the three laboratories had the information given to the last detail including the emergency contact numbers. However, with respect to the 2.2 ton roller compactor this wasn't the case: Although the procedure was set in place and the laboratory staff was informed of the documentation of the translation of field to laboratory, it was not enough. This was due to the short time within which the trial test and the actual project took place. The paving projects are usually planned in by contractors only a couple of weeks in advance. The trial tests with slab compactors took place well in advance and there was time enough to organise it better.

Tests done

The tests were performed at various laboratories. It was ensured that all the samples are tested at the same laboratory and with the same machine. The variation in the number of samples available for testing compared to those prescribed were due to the unavailability of the same. The deviation in the height of the samples for triaxial test was due the cores from the field are thinner and simulating the same in laboratory would also imply having thinner samples for testing.

Similarly, the improper coring of the samples from the field also lead to polishing the samples to a lower thickness than expected. For the all the tests performed in this project, trial tests were done on available additional samples before beginning the tests. This was to ensure that the tests can be performed well: everything for the actual tests are available, the machine is working and to check what can be expected. Despite these, there were unexpected breakdown of machines during the design project.

Analysis of results

Now that there has been lot of information collected from pavement projects using PQi and there are attempts to streamline these collected data, it is also essential for the laboratories to do the same. With the difficulty to define the effect of difference in the resulting test values, it becomes essential to streamline the laboratory test result data. These results in most laboratories are readily available and it is essential to begin with statistical analysis on such data to understand the pavement behaviour which are interpreted through these tests. One can see that this is difficult to do as it is not evident how much of a difference in the performance characteristics means something physically with respect to the mixture or pavement (Statistical significance, number of samples and relation to it).

The resulting compaction strategies for the field are restricted to the roller regime and temperature factors. The simulation of the field compaction in the laboratory also needs to be analysed from the perspective of impact of confinement. In the case of slab compactor and 2.2 ton roller compactor, the asphalt mixture was confined. The confinement was more in the case of slab compactor. To arrive at the instructions for operators, additional support from tools such as PaveCool were necessary.

Setting up of the PDEng project

Upon taking a very complex multi-faceted challenge as compaction, defining project boundaries very clearly with the experts in the very beginning of implementation of the methodology helps the project itself to be more streamlined. This also helps identify the areas where special skills are required for the trainee or the contractors. In this project, upon expecting several data analysis, I took the statistical analysis course which helped interpreting the data better. The key takeaway from the project is that, while addressing a very big cluster of complicated factors is involved in a process – setting boundaries is essential. This includes boundaries with respect to material, time, essential factors, and outcome. This improves the focus and efficiency of the methodology developed for a precise output.

5.3 Recommendations

The recommendations are made based on the critical reflection of this project. In this project, the statistical approach was followed. There was always a minimal statistical requirement met in this project, but this is not enough. In order to interpret the statistical data, there is also a need for the pavement industry to know the spectrum of variability of parameters and its corresponding influence on the pavement performance. This is still an area that needs to be explored. The availability of this information will enhance the accuracy and quality of strategies that can be derived from the methodology. Similarly, it is also very important to study the influence of density, a key indicator of performance of the asphalt mixtures. In order to take this project further, it is also recommended to use the compaction strategies in addition to the current experience on the field, and to verify if the compaction on the field could be strictly guided. The presence or absence of variability on that project could give more insight into the implementation and value of guided instructions. This would also help the commonly arising discussion of starting the compaction process in the laboratory and then implementing the same in the field. It is also recommended to study the effect of confinement of the mixture with respect to the slab compactor and if the compacting methods used for a slab compactor yields results which can sometimes be perceived as 'too good' to be true, especially with respect to density.

5.4 Lessons learnt

The lessons learnt from applying the methodology can be used to improve the approach towards developing guided operational strategies for asphalt compaction.

1. As work is dynamic when it comes to paving projects with very short notices, it is essential to work time bound to be prepared for the actual monitoring.
2. It is important to perform trial tests and sufficient time between trial and actual data collection is required. In addition to this, trial tests for monitoring, slab preparation and laboratory tests help in organising the resulting data also better as one knows what to expect and be prepared for it to the best of their capability.
3. The translation of the field compaction with respect to force in the laboratory must also consider the effect of confinement.
4. It is important to make a statistical analysis on the available data on different performance tests in the laboratory. This could help give more clarity with respect to critical difference.
5. It will be difficult to always have enough samples for statistical tests, like regression. So the compromise needs to be made based on the goals/reasons for performing the test.
6. The financial and practical aspects of monitoring projects, preparing slabs, testing samples are also important factors to be considered before implementing the methodology.
7. Upon involving experts from the industry, it is also important to inform them in the beginning the nature of PDEng courses and what is expected of them.
8. Communication, documentation and reflection is key at every single stage of employing the methodology.
9. For such PDEng projects where the scope of defining the beginning and end is large, the goals must be better defined, and much stricter boundaries need to be made in order.
10. Having clear boundaries set will also help the PDEng trainees choose their coursework accordingly, as this is usually expected to be completed by the ned of their first year.

References

Airey, G. D., and A. C. Collop. 2016. 'Mechanical and Structural Assessment of Laboratory- and Field-Compacted Asphalt Mixtures'. *International Journal of Pavement Engineering* 17(1): 50–63. http://dx.doi.org/10.1080/10298436.2014.925551.

ASPARi. 2014. *ASPARi Roadmap Naar 2020*.

Bijleveld, F.R. 2015. Civil Engineering 'Professionalising the Asphalt Construction Process: Aligning Information Technologies, Operators' Knowledge and Laboratory Practices'. University of Twente.

BOMAG GmbH. 2009. *Basic Principles of Asphalt CompactionBasic Principles of Asphalt Compaction*. First. Boppard: BOMAG GmbH.

Cheyyar Nageswaran, Priya Darshini. 2017. 'Detailed Test Plan_Priya_V2_ Strategies for Compaction'.

CROW. 2015. *Standaard RAW Bepalingen 2015*. Ede.

Dubois, Vincent, Chantal De La Roche, and Olivier Burban. 2010. 'Influence of the Compaction Process on the Air Void Homogeneity of Asphalt Mixtures Samples'. *Construction and Building Materials* 24: 885–97. http://dx.doi.org/10.1016/j.conbuildmat.2009.12.004.

Ghafoori Roozbahany, Ehsan, Manfred N. Partl, and Alvaro Guarin. 2017. 'Introducing a New Method for Studying the Field Compaction'. *Road Materials and Pavement Design* 18(November): 26–38. http://dx.doi.org/10.1080/14680629.2017.1304245.

Heurne, H.L. ter. 2004. 'Compaction of Asphalt Road Pavements: Using Finite Elements and Critical State Theory'. University of Twente.

Hu, Wei, Baoshan Huang, Xiang Shu, and Mark Woods. 2017. 'Road Materials and Pavement Design Utilising Intelligent Compaction Meter Values to Evaluate Construction Quality of Asphalt Pavement Layers Utilising Intelligent Compaction Meter Values to Evaluate Construction Quality of Asphalt Pavement Layers'. *Road Materials and Pavement Design* 18(4): 980–91. http://www.tandfonline.com/action/journalInformation?journalCode=trmp20%5Cnhttp://dx.doi.org/10.1080/14680629.2016.1194882.

Inc, The Transtec Group. 2018. *Intelligent Compaction and Infrared Scanning Field Projects with Consulting Support Intelligent Compaction and Infrared Scanning Field Projects with Consulting Support Final Report Missouri Department of Transportation*.

Indian Roads Congress. 2013. *Guidelines on Compaction Equipment for Road Works*. New Delhi, India.

Kassem, Emad, Arif Chowdhury, Tom Scullion, and Eyad Masad. 2016. 'Application of Ground-Penetrating Radar in Measuring the Density of Asphalt Pavements and Its Relationship to Mechanical Properties'. *International Journal of Pavement Engineering* 17(6): 503–16. http://dx.doi.org/10.1080/10298436.2015.1007225.

Lavin, Patrick. 2003. *Asphalt Pavements: A Pracatical Guide to Design,Production and Maintenance for Engineers and Architects*. London and New York: Spon Press.

Liu, Donghai, Min Lin, and Shuai Li. 2016. 'Real-Time Quality Monitoring and Control of Highway Compaction'. *Automation in Construction* 62: 114–23. http://dx.doi.org/10.1016/j.autcon.2015.11.007.

Masad, E. et al. 2016. 'Finite Element Modelling of Field Compaction of Hot Mix Asphalt. Part II: Applications'. *International Journal of Pavement Engineering* 17(1): 24–38.

Miller, Seirgei Rosario. 2010. *Hot Mix Asphalt Construction: Towards a More Professional Approach*. http://doc.utwente.nl/86949/.

Mollenhauer, Konrad, and Michael P. Wistuba. 2016. 'Influence of Asphalt Compaction Procedure on 3D Deformation Properties'. *International Journal of Pavement Engineering* 17(1): 5–12. http://www.tandfonline.com/doi/full/10.1080/10298436.2013.812213.

Muniandy, Ratnasamy, Fauzan Mohd Jakarni, Salihudin Hassim, and A. R. Mahmud. 2008. 'A Newly Developed Laboratory Slab Roller Compactor (Turamesin): An Overview'. *International Journal of Engineering, Transactions A: Basics* 21(2): 133–42.

National Asphalt Pavement Association. *Rolling and Compaction of Hot Mix Asphalt Pavement*.

Neff, Aaron M. 2013. 'Analysis of Intelligent Compaction Field Data on Layered Soil'. Colarado School of Mines.

Nikolaides, Athanassios. 2014. *Highway Engineering: Pavements, Materials and Control of Quality*. Boca Raton: CRC Press.

Plati, Christina, Panos Georgiou, and Andreas Loizos. 2016. 'Influence of Different Roller Compaction Modes on Asphalt Mix Performance'. *International Journal of Pavement Engineering* 17(1): 64–70. http://www.tandfonline.com/doi/abs/10.1080/10298436.2014.925552.

Thom, Nick. 2014. *Principles of Pavement Engineering*. Second. London: ICE Publishing.

Timm, David H, Vaughan R Voller, Eul-bum Lee, and John Harvey. 2001. 'Calcool: A Multi-Layer Asphalt Pavement Cooling Tool for Temperature Prediction during Construction'. *International Journal of Pavement Engineering* 2(3): 169–85.

Vasenev, A.N. 2015. 'Visualizing Asphalt Roller Trajectories in Context'. Univeristy of Twente.

VBW Asfalt. 1989. *Het Verdichten van Asfalt in de Praktijk*. Breukelen.

Wieringa, Roel J. 2014. *Design Science Methodology for Information Systems and Software Engineering*. Springer.

———. 2016. 'Framework for Design Methodology'.

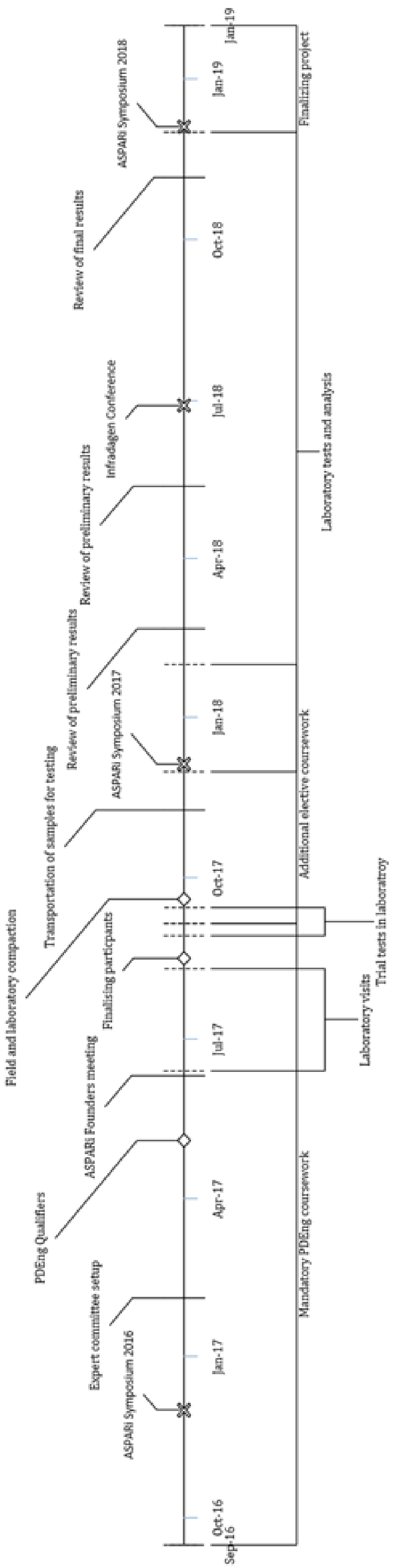
Wistuba, Michael P. 2015. 'The German Segmented Steel Roller Compaction Method – State-of-the-Art Report'. *International Journal of Pavement Engineering* 17(1): 81–86. http://www.tandfonline.com/doi/full/10.1080/10298436.2014.925555.

Xu, Qinwu, and George K. Chang. 2013. 'Evaluation of Intelligent Compaction for Asphalt Materials'. *Automation in Construction* 30: 104–12.

Xu, Qinwu, George K. Chang, and Victor L. Gallivan. 2012. 'Development of a Systematic Method for Intelligent Compaction Data Analysis and Management'. *Construction and Building Materials* 37: 470–80. http://dx.doi.org/10.1016/j.conbuildmat.2012.08.001.

Appendices

Appendix A. Project timeline



Appendix B. Assumptions made in the project

Selection of mixtures

After detailed discussions and due considerations, along with the advisory committee it was decided to limit the number of mixtures that will be tested in this project to two – $AC11_{surf}$ and PA16+. The premises on which these were chosen were based a number of factors and consciously set limitations as follows:

1. It was decided to test the surface mixtures.
2. It was decided to test two different mix – dense and porous.
3. Mixtures that are commonly used in the Netherlands[15].
4. Mixtures that pose challenges with respect to compaction, here, being under-compacted ($Ac11_{surf}$) and over-compacted (PA16+)[16].
5. Mixtures that does not include polymer modified bitumen or partial recycling(PR)[17].
6. The entire time allotted for the project itself is 2 years thus limiting the amount of work that can be done to reach the goals of the project.

It can still be argued that there are other mixtures which would fit these frame-work or those which could be more important for certain contractors/researchers for a few reasons. But it is more important to start the project at some point by drawing a few hard lines considering several factors.

Approach

The most critical factors for the chosen mixtures were identified as temperature and energy input.

Temperature: For any given asphalt mixture, it is known that temperature plays an important role for compaction because of the behaviour of the materials in the mixture on change in temperature.

Energy input: The compaction process also highly relies on the energy input on the mixtures by the roller. This can further be divided into three criterion – type of energy, magnitude and time.

9. The type of energy input, static or dynamic, is important. In this project, for AC11surf dynamic compaction is done to reach the target density whereas for PA16+ the type of energy input is static. A rough sketch of the effect of the type of input is shown in Figure 1.
10. The amount (magnitude) of energy input which also depends on the type of roller used is important.
11. The type and amount of energy must be put in at the right time on the mixture without any time lag between the rollers thus making time also a critical factor.

---

[15] Given that a PDEng project should have a design outcome for existing challenges also implies that the outcome should be implementable and useful in the near future. Thus it was decided to start with mixtures that are commonly used.

[16] Based on the expert opinion of my Advisory Committee.

[17] The aim is to use mixtures without PR. During the period of the project if there are only projects using PR for the chosen mixtures, then those mixtures will be used. Given that the use of PR in dense mixes are becoming common and Rijkwaterstraat (RWS) does approve of the same, it then also becomes more practical.

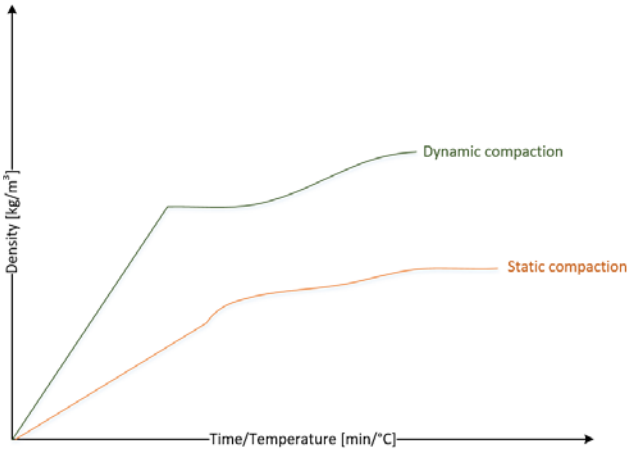


Figure 1A - Density progression representation.

Based on the critical factors identified above the approach to reach the goals of the project is as follows:

12. Two pavement construction projects, one for each mixture, will be identified[18].
13. Both the projects will then be monitored (PQi) at three points and cores will be made from them for further testing.
14. One representative point will be identified of the three monitored points and this methodology will be the reference for laboratory simulation of compaction.
15. The simulation of on-site compaction in the lab will be attempted using slab compactor and roller compactor using the reference procedure and two additional variations.
16. Once the slabs are made in the laboratory, the mechanical properties of the mixtures are put to test through those mentioned in Table 1. These tests are performed on the cores from the lab and the site.

Table 1 Mixtures and corresponding tests

Asphalt mixture	Tests
PA16+	1. Raveling (Abrasion/scuffing) 2. CT-Scans (porosity and air voids) 3. Indirect Tensile Strength (Cracking)
$AC11_{surf}$	1. Cyclic Indirect Tension Tests (Stiffness and Fatigue) 2. Indirect Tensile Strength (Cracking) 3. Cyclic compression tests (Permanent deformation)

17. The test results will then be analysed and compared to validate the lab simulation based on which the final design of the operational strategies will be made.

The detailed setup of the PQi and laboratory work can be viewed in file (Cheyyar Nageswaran 2017). Elaborating more on the details given above, there are few things which needs to be made explicit. The attempt to make the compaction process explicit is a very big gap to bridge and this

[18] Even though all the above said points hold, there are two major ruling factors – goal and time. Given that this is now the end of the 1st year of this project, the focus is more on having a genuine design outcome for the mixtures that would be tested. Thus in case of a situation where the proposed mixtures could not be tested due to the lack of projects in the given time-frame, in all probability, a different mixture would be tested which fits the time-frame.

project is only the first step towards it. Thus there are few points that are to be realised in case of this project.

18. During the execution of the road construction project outside, there are few factors which cannot be influenced such as the temperature and the magnitude of energy input.
19. It is also known that with the roller compactor that is designed to be used in the laboratory, the magnitude can be influenced to a very limited extent and that there will be edge effects on the slabs made.
20. From the detailed test plan (Cheyyar Nageswaran 2017) it can be seen that the slabs made are bigger (1x1m) than usual. This is to measure the influence of vibration (in case of $AC11_{surf}$) and in order to mimic the practices followed outside. This adds to necessity for compaction of bigger (1x1m) slabs than the usual (500x500mm). This might lead to the questions:
    a. Wouldn't this have more/less influence on the slabs because of the scale at which it is being done?
    b. What is the need to reciprocate the process in the lab?
    c. The answers to the above questions are that:
        i. The influence or the lack of it will be studied. Instead of leaving out the regular procedure of dynamic compaction of the AC mix and assuming the influence, it is better to try and rule it out or factor it in for effective simulation.
        ii. The answer for this is two-fold:
        iii. The goal as mentioned earlier is simulation of compaction in the lab and thus the best way to test it is by trying to reciprocate it in the lab.
        iv. In the long run if there is a choice between to try and simulate effective compaction in the lab or on-site, before actual construction, the obvious choice would be the former. This is because the time, material, effort and cost spent on it would then ideally be lesser with the advantage of using as many combinations as possible and hence more preferred.
21. Target density is one of the major criterion that is looked for on the constructions on-site. However, the direct relation of this to the mechanical properties of mixtures are not clear. Thus, this project also considers this factor and the influence of density on the mechanical properties will be studied.
22. This project aims to design a laboratory protocol for simulating on-site compaction in the lab and compaction strategies for asphalt mixtures. However, it is important to note that there are a number of less explored terrain such as reciprocating a temperature range similar to the on-site conditions, input of energy at the right temperature and so on which is included in this project.
23. The methods suggested in this project are different from the regular type-testing. This means using different compaction methods, temperature range in the lab, different sample sizes and so on. The advantages of this are that the comparison of the on-site and lab compaction will be on the same level as the procedures are similar and thus the outcome will be more concrete. The major disadvantage is the lack of experience with such conditions and thus the outcome of these tests is uncertain.

Outcome

Finally, it is essential to note that:

1. If the results are in such a way that there can be a clear fit between on-site and lab compaction leading to concrete operational strategies for compacting $AC11_{surf}$ and PA16+, then it shall put us a step further in looking into the whats' and hows' for other mixtures.
2. If not, the results will still be the basis for building up on the ways to design operational strategies for asphalt compaction, what are the critical factors and their inter-relationship and so on thus bridging the gap between the implicit and explicit knowledge.

Appendix C. Trial tests

This is a summary of the observations made on the practical matters during the trial slab preparation that took place on the 29th and 31st of August and the 12th of September. Few conclusions are made based on the observations to best suit the preparation of the 'real' slab which will be used for the project.

1. KWS - 29 August 2017

Three trial slabs were prepared on 29.08.2017 for the project 'Designing guided operational strategies for asphalt compaction'. Of these 2 slabs were made of PA16+ and one of $AC11_{surf}$ 30%PR.

PA16+

The compaction of the first slab started at 8:00 hrs. with PA16+. The entire slab preparation time took 35 min in total. The mix was first compacted to 55mm (pre-compaction) using position control and then switched to the ALP-A control for further compaction. The actual end height after the completion of compaction was 47.06 mm instead of the target of 50 mm.

Points to note:

1. The mould and the segment were not pre-heated.
2. The thermocouples were placed in the centre of the plate. There were problems with the thermocouples and IR camera. The temperature readings were faulty.
3. At this point the starting height of each phase were not set (2mm) higher than the end height of the previous phase as mentioned in the protocol.

The compaction of second slab started at 13.10 hrs. with PA16+. The entire slab preparation time took 40 min in total. The mix was first compacted to 55mm (pre-compaction) using position control. Then switched to the ALP-A control for further compaction. The actual end height after the completion of compaction was 47.30 mm instead of the target of 50 mm.

Points to note:

1. The mould and the segment were not pre-heated.
2. The thermocouples were placed, one at a corner of the slab and the other along the side in such a way that the end of the thermocouples were free and in contact with the mixture to measure the temperature as shown in Figure 1. Even after this the measurements were not accurate enough and thus the decisions of compacting further based on temperature phase were made based on the measurements from the IR camera (surface temperature).

Figure 2B - Image showing the position of thermocouples on the slab

3. The initial temperature measured was less than 150°C and thus the compaction was already started and was continued till phase 2 (125°C). For example, the temperature measured after reaching 55mm was 120°C. The procedure was continued till the second phase because of the low temperature. Later we waited for the mixture to cool to 80°C and 60°C.
4. The cooling rate of the mixture was too quick and I believe this can be attributed also to the fact that the mould and the segment was not pre-heated.
5. The start height was manually changed every time 2mm plus the end height from the previous phase in the position-control mode. This was done so because changing the height in ALP-A was not an option.

AC11surf

The compaction of the third and the final slab for the day started at 15.15 hrs. with $AC11_{surf}$. The entire slab preparation time took 3.5 hrs. in total. The mix was first compacted to 42mm (pre-compaction) using position control. Then switched to the ALP-A control for further compaction. The actual end height after the completion of compaction was 34.48 mm instead of the target of 35 mm.

Points to note:

1. The thermocouples used were tested before actual use and the ones that measured the right temperature were used. They were placed at one of the sides of the mould so that enough length was left open inside the mixture for measurement as shown in Figure 2. This side was also where there was enough distance between the segment and the mould for a thermocouple so that the thermocouple isn't broken. This was also to ensure that even when there is more pressure on the thermocouples, the ends still stay within the mixture. However they were not taped enough and was not straight enough. Having less tape could end up being a difficulty once the moulds start getting hotter and not having the thermocouple straight might make them prone to breaking. During this test both the above mentioned consequences did not occur.

Figure 3B - Image showing the position of thermocouples on the mould

2. The initial temperature was measured using the thermocouples. Once the measurements from the thermocouples were wrong or broken the decisions of compacting further, based on temperature phase, were made based on the measurements from the IR camera (surface temperature).
3. The mould and the segment were pre heated to 130°C (20°C less than the ideal starting temperature). The heating of the mould was then turned off and only the segment remained heated throughout the compaction process. The heat of the segment was reduced 20°C with each phase. This way the segment was still hot enough for proper compaction without influencing the heat of the mixture and without the mixture sticking to the segment.
4. The heating of the mould was turned off only after the second phase of compaction. This caused the mixture to cool down at a very slow rate. Hence after this 2 small table fans were used to cool down the mixture.
5. The start height was manually changed every time 2mm plus the end height from the previous phase in the position-control mode. This was done so because changing the height in ALP-A was not an option.
6. Apart from these it was also note that few functions in the program were linked to each other and changed simultaneously when one of them were changed. These functions are shown in Figure 4. Thus few choices had to be made so that this way the forces would be uniform. The yellow coloured functions all have equal value and cannot be changed individually. With the green coloured functions, one has an influence on the other and increases the final value by 0.004kN. The blue coloured function has values, which increases by 0.02 mm/AO.

2. Ooms – 31 August 2017

One trial slab was made from $AC11_{surf}$ 30%PR on 31.08.2017 for the project 'Designing guided operational strategies for asphalt compaction'.

AC11surf

The compaction of the AC11surf mixture started at 10.35 hrs and the entire time for slab preparation was 3 hours. The mix was first compacted to 42mm (pre-compaction) using position control. Then switched to the ALP-A control for further compaction. The actual end height after the completion of compaction was around 33 mm instead of the target of 35 mm.

Points to note:

1. The thermocouple used was placed in the centre of the slab as shown in Figure 3. After phase 3, the thermocouple showed a measurement which was thought to belongs to that of the mould. The difference between the surface and the core temperature was measured already in the beginning to be around 4°C. Once the thermocouple measurement failed, the surface temperature measurement using the thermal imaging camera was relied on for to differentiate between phases.

Figure 4B - Image showing the position of thermocouples on the base slab

2. The mould and the segment were preheated to 80°C. After pre-compaction, the heat on the only the heating of the mould was turned off.
3. The procedure mentioned in Section 1.2 point 5, was not used because it had no effect on the compaction procedure. This could also be because the height set manually was in a different control and the compaction was done in a different control.
4. After pouring the mixture into the mould and scaling it, the evenness (flatness) of the surface was measured using a spirit level (bubble level).

3. Dura Vermeer – 12 September 2017

Two trial slabs - one of PA16+ and one of $AC11_{surf}$ 30%PR were prepared on 12.09.2017 for the project 'Designing guided operational strategies for asphalt compaction'.

AC11surf

The compaction of the AC slab started at 09.00 hrs. The entire slab preparation time took 1.25 hrs. in total. The mix was first compacted to 42mm (pre-compaction) using position control. Then switched to the ALP-A control for further compaction. The actual end height after the completion of compaction was 34.8 mm (target 35 mm).

Points to note:

1. Three thermocouples used were tested before actual use. Two of the three were placed on one side (See Figure 4) of the mould in such a way that the temperature measurement would be along the edges of the slab. This side was also where there was enough distance between the segment and the mould for a thermocouple so that the thermocouple isn't

broken. This was also to ensure that even when there is more pressure on the thermocouples, the ends still stay within the mixture. The other one was placed in the centre (See Figure 4) of the mould in such a way that the core temperature can be measured. From the results of the previous trial slabs it was known that the better choice would be to use thermocouples which are more robust. Similarly, more robust thermocouples were taped in place. However, it was seen that the thermocouples were probably too thick and one of them along the sides broke and gave inaccurate reading. Thermal imaging camera was also used to measure the surface temperature. It can be clearly seen from Figure 7 that the temperature at the edge is lower than that at the core.

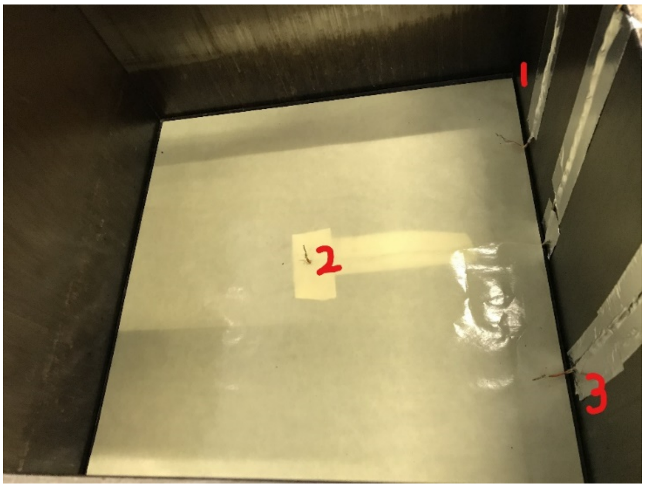


Figure 5 Image showing the placement of the three thermocouples in the mould

2. Trying to match the on-site circumstances also keeping in mind the actual temperature of the steel mould the mould and the segment were heated to 35°C. The initial temperature of the mix on levelling was already 120°C. Due to this and the continuous temperature drop, the first few phases were done continuously one after the other to keep up. During the entire period of slab preparation the segment and the mould remained at 35°C.
3. The number of passes were different from the those used during the slab preparation at Ooms and KWS. This was because three functions as Shown in Figure 5 are linked in such a way that it their values remain change together. Thus based on the effective total passes these numbers were then changed. For detailed calculation see Appendix 1 Figure 6.
4. The resulting height was around ~34.8 mm which seems to be an improvement from the other two slabs. So this method of considering the total effective passes seems to have worked out well and could be continued during the actual slab preparation.

PA16+

The compaction of the first slab started at 12:20 hrs. with PA16+. The entire slab preparation time took 1.5 hrs in total. The mix was first compacted to 55mm (pre-compaction) using position control and then switched to the ALP-A control for further compaction. The actual end height after the completion of compaction was ~47.2 mm instead of the target of 50 mm.

Points to note:

1. Three thermocouples were placed as shown in Figure 4. The surface temperature was measured using the thermal imaging camera. The thermocouples were not affected this time as they were untwined to make them thinner.

2. The mould and the segment were heated to 60°C (temperature of the last phase) to avoid rapid cooling down of the mixture. It was seen that the temperature gradually decreased giving enough time for each phase. It must also be noted that when the mixture was filled in it was already not at a temperature more than 150°C.
3. The number of passes were also altered as mentioned in Section 3.1 point 3. For detailed calculation and changes see Appendix 2.

Discussion and conclusion

The following are the factors that needs to be looked into while preparing slabs using roller compactor based on the observations also made at all three labs:

MEASURING TEMPERATURE

Position of the thermocouples which influences not only the temperature measurement but also the places from where the cores can be made later for testing. After placing the thermocouples for 3 measurements as done in Dura Vermeer, it can be clearly seen that thermocouples cause hindrances during and after slab preparation. During slab preparation there is always the risk of losing the reading because they break or the readings are no more from the core rather more from the mould itself. After slab preparation, care needs to be taken while coring the samples. The sturdier thermal loggers also tend to take up more space leaving very less space between cores thus making the coring process difficult. This puts a high reliability on the surface measurement of temperature with the thermal imaging or infrared camera.

Conclusion: It is better to not to use the thermocouples during slab preparation using slab compactor.

The reasons are as follows:

1. This removes the difficulty in deciding in which of the thermocouples to rely on for to decide the commencement of each phase.
2. One thermocouple would be too less a reading and there is always the risk of no or wrong measurement. This leads switching the reliability on thermal camera which probably would not be relied on but only monitored, in the first place.
3. When the moulds are hot it is also difficult for the thermocouples to stick on the mould.
4. The use of sturdier thermocouples imply the use of those with bigger diameter.
5. This way it is also easier to obtain cores without having to forego the space used up by the thermocouples.

Alternative: Phase decisions would be made based on the measurements from thermal imaging camera (surface temperature).

1. Figure 7 and 9 in Appendix 1 and 2 respectively shows that the temperature between the core and surface varies significantly for AC mix. However this is not the case with PA.
2. Thus the decisions for commencement of each phase can be made based on the thermal imaging camera by hovering the camera over the slab surface after each phase.
3. For PA16+ the phases can be decided based on the readings from thermal camera as such, since there is not a lot of difference in the core and surface temperature.
4. For AC11surf however it is better to add an average of 4°C to that from the thermal camera for each phase.

Comments:

1. It is true that the temperature measurement will be based on thermal camera now also inclines a little bit towards the educated intuition of the technician and manual measuring and recording. However, this also holds true when the thermocouple breaks. I believe the risk is higher in case of broken thermocouple than the proposed method.
2. The Figures 7 and 9 in Appendices 1 and 2 are based on the results from DV. To have an exact number for extrapolation I would also need to check those from KWS and Ooms.

PRE-HEATING THE MOULD

There is definitely a need to pre-heat the mould and the segment. This is so because, at high temperature the mixture if the mould and segment is cold then the mixture cools down at a rapid rate possibly more than that outside. However continued heating will decrease the cooling rate too much. Even though it is true that the there is no pre-heating involved on site, the same cannot be repeated in the lab for the reasons mentioned above. Also in an attempt to not overdo the heating of the mould, it is better to use a minimum temperature for pre-heating the mould and the segment then switching it off at the beginning of slab preparation.

Conclusion: Pre-heat the mould and segment to the minimum temperature (usually the temperature of the last phase) and switch off the heating after pre-compaction.

The reasons are:

1. This avoids rapid cooling down of the mixture and providing sufficient time for each phase.
2. At the same time not over heat than what is necessary thus reducing the waiting time.

ROLLER PASSES IN THE SLAB

Since few functions of the program are interlinked, an average value was chosen for the trial tests at KWS and Ooms (See Figure 5). However on calculating the effective passes, it was observed that the total number of passes used were higher than the originally assigned. Hence it was then chosen to match the effective number of the original passes and changes were made during the trial at Dura Vermeer. For detailed calulcation see Figures 6 and 8 in appendices 1 and 2. It was also observed that the change in this procedure indeed have some changes in the final thickness of the slab at Dura Vermeer.

Conclusion: On translating the original number of roller passes similar to that going on outside, the effective number of roller passes must be calculated. This further needs to be converted in such a way that it fits the program of slab compactor. The starting height can thus remain the same as assumed.

	verdichtingsprocedure 1		Fase 1 (150 °C)	Fase 2 (125 °C)	Fase 3 (100 °C)	Fase 4 (90 °C)	Fase 5 (70 °C)	Fase 6 (50 °C)		
	verdichtingsprocedure 2									
	verdichtingsprocedure 3									
	Starthoogte		42.00	eindhoogte fase1 + 2 mm	eindhoogte fase2 + 2 mm	eindhoogte fase3 + 2 mm	eindhoogte fase4 + 2 mm	eindhoogte fase5 + 2 mm	mm	Moet passend bij de vulhoogte worden ingesteld
	V-Vorm	↔	240.00	240.00	240.00	240.00	240.00	240.00	mm/sec	Verplaatsing snelheid proefvorm
	V-Pauze	↔	0.2	0.2	0.2	0.2	0.2	0.2	sec	Pauze bij richtingomkeer op tafelkeerpunt
Voorlast	V-Helling	↓	0.25	0.25	0.25	0.25	0.25	0.25	mm/AO	Belastingssnelheid van de sector in mm afzonderlijke overgang
	V-Last		0.02	0.02	0.02	0.02	0.02	0.02	kN/cm	Belasting voor voorcompressie als lijnlast
	V-Last		1.000	1.000	1.000	1.000	1.000	1.000	kN	Voorcompressie absoluut (afhankelijke van waslsector breedte)
	V Vasthouden		1	1	1	1	1	1	AO	aantal afzonderlijke overgangen met voorlast
	V-Helling	↑	0.25	0.25	0.25	0.25	0.25	0.25	mm/AO	Ontlastingsnelheid in mm/afzonderlijke overgang
	H-Vorm	↔	240.0	240.0	240.0	240.0	240.0	240.0	mm/sec	Verplaatsing snelheid proefvorm voor hoofdcompressie
	H-Pauze	↔	0.2	0.2	0.2	0.2	0.2	0.2	sec	Pauze bij richtingomkeer op tafelkeerpunt
	H egaliseren		0.28	0.28	0.28	0.50	0.50	0.50	kN/cm	Belasting voor de egalisatiefase als lijnlast
	H egaliseren		14.000	14.000	14.000	25.000	25.000	25.000	kN	Belasting egalisatiefase absoluut (afhankelij van walssector breedte)
Hoofdlast	H egaliseren		6	8	4	4	4	4	AO	Aantal afzonderlijke overgangen voor de egalisatiefase
	H- Helling	↓	2	2	2	2	2	2	AO	Aantal afzonderlijke overgangen voor eindlast
	H-Last		0.0	0.0	0.0	0.0	0.0	0.0	kN/cm	Hoofdcompressie als lijnlast
	H-Last		0.000	0.000	0.000	0.000	0.000	0.000	kN	Hoofdcompressie absoluut (afhankelijk van walssector breedte)
	H-Helling	↑	2	2	2	2	2	2	AO	Aantal afzondelijke overgangen voor de ontlasting
Temperatuur			131	125	108	90	70	50		gemeten met thermokoppel en infrarood thermometer
start hoogte			41.84	38.4	37.12	36.58	36.12	36.06		Gemaakt met mal verwarming van 130°C bij de start. Na de eerste
eind hoogte			37.24	36.22	35.6	34.96	34.58	34.48		
start tijd			15:22:37	15:38:31	16:06:00	16:39:23	17:19:48	18:35:39		
wachttijd			00:08:17	00:15:54	00:27:29	00:33:23	00:40:25	01:15:51	03:21:19	totale tijd verdichten
	H egaliseren		4	4	4	3	3	3		gekoppeld in platen machine sorfware. Instelling:
	H- Helling		4	4	4	3	3	3		
	H-Helling		4	4	4	3	3	3		
	V-Helling		0.26	0.26	0.26	0.26	0.26	0.26		in te stellen in stappen van 0,02. Instelling:
	H egaliseren		0.28	0.28	0.28	0.5	0.5	0.5		gekoppeld in platen machine sorfware. Instelling:
	H egaliseren		14.004	14.004	14.004	25.004	25.004	25.004		

Figure 6 Screenshot showing the linked functions and the new average values used for AC11$_{surf}$ at KWS

	H-Vorm	↔	240.0	240.0	240.0	240.0	240.0	240.0	mm/sec
	H-Pauze	↔	0.2	0.2	0.2	0.2	0.2	0.2	sec
	H egaliseren		0.28	0.28	0.28	0.50	0.50	0.50	kN/cm
	H egaliseren		14.000	14.000	14.000	25.000	25.000	25.000	kN
Hoofdlast	H egaliseren		6	8	4	4	4	4	AO
	H- Helling	↓	2	2	2	2	2	2	AO
	H-Last		0.0	0.0	0.0	0.0	0.0	0.0	kN/cm
	H-Last		0.000	0.000	0.000	0.000	0.000	0.000	kN
	H-Helling	↑	2	2	2	2	2	2	AO
	Original TOTAL		**10**	**12**	**8**	**8**	**8**	**8**	**54**
First modification KWS	H egaliseren		4	4	4	3	3	3	
	H- Helling	↓	4	4	4	3	3	3	
	H-Helling	↑	4	4	4	3	3	3	
	Modified 1 Total		**12**	**12**	**12**	**9**	**9**	**9**	**63**
Second modification DV	H egaliseren		3	4	3	3	2	3	
	H- Helling	↓	3	4	3	3	2	3	
	H-Helling	↑	3	4	3	3	2	3	
	Modified 2 Total		**9**	**12**	**9**	**9**	**6**	**9**	**54**

Figure 7 Total number of passes calculations for each phase based on the interlinked functions for AC11$_{surf}$

Time	Temperature					
	Edge 1 T1	Centre T2	Edge 2 T3	Average slab	IR T4	Difference between surface and core
[hh:mm]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
09:14	108	120	108	112	115.00	3.00
09:17	93	110	90	98	106.00	8.33
09:21	74	97	76	82	90.00	7.67
09:27	63	85		74	80.00	6.00
09:30	60	81		71	78.00	7.50
09:41	51	69		60	67.00	7.00
10:11	43	50		47	48.00	1.50
Average difference						**5.86**

Figure 8 Calculation of difference in temperature between the surface and the core of the slab for AC11$_{surf}$

	H-Vorm	↔	240.0	240.0	240.0	240.0	240.0	240.0	mm/sec
	H-Pauze	↔	0.2	0.2	0.2	0.2	0.2	0.2	sec
	H egaliseren		0.28	0.28	0.28	0.28	0.28	0.28	kN/cm
	H egaliseren		14.000	14.000	14.000	14.000	14.000	14.000	kN
Hoofdlast	H egaliseren		4	4	2	2	2	2	AO
	H- Helling	↓	2	2	2	2	2	2	AO
	H-Last		0.0	0.0	0.0	0.0	0.0	0.0	kN/cm
	H-Last		0.000	0.000	0.000	0.000	0.000	0.000	kN
	H-Helling	↑	2	2	2	2	2	2	AO
	Original TOTAL		**8**	**8**	**6**	**6**	**6**	**6**	**40**
First modification KWS	H egaliseren		3	3	3	3	3	3	
	H- Helling	↓	3	3	3	3	3	3	
	H-Helling	↑	3	3	3	3	3	3	
	Modified 1 Total		**9**	**9**	**9**	**9**	**9**	**9**	**54**
Second modification DV	H egaliseren		3	3	2	2	2	2	
	H- Helling	↓	3	3	2	2	2	2	
	H-Helling	↑	3	3	2	2	2	2	
	Modified 2 Total		**9**	**9**	**6**	**6**	**6**	**6**	**42**

Figure 9 Total number of passes calculations for each phase based on the interlinked functions for PA16+

Time	Temperature					
	Edge 1 T1	Centre T2	Edge 2 T3	Average slab	IR T4	Difference between surface and core
[hh:mm]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
12:26	127	130	125	127.33	120	-7.33
12:28	116	123	110	116.33	117	0.67
12:31	107	118	102	109.00	110	1.00
12:36	96	110	92	99.33	105	5.67
12:54	76	90	74	80.00	80	0.00
13:06	69	80	67	72.00	72	0.00
13:47	56	60	54	56.67	51	-5.67
Average difference						**-0.81**

Figure 10 Calculation of difference in temperature between the surface and the core of the slab for PA16+

Appendix D. Compaction data used in the project

Table 2 Roller regime for laboratory compaction for Procedures 1 and 2

Roller	Procedure 1	Procedure 2

Static/Dynamic	Type	Front/Back	Temperature [°C]	
Static	Tandem	Front	150	130
Dynamic	Tandem	Back	150	130
Static	Tandem	Front	130	110
Dynamic	Tandem	Back	130	110
Static	3 drum	Front	80	60
Static	3 drum	Back	75	55
Static	3 drum	Front	75	55
Static	3 drum	Back	65	45
Static	3 drum	Front	55	35
Static	3 drum	Back	50	30

Table 3 Roller regime for laboratory compaction for Procedure 3

Roller			Procedure3
Static/Dynamic	**Type**	**Front/Back**	**Temperature [°C]**
Static	Tandem	Front	150
Dynamic	Tandem	Back	150
Static	Tandem	Front	140
Dynamic	Tandem	Back	140
Static	Tandem	Front	130
Dynamic	Tandem	Back	130
Static	3 drum	Front	80
Static	3 drum	Back	80
Static	3 drum	Front	75
Static	3 drum	Back	75
Static	3 drum	Front	65
Static	3 drum	Back	65
Static	3 drum	Front	50
Static	3 drum	Back	50

Table 4 Roller regime for 2.2 ton roller compactor for Procedures 1 and 2

Roller		Procedure 1	Procedure 2
Static/Dynamic	**Front/Back**	**Temperature [°C]**	
Static	Front	116	96
Static	Back	115	95
Dynamic	Front	106	86
Dynamic	Back	106	86
Static	Front	104	84
Static	Back	103	83
Static	Front	80	60
Static	Back	80	60
Static	Front	70	50
Static	Back	70	50

Static	Front	50	30
Static	Back	50	30
Static	Front	45	30
Static	Back	45	30

Table 5 Roller regime for 2.2 ton roller compactor for procedure 3

Procedure3		
Static/Dynamic	**Front/Back**	**Temperature [°C]**
Static	Front	120
Static	Back	120
Dynamic	Front	115
Dynamic	Back	115
Static	Front	110
Dynamic	Back	110
Static	Front	100
Static	Back	100
Static	Front	100
Static	Back	80
Static	Front	80
Static	Back	80
Static	Front	70
Static	Back	70
Static	Front	70
Static	Back	50
Static	Front	50
Static	Back	50
Static	Front	45
Static	Back	45
Static	Front	45

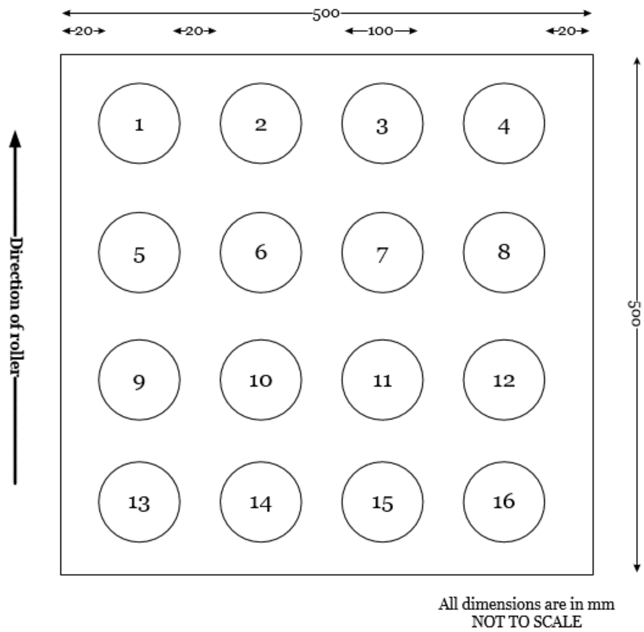


Figure 11 Dimensions of slab and cores prepared from a slab compactor

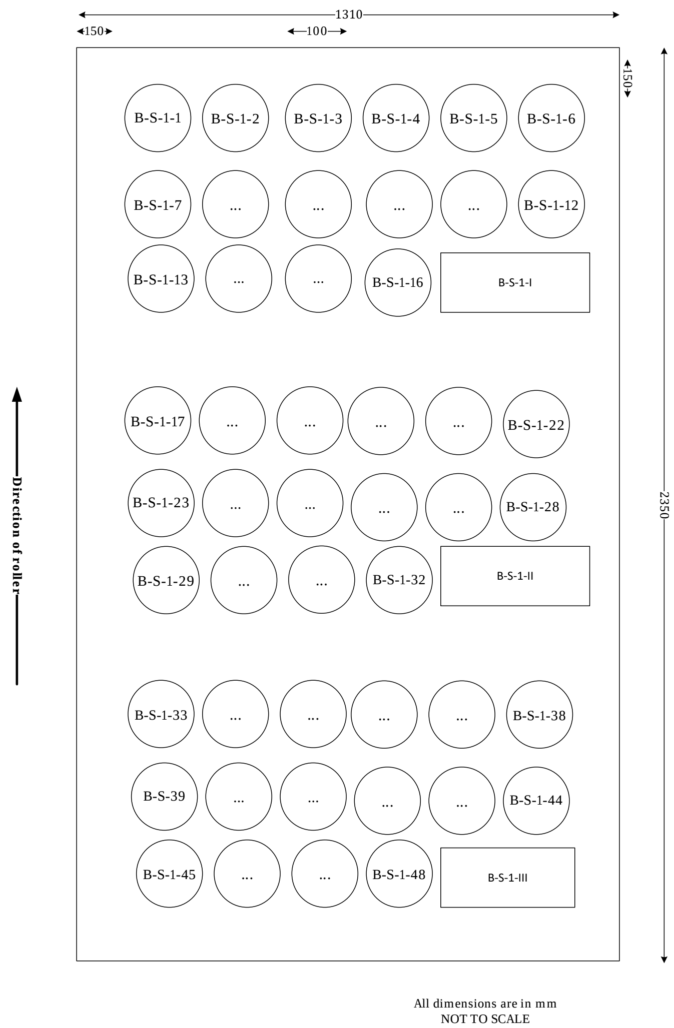
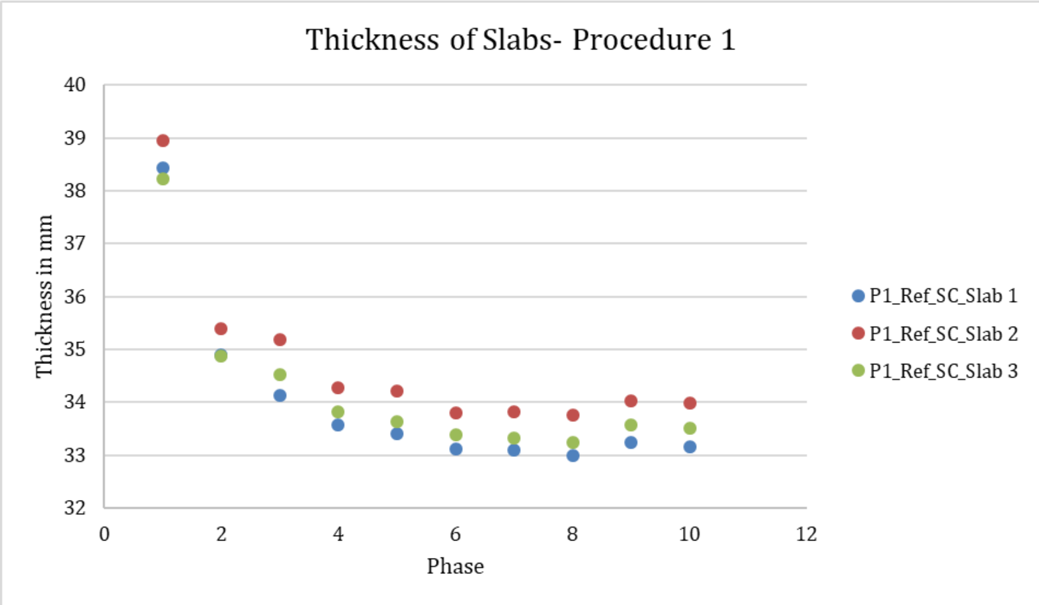
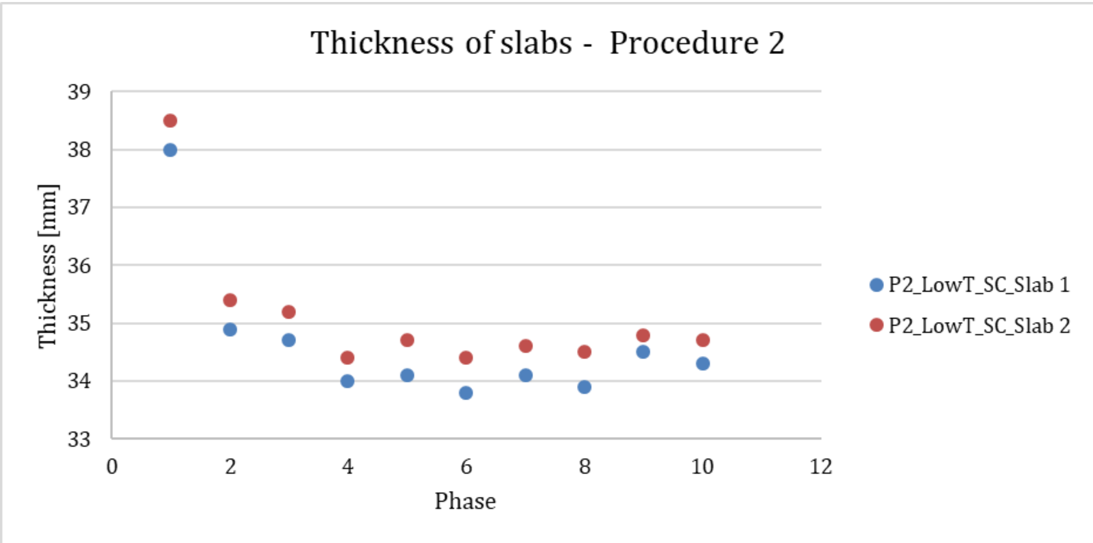
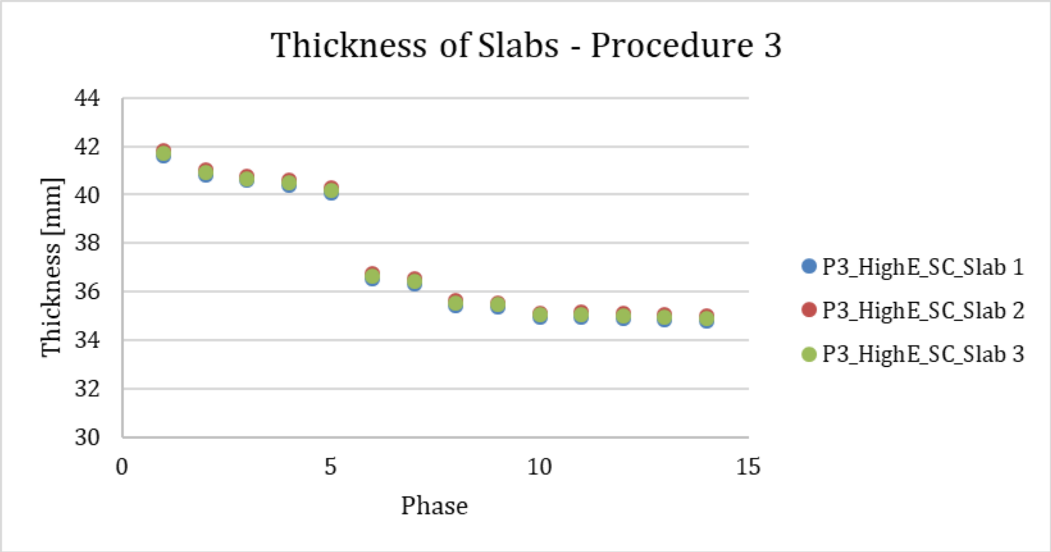


Figure 12 Dimensions of slab and cores prepared from a 2.2 ton roller compactor


Thickness of Slabs- Procedure 1
Thickness in mm
40
39
38
37
36
35
34
33
32
0
2
4
6
8
10
12
Phase
P1_Ref_SC_Slab 1
P1_Ref_SC_Slab 2
P1_Ref_SC_Slab 3


Thickness of slabs - Procedure 2
Thickness [mm]
39
38
37
36
35
34
33
0
2
4
6
8
10
12
Phase
P2_LowT_SC_Slab 1
P2_LowT_SC_Slab 2



Appendix E. Statistical test results

1. Indirect Tensile Strength Ratio test

i. ANOVA

Test of Homogeneity of Variances

ITSd_MPa

Levene Statistic	df1	df2	Sig.
.834	8	36	.579

Test of Homogeneity of Variances

ITSw_MPa

Levene Statistic	df1	df2	Sig.
2.330	5	30	.067

ANOVA

ITSd_MPa

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5.788	8	.724	37.421	.000
Within Groups	.696	36	.019		
Total	6.484	44			

ANOVA

ITSw_MPa

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6.340	5	1.268	55.054	.000
Within Groups	.691	30	.023		
Total	7.031	35			

Multiple Comparisons

Dependent Variable: ITSd_MPa
Tukey HSD

(I) Procedure	(J) Procedure	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
P1_Ref_SC	P2_LowT_SC	-.532317*	.080279	.000	-.79700	-.26763
	P3_HighE_SC	-.933358*	.080279	.000	-1.19804	-.66867
	P1_Ref_RC	.081000	.080279	.983	-.18369	.34569
	P2_LowT_RC	.196167	.080279	.293	-.06852	.46085
	P3_HighE_RC	-.109000	.080279	.906	-.37369	.15569
	M1_Site_Ref	-.402333*	.098321	.006	-.72651	-.07816
	M2_Site	-.372333*	.098321	.014	-.69651	-.04816
	M3_Site	-.375667*	.098321	.013	-.69984	-.05149
P2_LowT_SC	P1_Ref_SC	.532317*	.080279	.000	.26763	.79700
	P3_HighE_SC	-.401040*	.080279	.000	-.66573	-.13635
	P1_Ref_RC	.613317*	.080279	.000	.34863	.87800
	P2_LowT_RC	.728484*	.080279	.000	.46380	.99317
	P3_HighE_RC	.423317*	.080279	.000	.15863	.68800
	M1_Site_Ref	.129984	.098321	.918	-.19419	.45416
	M2_Site	.159984	.098321	.784	-.16419	.48416
	M3_Site	.156651	.098321	.802	-.16752	.48082
P3_HighE_SC	P1_Ref_SC	.933358*	.080279	.000	.66867	1.19804
	P2_LowT_SC	.401040*	.080279	.000	.13635	.66573
	P1_Ref_RC	1.014358*	.080279	.000	.74967	1.27904
	P2_LowT_RC	1.129524*	.080279	.000	.86484	1.39421
	P3_HighE_RC	.824358*	.080279	.000	.55967	1.08904
	M1_Site_Ref	.531024*	.098321	.000	.20685	.85520
	M2_Site	.561024*	.098321	.000	.23685	.88520
	M3_Site	.557691*	.098321	.000	.23352	.88186
P1_Ref_RC	P1_Ref_SC	-.081000	.080279	.983	-.34569	.18369
	P2_LowT_SC	-.613317*	.080279	.000	-.87800	-.34863
	P3_HighE_SC	-1.014358*	.080279	.000	-1.27904	-.74967
	P2_LowT_RC	.115167	.080279	.877	-.14952	.37985
	P3_HighE_RC	-.190000	.080279	.332	-.45469	.07469
	M1_Site_Ref	-.483333*	.098321	.001	-.80751	-.15916
	M2_Site	-.453333*	.098321	.001	-.77751	-.12916
	M3_Site	-.456667*	.098321	.001	-.78084	-.13249
P2_LowT_RC	P1_Ref_SC	-.196167	.080279	.293	-.46085	.06852
	P2_LowT_SC	-.728484*	.080279	.000	-.99317	-.46380
	P3_HighE_SC	-1.129524*	.080279	.000	-1.39421	-.86484
	P1_Ref_RC	-.115167	.080279	.877	-.37985	.14952
	P3_HighE_RC	-.305167*	.080279	.014	-.56985	-.04048
	M1_Site_Ref	-.598500*	.098321	.000	-.92267	-.27433
	M2_Site	-.568500*	.098321	.000	-.89267	-.24433
	M3_Site	-.571833*	.098321	.000	-.89601	-.24766
P3_HighE_RC	P1_Ref_SC	.109000	.080279	.906	-.15569	.37369
	P2_LowT_SC	-.423317*	.080279	.000	-.68800	-.15863
	P3_HighE_SC	-.824358*	.080279	.000	-1.08904	-.55967
	P1_Ref_RC	.190000	.080279	.332	-.07469	.45469
	P2_LowT_RC	.305167*	.080279	.014	.04048	.56985
	M1_Site_Ref	-.293333	.098321	.102	-.61751	.03084
	M2_Site	-.263333	.098321	.192	-.58751	.06084
	M3_Site	-.266667	.098321	.179	-.59084	.05751
M1_Site_Ref	P1_Ref_SC	.402333*	.098321	.006	.07816	.72651
	P2_LowT_SC	-.129984	.098321	.918	-.45416	.19419
	P3_HighE_SC	-.531024*	.098321	.000	-.85520	-.20685
	P1_Ref_RC	.483333*	.098321	.001	.15916	.80751
	P2_LowT_RC	.598500*	.098321	.000	.27433	.92267
	P3_HighE_RC	.293333	.098321	.102	-.03084	.61751
	M2_Site	.030000	.113531	1.000	-.34432	.40432
	M3_Site	.026667	.113531	1.000	-.34766	.40099
M2_Site	P1_Ref_SC	.372333*	.098321	.014	.04816	.69651
	P2_LowT_SC	-.159984	.098321	.784	-.48416	.16419
	P3_HighE_SC	-.561024*	.098321	.000	-.88520	-.23685
	P1_Ref_RC	.453333*	.098321	.001	.12916	.77751
	P2_LowT_RC	.568500*	.098321	.000	.24433	.89267
	P3_HighE_RC	.263333	.098321	.192	-.06084	.58751
	M1_Site_Ref	-.030000	.113531	1.000	-.40432	.34432
	M3_Site	-.003333	.113531	1.000	-.37766	.37099
M3_Site	P1_Ref_SC	.375667*	.098321	.013	.05149	.69984
	P2_LowT_SC	-.156651	.098321	.802	-.48082	.16752
	P3_HighE_SC	-.557691*	.098321	.000	-.88186	-.23352
	P1_Ref_RC	.456667*	.098321	.001	.13249	.78084
	P2_LowT_RC	.571833*	.098321	.000	.24766	.89601
	P3_HighE_RC	.266667	.098321	.179	-.05751	.59084
	M1_Site_Ref	-.026667	.113531	1.000	-.40099	.34766
	M2_Site	.003333	.113531	1.000	-.37099	.37766

*. The mean difference is significant at the 0.05 level.

Multiple Comparisons

Dependent Variable: ITSw_MPa
Tukey HSD

(I) Procedure	(J) Procedure	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
P1_Ref_SC	P2_LowT_SC	-.527569*	.087622	.000	-.79408	-.26106
	P3_HighE_SC	-.892886*	.087622	.000	-1.15940	-.62637
	P1_Ref_RC	.107333	.087622	.821	-.15918	.37384
	P2_LowT_RC	.379333*	.087622	.002	.11282	.64584
	P3_HighE_RC	-.174833	.087622	.368	-.44134	.09168
P2_LowT_SC	P1_Ref_SC	.527569*	.087622	.000	.26106	.79408
	P3_HighE_SC	-.365317*	.087622	.003	-.63183	-.09881
	P1_Ref_RC	.634902*	.087622	.000	.36839	.90141
	P2_LowT_RC	.906902*	.087622	.000	.64039	1.17341
	P3_HighE_RC	.352735*	.087622	.004	.08622	.61925
P3_HighE_SC	P1_Ref_SC	.892886*	.087622	.000	.62637	1.15940
	P2_LowT_SC	.365317*	.087622	.003	.09881	.63183
	P1_Ref_RC	1.000219*	.087622	.000	.73371	1.26673
	P2_LowT_RC	1.272219*	.087622	.000	1.00571	1.53873
	P3_HighE_RC	.718052*	.087622	.000	.45154	.98456
P1_Ref_RC	P1_Ref_SC	-.107333	.087622	.821	-.37384	.15918
	P2_LowT_SC	-.634902*	.087622	.000	-.90141	-.36839
	P3_HighE_SC	-1.000219*	.087622	.000	-1.26673	-.73371
	P2_LowT_RC	.272000*	.087622	.043	.00549	.53851
	P3_HighE_RC	-.282167*	.087622	.033	-.54868	-.01566
P2_LowT_RC	P1_Ref_SC	-.379333*	.087622	.002	-.64584	-.11282
	P2_LowT_SC	-.906902*	.087622	.000	-1.17341	-.64039
	P3_HighE_SC	-1.272219*	.087622	.000	-1.53873	-1.00571
	P1_Ref_RC	-.272000*	.087622	.043	-.53851	-.00549
	P3_HighE_RC	-.554167*	.087622	.000	-.82068	-.28766
P3_HighE_RC	P1_Ref_SC	.174833	.087622	.368	-.09168	.44134
	P2_LowT_SC	-.352735*	.087622	.004	-.61925	-.08622
	P3_HighE_SC	-.718052*	.087622	.000	-.98456	-.45154
	P1_Ref_RC	.282167*	.087622	.033	.01566	.54868
	P2_LowT_RC	.554167*	.087622	.000	.28766	.82068

*. The mean difference is significant at the 0.05 level.

Test of Homogeneity of Variances

FE_d

Levene Statistic	df1	df2	Sig.
1.226	8	36	.312

ii. Regression

Descriptive Statistics

	Mean	Std. Deviation	N
ITSR	89.7063	9.46030	45
Density	2371.37	44.564	45

Correlations

		ITSR	Density
Pearson Correlation	ITSR	1.000	.500
	Density	.500	1.000
Sig. (1-tailed)	ITSR	.	.000
	Density	.000	.
N	ITSR	45	45
	Density	45	45

0.50 correlation (positive) and p (2 tail) << 0.05 (test is significant) There is a significant relationship between avg density and avg ITSR.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.500[a]	.250	.233	8.28733	.250	14.337	1	43	.000

a. Predictors: (Constant), Density

b. Dependent Variable: ITSR

- Note: Regression for N = 45
- 23% of variance in avg. density is (can be) explained by the avg. density [Taking Adjusted r square because of low sample size]
- $H_0 = \beta = 0$ (There is no change in ITSR with change in avg. density)
- $H_A = \beta \neq 0$ (There is change in ITSR with change in avg. density)

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	984.647	1	984.647	14.337	.000[b]
	Residual	2953.234	43	68.680		
	Total	3937.880	44			

a. Dependent Variable: ITSR

b. Predictors: (Constant), Density

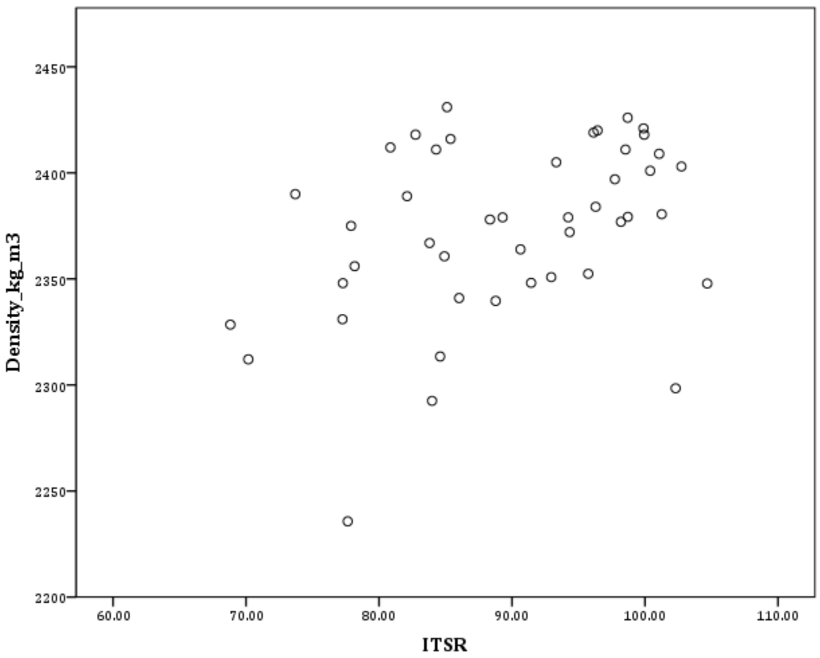
- P << 0.05 significant. (Reject H_0)
- **Conclusion: $H_A = \beta \neq 0$ (There is change in ITSR with change in avg. density)**

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-162.021	66.494		-2.437	.019	-296.119	-27.924
	Density	.106	.028	.500	3.786	.000	.050	.163

a. Dependent Variable: ITSR

- ITSR = -162.021 + .106 *Density
- **Density and constant are statistically significant in predicting ITSR and hence good predictors (p<< 0.05)**
- ITSR (2360) = -162.021 + .106 *2360 = 88.139%



2. Triaxial Cyclic Compression test

The significance level used in this study for all the analysis is 5% or 0.05.

i. Analysis of Variance (ANOVA)

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
Perm_def	2.418	6	14	.081
fc	2.165	6	14	.110

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Perm_def	Between Groups	2.817	6	.470	7.966	.001
	Within Groups	.825	14	.059		
	Total	3.642	20			
fc	Between Groups	5.671	6	.945	12.547	.000
	Within Groups	1.055	14	.075		
	Total	6.725	20			

Robust Tests of Equality of Means

		Statistic[a]	df1	df2	Sig.
Perm_def	Brown-Forsythe	7.966	6	5.385	.016
fc	Brown-Forsythe	12.547	6	7.356	.002

a. Asymptotically F distributed.

Figure 13 Results of ANOVA test for permanent deformation and creep rate

ANOVA tests were performed on the permanent deformation and creep rate of the samples prepared by different compaction procedures. The test of homogeneity shows that the results

Multiple Comparisons

Dependent Variable: fc
Tukey HSD

(I) Procedure	(J) Procedure	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
P1_Ref_SC	P2_LowT_SC	.34000	.22410	.731	-.4252	1.1052
	P3_HighE_SC	.41667	.22410	.534	-.3485	1.1819
	P1_Ref_RC	-.67333	.22410	.102	-1.4385	.0919
	P2_LowT_RC	-1.04000*	.22410	.005	-1.8052	-.2748
	P3_HighE_RC	-.65333	.22410	.119	-1.4185	.1119
	M1_Ref_Site	.02000	.22410	1.000	-.7452	.7852
P2_LowT_SC	P1_Ref_SC	-.34000	.22410	.731	-1.1052	.4252
	P3_HighE_SC	.07667	.22410	1.000	-.6885	.8419
	P1_Ref_RC	-1.01333*	.22410	.007	-1.7785	-.2481
	P2_LowT_RC	-1.38000*	.22410	.000	-2.1452	-.6148
	P3_HighE_RC	-.99333*	.22410	.008	-1.7585	-.2281
	M1_Ref_Site	-.32000	.22410	.779	-1.0852	.4452
P3_HighE_SC	P1_Ref_SC	-.41667	.22410	.534	-1.1819	.3485
	P2_LowT_SC	-.07667	.22410	1.000	-.8419	.6885
	P1_Ref_RC	-1.09000*	.22410	.004	-1.8552	-.3248
	P2_LowT_RC	-1.45667*	.22410	.000	-2.2219	-.6915
	P3_HighE_RC	-1.07000*	.22410	.004	-1.8352	-.3048
	M1_Ref_Site	-.39667	.22410	.586	-1.1619	.3685
P1_Ref_RC	P1_Ref_SC	.67333	.22410	.102	-.0919	1.4385
	P2_LowT_SC	1.01333*	.22410	.007	.2481	1.7785
	P3_HighE_SC	1.09000*	.22410	.004	.3248	1.8552
	P2_LowT_RC	-.36667	.22410	.664	-1.1319	.3985
	P3_HighE_RC	.02000	.22410	1.000	-.7452	.7852
	M1_Ref_Site	.69333	.22410	.088	-.0719	1.4585
P2_LowT_RC	P1_Ref_SC	1.04000*	.22410	.005	.2748	1.8052
	P2_LowT_SC	1.38000*	.22410	.000	.6148	2.1452
	P3_HighE_SC	1.45667*	.22410	.000	.6915	2.2219
	P1_Ref_RC	.36667	.22410	.664	-.3985	1.1319
	P3_HighE_RC	.38667	.22410	.612	-.3785	1.1519
	M1_Ref_Site	1.06000*	.22410	.005	.2948	1.8252
P3_HighE_RC	P1_Ref_SC	.65333	.22410	.119	-.1119	1.4185
	P2_LowT_SC	.99333*	.22410	.008	.2281	1.7585
	P3_HighE_SC	1.07000*	.22410	.004	.3048	1.8352
	P1_Ref_RC	-.02000	.22410	1.000	-.7852	.7452
	P2_LowT_RC	-.38667	.22410	.612	-1.1519	.3785
	M1_Ref_Site	.67333	.22410	.102	-.0919	1.4385
M1_Ref_Site	P1_Ref_SC	-.02000	.22410	1.000	-.7852	.7452
	P2_LowT_SC	.32000	.22410	.779	-.4452	1.0852
	P3_HighE_SC	.39667	.22410	.586	-.3685	1.1619
	P1_Ref_RC	-.69333	.22410	.088	-1.4585	.0719
	P2_LowT_RC	-1.06000*	.22410	.005	-1.8252	-.2948
	P3_HighE_RC	-.67333	.22410	.102	-1.4385	.0919

*. The mean difference is significant at the 0.05 level.

Multiple Comparisons

Dependent Variable: Perm_def
Tukey HSD

(I) Procedure	(J) Procedure	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
P1_Ref_SC	P2_LowT_SC	.65933	.19823	.058	-.0175	1.3362
	P3_HighE_SC	.59300	.19823	.104	-.0839	1.2699
	P1_Ref_RC	.06800	.19823	1.000	-.6089	.7449
	P2_LowT_RC	-.30767	.19823	.712	-.9845	.3692
	P3_HighE_RC	.24833	.19823	.862	-.4285	.9252
	M1_Ref_Site	.75747*	.19823	.024	.0806	1.4343
P2_LowT_SC	P1_Ref_SC	-.65933	.19823	.058	-1.3362	.0175
	P3_HighE_SC	-.06633	.19823	1.000	-.7432	.6105
	P1_Ref_RC	-.59133	.19823	.106	-1.2682	.0855
	P2_LowT_RC	-.96700*	.19823	.004	-1.6439	-.2901
	P3_HighE_RC	-.41100	.19823	.416	-1.0879	.2659
	M1_Ref_Site	.09813	.19823	.999	-.5787	.7750
P3_HighE_SC	P1_Ref_SC	-.59300	.19823	.104	-1.2699	.0839
	P2_LowT_SC	.06633	.19823	1.000	-.6105	.7432
	P1_Ref_RC	-.52500	.19823	.183	-1.2019	.1519
	P2_LowT_RC	-.90067*	.19823	.006	-1.5775	-.2238
	P3_HighE_RC	-.34467	.19823	.604	-1.0215	.3322
	M1_Ref_Site	.16447	.19823	.977	-.5124	.8413
P1_Ref_RC	P1_Ref_SC	-.06800	.19823	1.000	-.7449	.6089
	P2_LowT_SC	.59133	.19823	.106	-.0855	1.2682
	P3_HighE_SC	.52500	.19823	.183	-.1519	1.2019
	P2_LowT_RC	-.37567	.19823	.514	-1.0525	.3012
	P3_HighE_RC	.18033	.19823	.965	-.4965	.8572
	M1_Ref_Site	.68947*	.19823	.045	.0126	1.3663
P2_LowT_RC	P1_Ref_SC	.30767	.19823	.712	-.3692	.9845
	P2_LowT_SC	.96700*	.19823	.004	.2901	1.6439
	P3_HighE_SC	.90067*	.19823	.006	.2238	1.5775
	P1_Ref_RC	.37567	.19823	.514	-.3012	1.0525
	P3_HighE_RC	.55600	.19823	.143	-.1209	1.2329
	M1_Ref_Site	1.06513*	.19823	.001	.3883	1.7420
P3_HighE_RC	P1_Ref_SC	-.24833	.19823	.862	-.9252	.4285
	P2_LowT_SC	.41100	.19823	.416	-.2659	1.0879
	P3_HighE_SC	.34467	.19823	.604	-.3322	1.0215
	P1_Ref_RC	-.18033	.19823	.965	-.8572	.4965
	P2_LowT_RC	-.55600	.19823	.143	-1.2329	.1209
	M1_Ref_Site	.50913	.19823	.208	-.1677	1.1860
M1_Ref_Site	P1_Ref_SC	-.75747*	.19823	.024	-1.4343	-.0806
	P2_LowT_SC	-.09813	.19823	.999	-.7750	.5787
	P3_HighE_SC	-.16447	.19823	.977	-.8413	.5124
	P1_Ref_RC	-.68947*	.19823	.045	-1.3663	-.0126
	P2_LowT_RC	-1.06513*	.19823	.001	-1.7420	-.3883
	P3_HighE_RC	-.50913	.19823	.208	-1.1860	.1677

*. The mean difference is significant at the 0.05 level.

Figuur 14Post-hoc Tukey's test results comparing different compaction methods and procedures

ii. Regression

Descriptive Statistics

	Mean	Std. Deviation	N
fc	1.2196	.52582	27
Density	2315.15	65.078	27

Correlations

		fc	Density
Pearson Correlation	fc	1.000	-.756
	Density	-.756	1.000
Sig. (1-tailed)	fc	.	.000
	Density	.000	.
N	fc	27	27
	Density	27	27

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Density[b]	.	Enter

a. Dependent Variable: fc
b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics: R Square Change	F Change	df1	df2	Sig. F Change
1	.756[a]	.572	.554	.35101	.572	33.347	1	25	.000

a. Predictors: (Constant), Density

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4.109	1	4.109	33.347	.000[b]
	Residual	3.080	25	.123		
	Total	7.189	26			

a. Dependent Variable: fc
b. Predictors: (Constant), Density

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	15.361	2.450		6.270	.000
	Density	-.006	.001	-.756	-5.775	.000

a. Dependent Variable: fc

Figure 15 Result of regression of creep rate on density

A Pearson correlation value -0.756 in Figure 15indicates that the relation between creep rate (f_c) and density is strong and negative. The p-value is less than 0.05 implies that there is a significant relationship between density and creep rate. It is important to note that the sample size 27. The adjusted R^2 value is taken into consideration due to the same sample size. Thus, the adjusted R^2 value of 0.554 implies that 55.4% of the variance in creep rate can be explained by density. The p-value from the ANOVA table is much less than 0.05 which implies that there is significant change in creep rate with change in density. The p-value from the coefficients table is much less than 0.05 which implies that the constant value and density are statistically significant in predicting the creep rate and hence are good predictors. Thus, the regression equation can be given as follows:

$$f_c = 15.361 - 0.06Density$$

Descriptive Statistics

	Mean	Std. Deviation	N
Perm_def	1.5637	.40818	27
Density	2315.15	65.078	27

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.382[a]	.146	.112	.38469	.146	4.272	1	25	.049

a. Predictors: (Constant), Density

Correlations

		Perm_def	Density
Pearson Correlation	Perm_def	1.000	-.382
	Density	-.382	1.000
Sig. (1-tailed)	Perm_def	.	.025
	Density	.025	.
N	Perm_def	27	27
	Density	27	27

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.632	1	.632	4.272	.049[b]
	Residual	3.700	25	.148		
	Total	4.332	26			

a. Dependent Variable: Perm_def

b. Predictors: (Constant), Density

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Density[b]	.	Enter

a. Dependent Variable: Perm_def

b. All requested variables entered.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	7.111	2.685		2.648	.014
	Density	-.002	.001	-.382	-2.067	.049

a. Dependent Variable: Perm_def

Figure 16 Result of regression of permanent deformation on density

A Pearson correlation value -0.382 in Figure 16 indicates that the relation between permanent deformation (Perm_def) and density is moderate and negative. The p-value is less than 0.05 implies that there is a significant relationship between density and permanent deformation. It is important to note that the sample size 27. The adjusted R^2 value is taken into consideration due to the same sample size. Thus, the adjusted R^2 value of 0.112 implies that 11.2% of the variance in creep rate can be explained by density. The p-value from the ANOVA table is 0.049 which is very close to 0.05 implies that there is no significant change in permanent deformation with change in density. The p-value from the coefficients table is 0.049 which is very close to 0.05 which implies that the density is not statistically significant in predicting the permanent deformation and hence is not a good predictor.

3. Cyclic indirect tension test

i. ANOVA

Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
SM_30Hz	1.211	8	35	.321
SM_8Hz	1.473	8	35	.202
Density	1.837	8	35	.103

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
SM_30Hz	Between Groups	36304330.42	8	4538041.302	14.465	.000
	Within Groups	10980283.47	35	313722.385		
	Total	47284613.89	43			
SM_8Hz	Between Groups	33948040.12	8	4243505.015	24.074	.000
	Within Groups	6169542.133	35	176272.632		
	Total	40117582.25	43			
Density	Between Groups	60278.398	8	7534.800	24.176	.000
	Within Groups	10908.033	35	311.658		
	Total	71186.432	43			

Multiple Comparisons

Tukey HSD

Dependent Variable	(I) Procedure	(J) Procedure	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

*. The mean difference is significant at the 0.05 level.

ii. Regression

Correlations

		SM_30Hz	Density
Pearson Correlation	SM_30Hz	1.000	.241
	Density	.241	1.000
Sig. (1-tailed)	SM_30Hz	.	.058
	Density	.058	.
N	SM_30Hz	44	44
	Density	44	44

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.241[a]	.058	.036	1029.798	.058	2.588	1	42	.115	1.083

a. Predictors: (Constant), Density

b. Dependent Variable: SM_30Hz

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2744309.923	1	2744309.923	2.588	.115[b]
	Residual	44540303.96	42	1060483.428		
	Total	47284613.89	43			

a. Dependent Variable: SM_30Hz

b. Predictors: (Constant), Density

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-4945.012	9179.236		-.539	.593
	Density	6.209	3.860	.241	1.609	.115

a. Dependent Variable: SM_30Hz

Correlations

		SM_8Hz	Density
Pearson Correlation	SM_8Hz	1.000	.191
	Density	.191	1.000
Sig. (1-tailed)	SM_8Hz	.	.107
	Density	.107	.
N	SM_8Hz	44	44
	Density	44	44

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.191[a]	.037	.014	959.269	.037	1.597	1	42	.213	.703

a. Predictors: (Constant), Density

b. Dependent Variable: SM_8Hz

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1469294.973	1	1469294.973	1.597	.213[b]
	Residual	38648287.28	42	920197.316		
	Total	40117582.25	43			

a. Dependent Variable: SM_8Hz

b. Predictors: (Constant), Density

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-3497.315	8550.570		-.409	.685
	Density	4.543	3.595	.191	1.264	.213

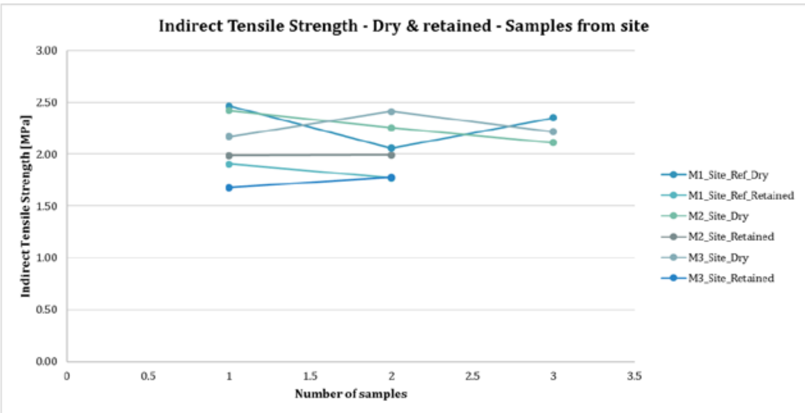
a. Dependent Variable: SM_8Hz

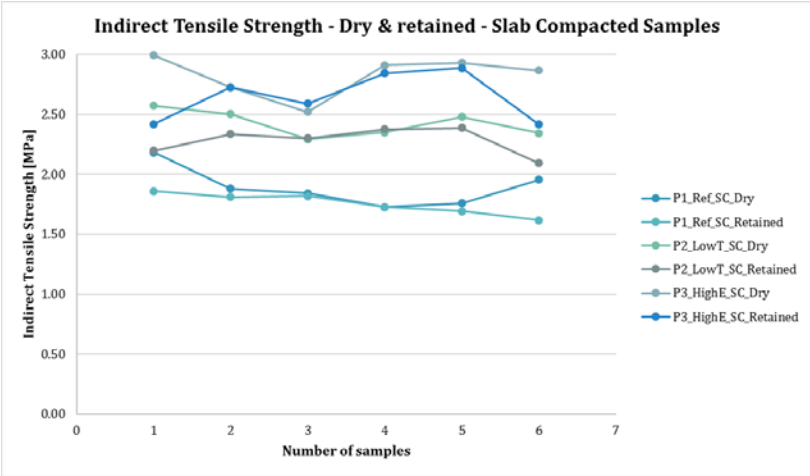
Appendix F. Test results

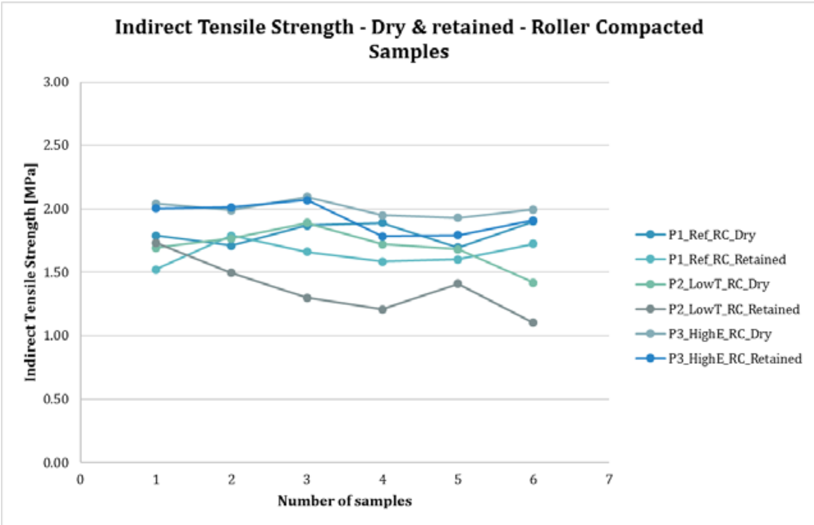
1. Extraction test

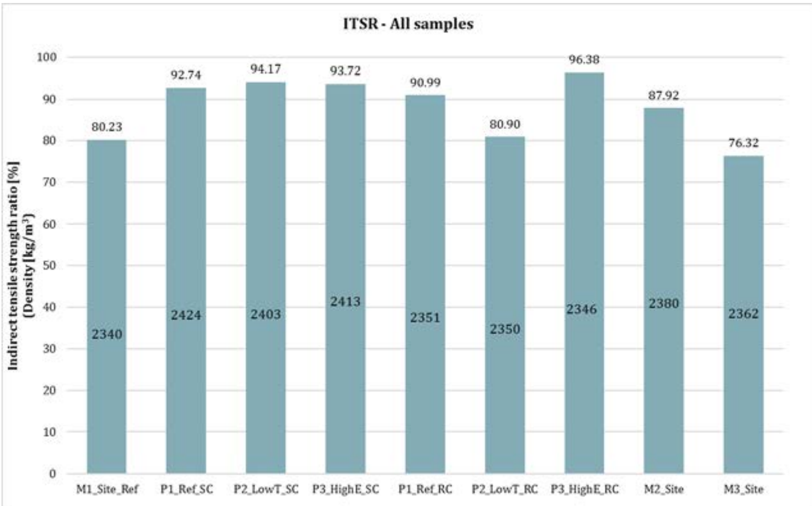
On Sieve	Heijmans	Boskalis		Ooms		Dura Vermeer				Infralinq			
	Percentage	Weight	Percentage	Weight	Percentage	Weight	Percentage	Weight	Percentage	Weight	Percentage	Weight	Percentage
	[%]	[g]	[%]	[g]	[%]	[g]	[%]	[g]	[%]	[g]	[%]	[g]	[%]
C 31.5													
C 22.4		0	100										
C 16	100	0	100	0	100					0.00			
C11.2	98	52.9	96.61	23.3	98.5	28.4	97.5	12.7	99.1	9.20	98.58	12.80	98.09
C8	85	238.7	84.69	281.8	81.4	196.7	82.9	202.2	84.9	68.60	89.44	88.50	86.78
C 5.6		584.4	62.53	607.8	59.8	429.0	62.7	469.9	65.0	200.40	69.16	213.40	68.13
C 4				762	49.6								
2.8 mm													
2 mm	45	889.5	42.97	878.8	41.9	623.6	45.7	706.2	47.4	335.30	48.41	350.80	47.60
1 mm													
0.5 mm		1207.4	22.58	1168	22.8	836.9	27.1	968.9	27.8	462.40	28.85	476.90	28.77
0.25 mm													
0.18 mm		1358.7	12.88	1319.4	12.8	939.3	18.2	1,091.8	18.6	526.20	19.03	542.20	19.01
0.125 mm	10					965.8	15.9	1,123.2	16.3	539.90	16.93	556.40	16.89
0.063 mm	7	1432.9	8.12	1392.3	8.0	987.3	8.3	1,149.2	8.5	550.60	9.40	567.30	9.60
< 0.063 mm				120.7	8.0	987.7	92.2	1,149.8					
PAN		1433.8											
Subtotal		1559.6	93.71	1513	93.85	1,077.0	93.77	1,256.1	93.6	607.40	93.46	627.30	93.70
Bitumen (IN)	**6.0**	104.6	**6.3**	99.2	**6.2**	71.6	**6.2**	85.8	**6.4**	42.5	**6.5**	42.2	**6.3**
Total		1664.2	100.00	1612.2	100	1148.6	100.00	1341.9	100	649.90	100.00	669.50	100.00

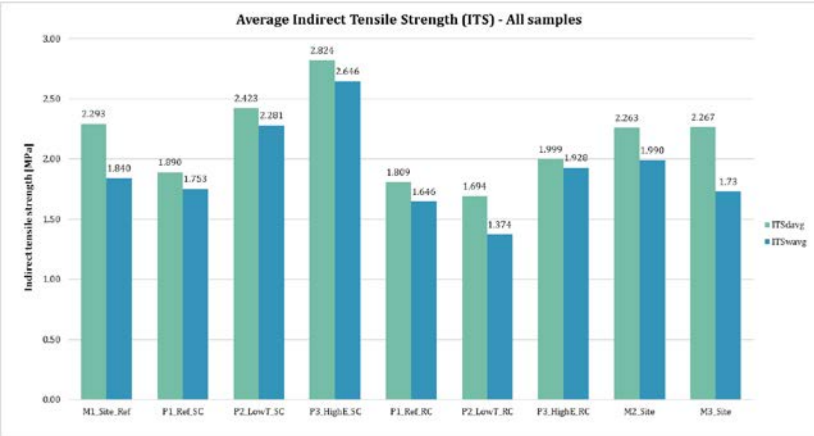
2. Indirect Tensile Strength Ratio test

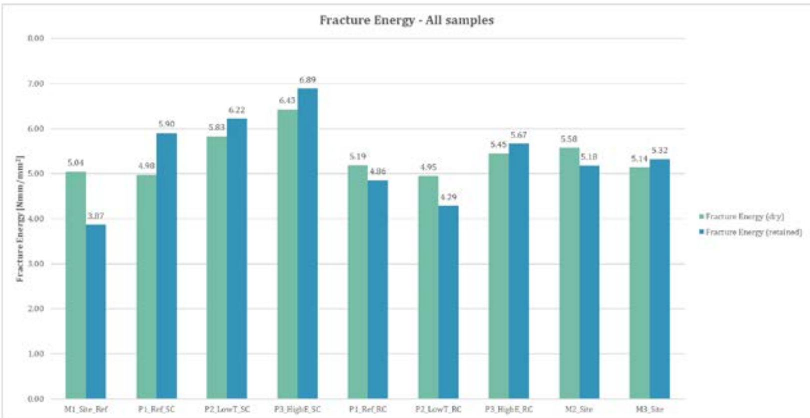



Indirect Tensile Strength - Dry & retained - Slab Compacted Samples
Indirect Tensile Strength [MPa]
Number of samples
P1_Ref_SC_Dry
P1_Ref_SC_Retained
P2_LowT_SC_Dry
P2_LowT_SC_Retained
P3_HighE_SC_Dry
P3_HighE_SC_Retained


Indirect Tensile Strength - Dry & retained - Roller Compacted Samples
Indirect Tensile Strength [MPa]
Number of samples
P1_Ref_RC_Dry
P1_Ref_RC_Retained
P2_LowT_RC_Dry
P2_LowT_RC_Retained
P3_HighE_RC_Dry
P3_HighE_RC_Retained


ITSR - All samples
Indirect tensile strength ratio [%] (Density [kg/m³])
80.23
92.74
94.17
93.72
90.99
80.90
96.38
87.92
76.32
2340
2424
2403
2413
2351
2350
2346
2380
2362
M1_Site_Ref
P1_Ref_SC
P2_LowT_SC
P3_HighE_SC
P1_Ref_RC
P2_LowT_RC
P3_HighE_RC
M2_Site
M3_Site





3. Triaxial cyclic compression test

i. Type test data

The type test data shows that the performance of the asphalt mixture stays well within the limits prescribed by the Dutch pavement standards. One must remember that these samples were laboratory mixed and tested. Thus

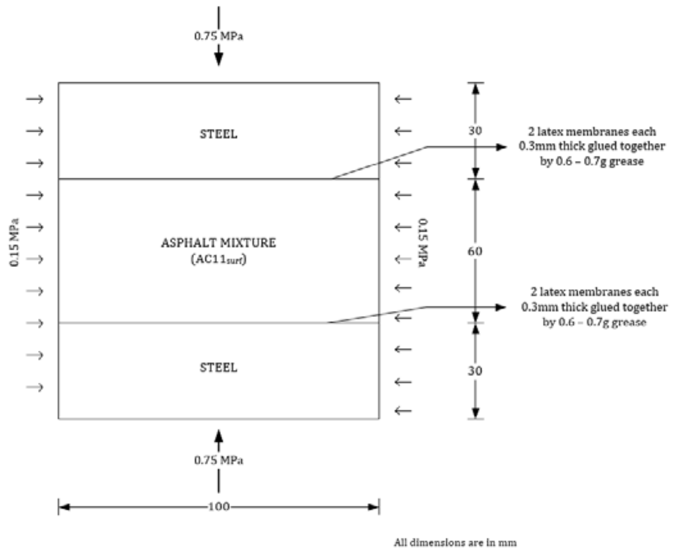


Figure 17 Schematic diagram of the friction reduction system used in the TCC type test

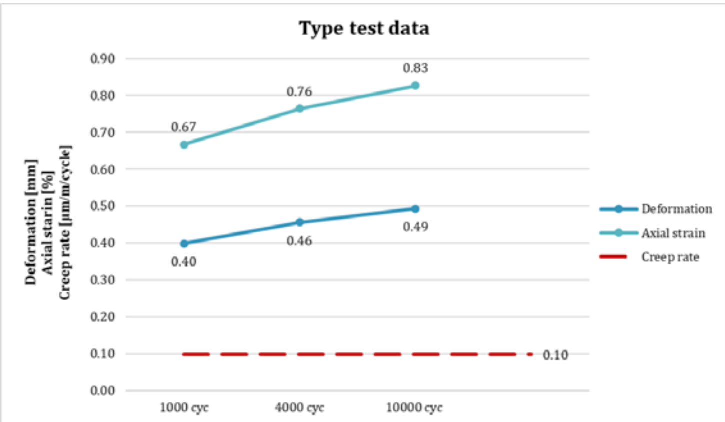
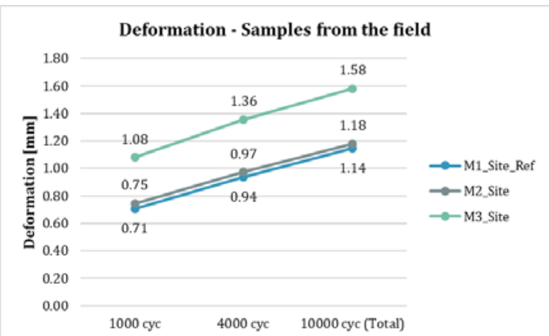
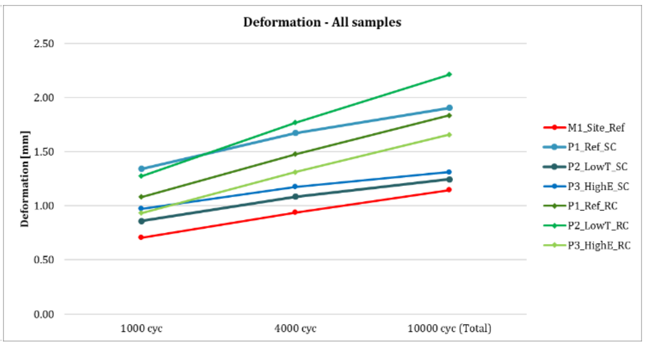


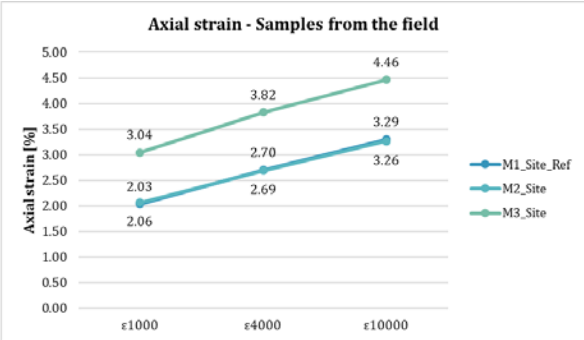
Figure 18 Average deformation, axial strain and creep rate of the samples from the type test

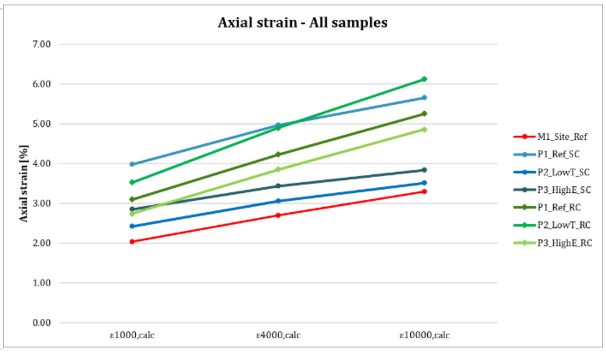
ii. Permanent deformation

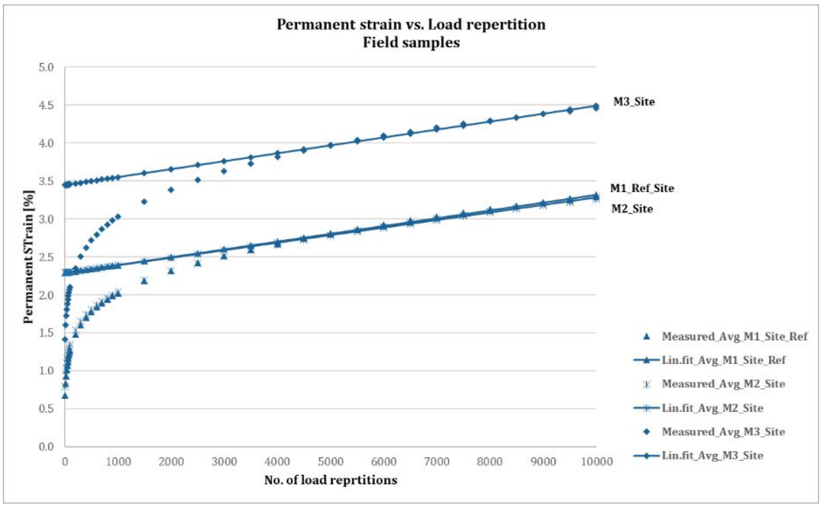


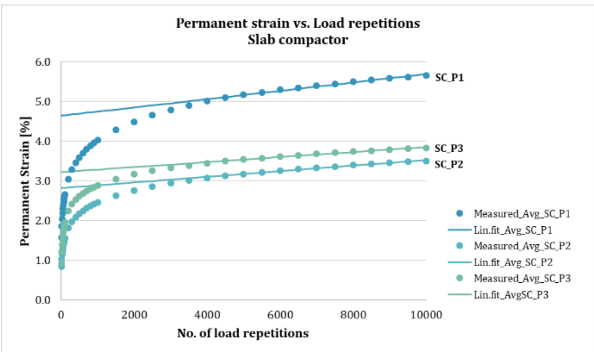


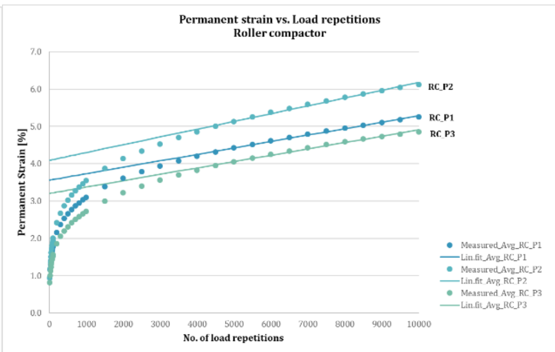
iii. Axial strain


Axial strain - Samples from the field
Axial strain [%]
ε1000
ε4000
ε10000
3.04
3.82
4.46
2.03
2.06
2.70
2.69
3.29
3.26
M1_Site_Ref
M2_Site
M3_Site

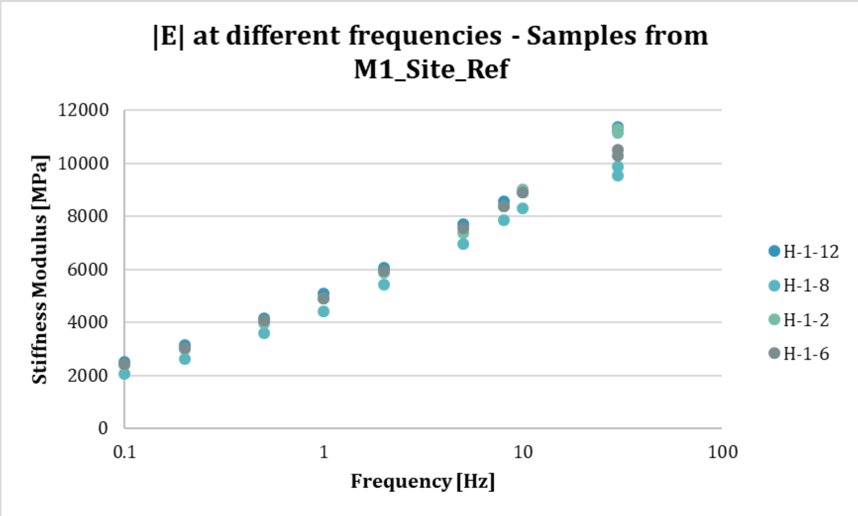

Axial strain - All samples
Axial strain [%]
ε1000,calc
ε4000,calc
ε10000,calc
M1_Site_Ref
P1_Ref_SC
P2_LowT_SC
P3_HighE_SC
P1_Ref_RC
P2_LowT_RC
P3_HighE_RC

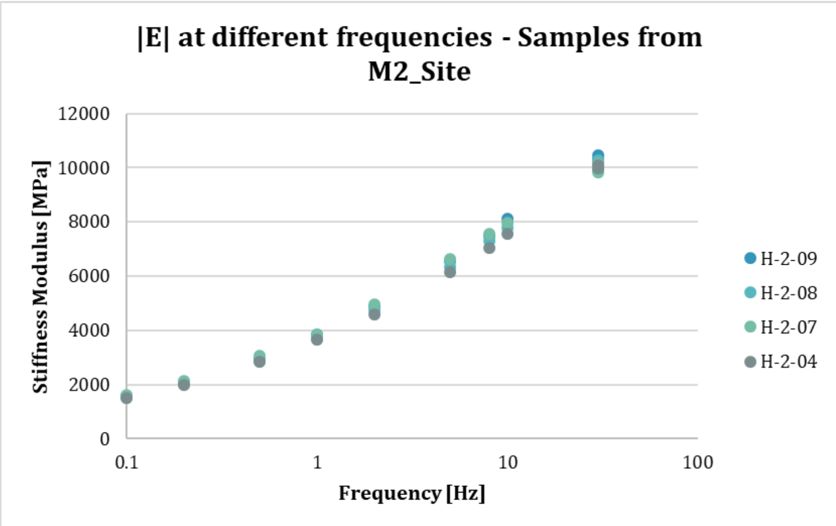

Permanent strain vs. Load repertition
Field samples
Permanent STrain [%]
No. of load reprtitions
M3_Site
M1_Ref_Site
M2_Site
Measured_Avg_M1_Site_Ref
Lin.fit_Avg_M1_Site_Ref
Measured_Avg_M2_Site
Lin.fit_Avg_M2_Site
Measured_Avg_M3_Site
Lin.fit_Avg_M3_Site

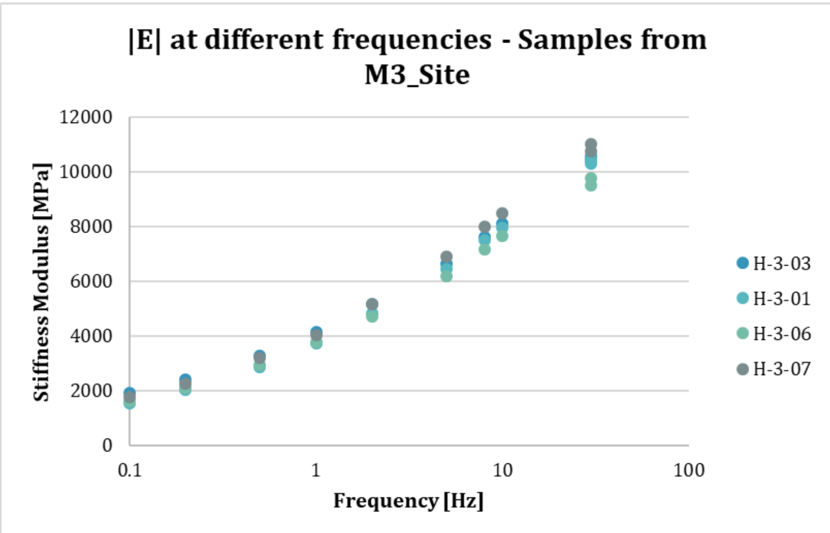

Permanent strain vs. Load repetitions
Slab compactor
Permanent Strain [%]
No. of load repetitions
SC_P1
SC_P3
SC_P2
Measured_Avg_SC_P1
Lin.fit_Avg_SC_P1
Measured_Avg_SC_P2
Lin.fit_Avg_SC_P2
Measured_Avg_SC_P3
Lin.fit_AvgSC_P3

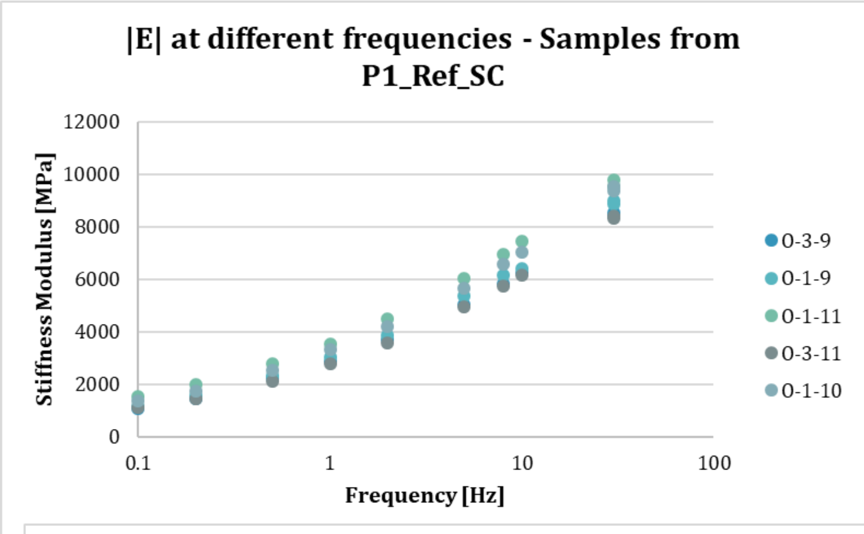

Permanent strain vs. Load repetitions
Roller compactor
Permanent Strain [%]
No. of load repetitions
RC_P2
RC_P1
RC_P3

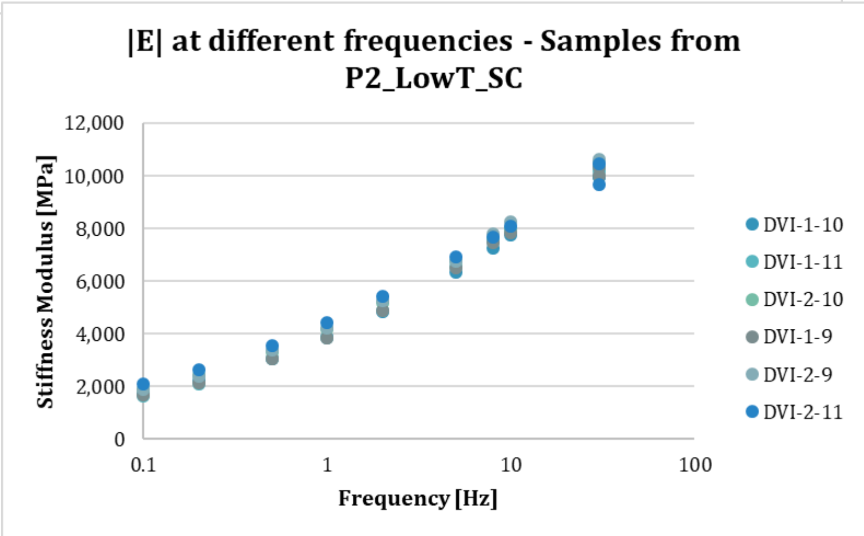
4. Cyclic Indirect Tensile Test

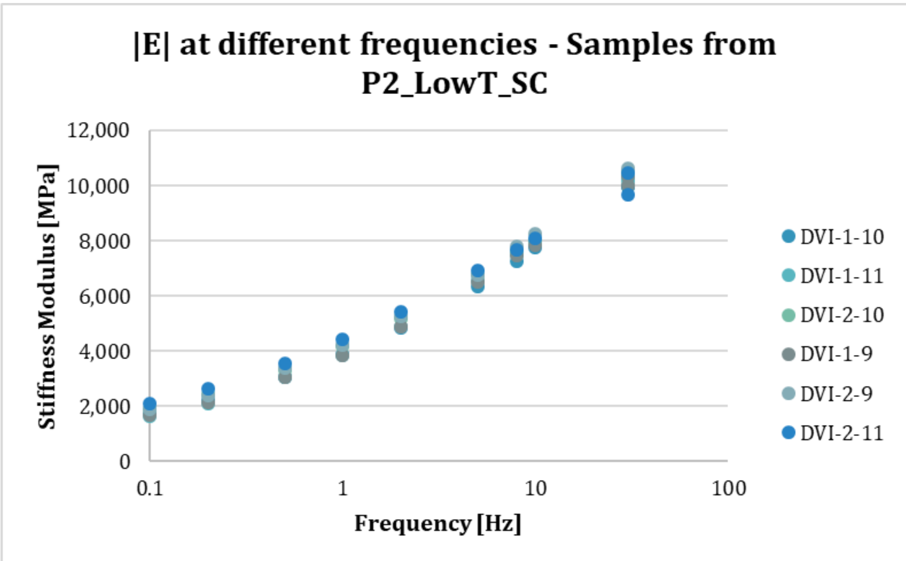


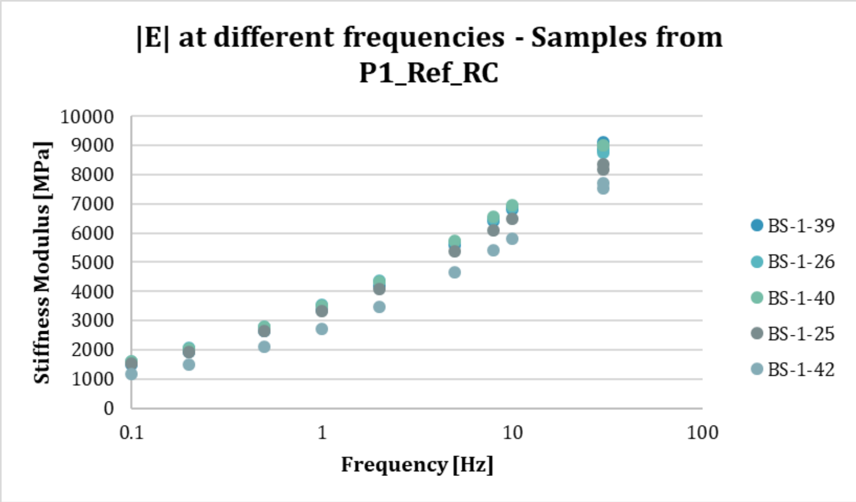


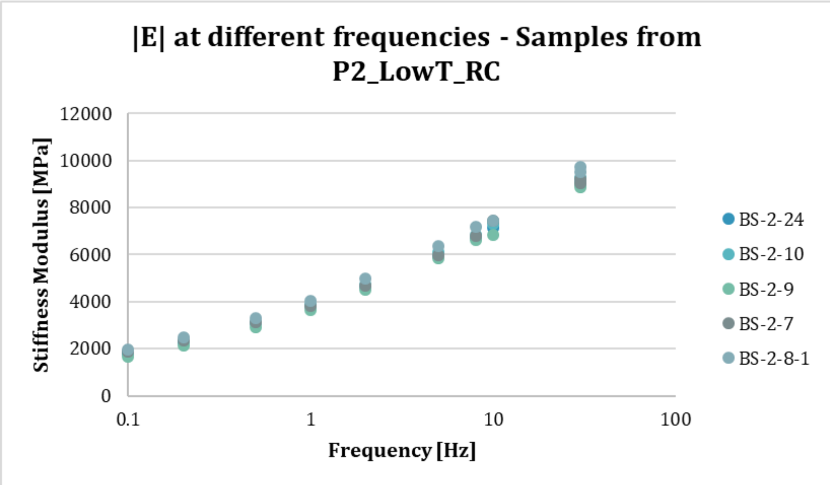


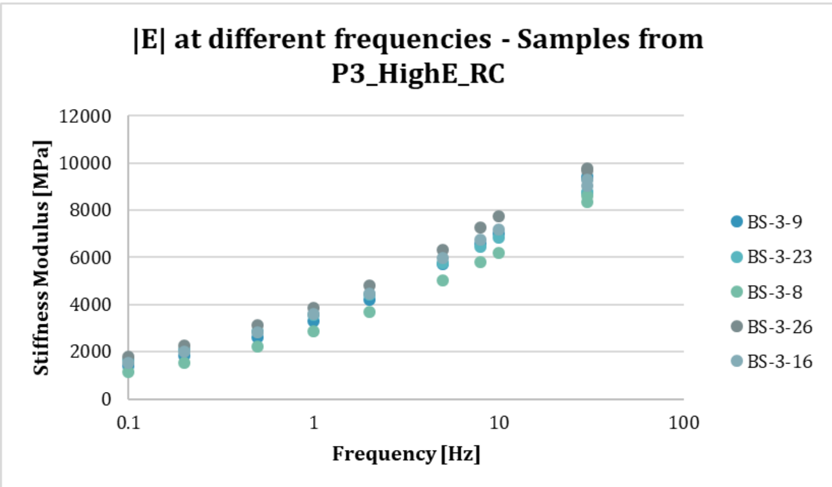

|E| at different frequencies - Samples from P1_Ref_SC
Stiffness Modulus [MPa]
12000
10000
8000
6000
4000
2000
0
0.1
1
10
100
Frequency [Hz]
0-3-9
0-1-9
0-1-11
0-3-11
0-1-10

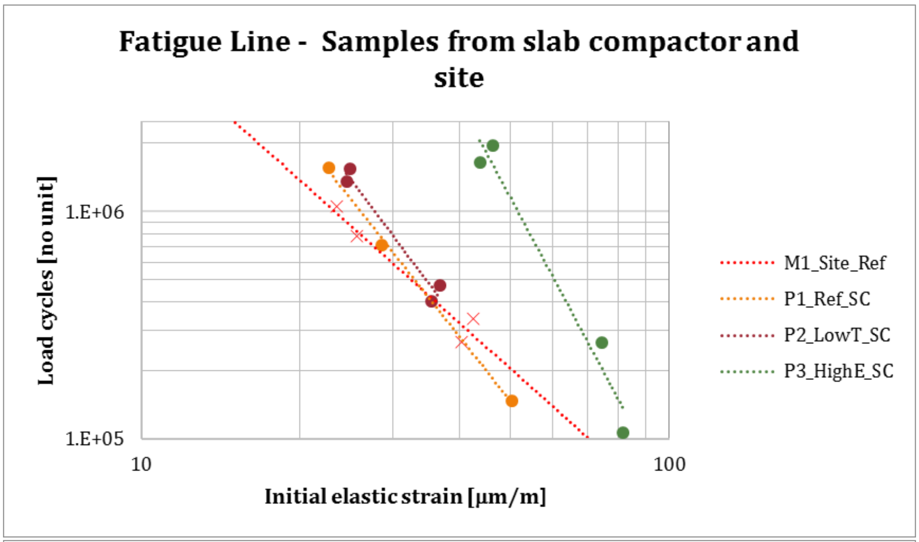

|E| at different frequencies - Samples from P2_LowT_SC
Stiffness Modulus [MPa]
12,000
10,000
8,000
6,000
4,000
2,000
0
0.1
1
10
100
Frequency [Hz]
DVI-1-10
DVI-1-11
DVI-2-10
DVI-1-9
DVI-2-9
DVI-2-11

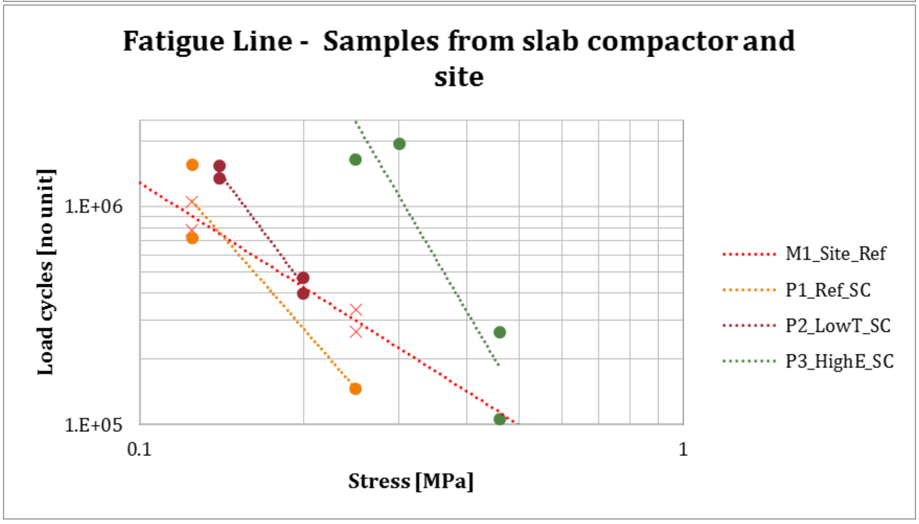

|E| at different frequencies - Samples from P2_LowT_SC
Stiffness Modulus [MPa]
12,000
10,000
8,000
6,000
4,000
2,000
0
0.1
1
10
100
Frequency [Hz]
DVI-1-10
DVI-1-11
DVI-2-10
DVI-1-9
DVI-2-9
DVI-2-11

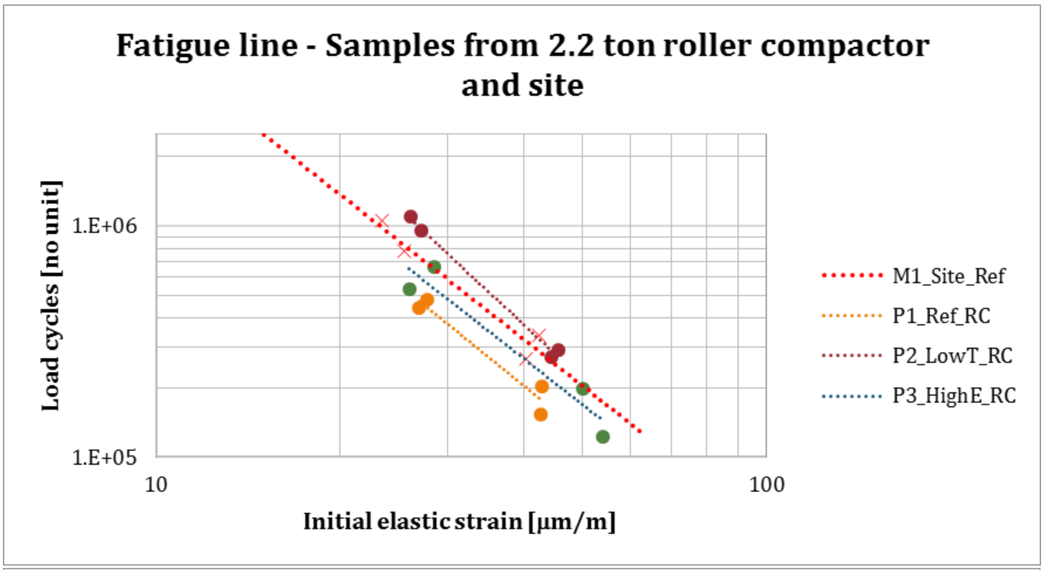

|E| at different frequencies - Samples from P1_Ref_RC
Stiffness Modulus [MPa]
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.1
1
10
100
Frequency [Hz]
BS-1-39
BS-1-26
BS-1-40
BS-1-25
BS-1-42

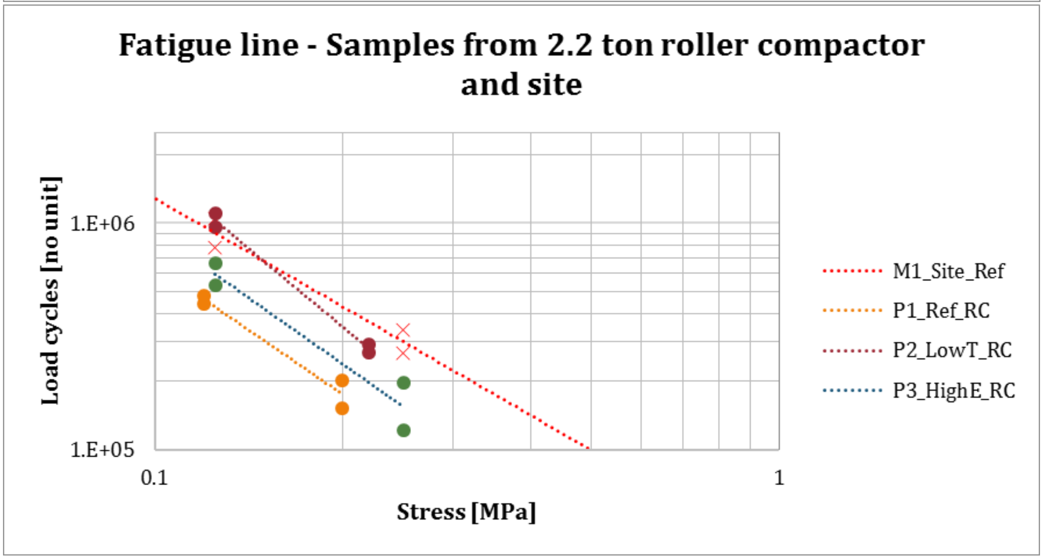

|E| at different frequencies - Samples from P2_LowT_RC
Stiffness Modulus [MPa]
12000
10000
8000
6000
4000
2000
0
0.1
1
10
100
Frequency [Hz]
BS-2-24
BS-2-10
BS-2-9
BS-2-7
BS-2-8-1

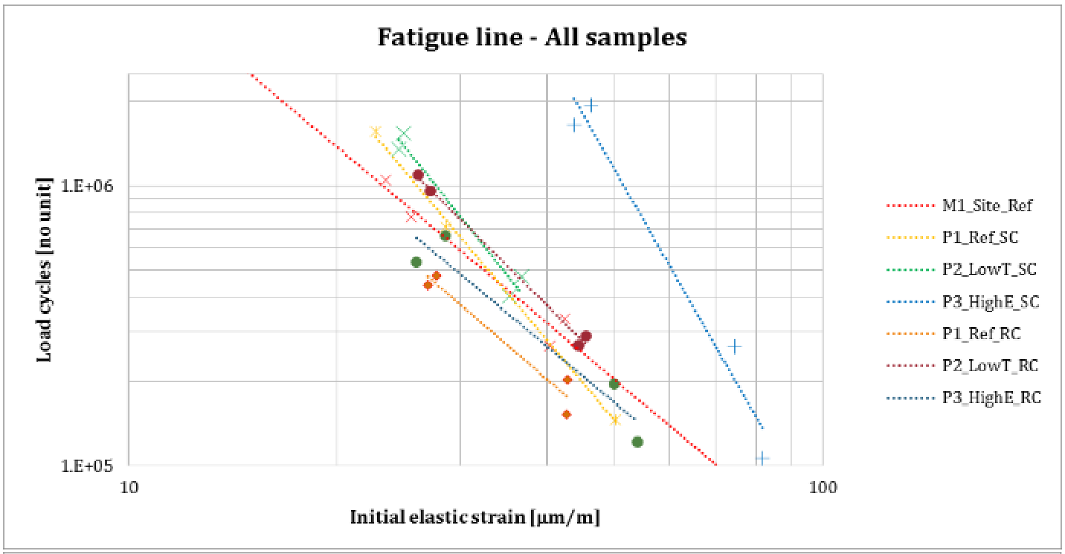

|E| at different frequencies - Samples from P3_HighE_RC
Stiffness Modulus [MPa]
12000
10000
8000
6000
4000
2000
0
0.1
1
10
100
Frequency [Hz]
BS-3-9
BS-3-23
BS-3-8
BS-3-26
BS-3-16

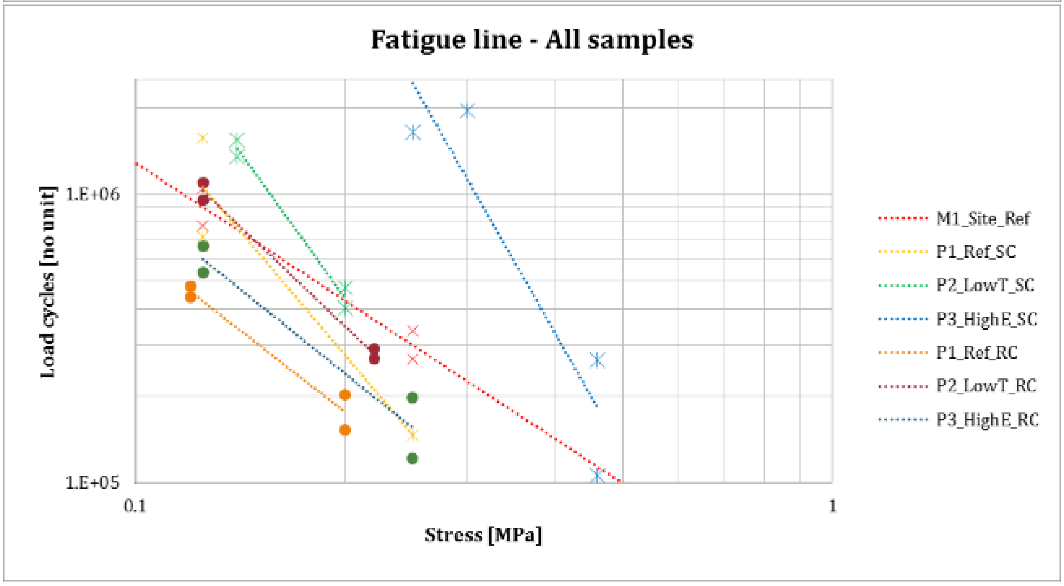

Fatigue Line - Samples from slab compactor and site
Load cycles [no unit]
1.E+06
1.E+05
10
100
Initial elastic strain [µm/m]
M1_Site_Ref
P1_Ref_SC
P2_LowT_SC
P3_HighE_SC


Fatigue Line - Samples from slab compactor and site
Load cycles [no unit]
1.E+06
1.E+05
0.1
1
Stress [MPa]
M1_Site_Ref
P1_Ref_SC
P2_LowT_SC
P3_HighE_SC


Fatigue line - Samples from 2.2 ton roller compactor and site
Load cycles [no unit]
1.E+06
1.E+05
10
100
Initial elastic strain [µm/m]
M1_Site_Ref
P1_Ref_RC
P2_LowT_RC
P3_HighE_RC


Fatigue line - Samples from 2.2 ton roller compactor and site
Load cycles [no unit]
1.E+06
1.E+05
0.1
1
Stress [MPa]
M1_Site_Ref
P1_Ref_RC
P2_LowT_RC
P3_HighE_RC


Fatigue line - All samples
Load cycles [no unit]
1.E+06
1.E+05
10
100
Initial elastic strain [µm/m]
M1_Site_Ref
P1_Ref_SC
P2_LowT_SC
P3_HighE_SC
P1_Ref_RC
P2_LowT_RC
P3_HighE_RC


Fatigue line - All samples
Load cycles [no unit]
1.E+06
1.E+05
0.1
1
Stress [MPa]
M1_Site_Ref
P1_Ref_SC
P2_LowT_SC
P3_HighE_SC
P1_Ref_RC
P2_LowT_RC
P3_HighE_RC