Effect of Compaction and Asphalt Temperature During Paving on Asphalt Lifespan

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PREFACE

This is the bachelor thesis of Sam Rutten. A special thanks needs to be given to my supervisors: Marco Oosterveld and Seirgei Miller. Without them I would not have been able to do this project. I also want to thank Denis Makarov and Bert Onnink for helping in multiple ways during the execution of this assignment. I discussed various aspects of road construction with some experts. Their input was very useful in gaining a background understanding of the topic. Some of their input has been used in the paper and a lot of their input has been used to expand my own background knowledge. Because of their help Johan Antonissen, Erwin van de Jagt, Christiaan Flentge, and Rene Kaandorp deserve a big thank you. Additionally, I want to thank Rutger Krans and Frank Bouman from Rijkswaterstaat form helping met get data which was not directly available to me. Without that data a large part of the research could not have been performed. Finally, the entire ASPARi and BAM teams which made this bachelor assignment possible need to be acknowledged and thanked.

ENGLISH SUMMARY

Asphalt is the most widely used road paving material. It has become this popular because it is durable and still flexible. There are also a wide variety of asphalt mixtures, each having a different mixture design for a different purpose. Simply put, asphalt is a mixture of aggregate and bitumen binder. When manufacturing asphalt choices need to be made regarding the aggregate types, aggregate size, aggregate proportions, bitumen amount, air voids amount, and other additives which give the asphalt other features, for example, decreased stiffness.

In this paper the methods literature study, expert interviews and empirical study are employed to answer the question: **What relation is there between asphalt processing, particularly compaction and temperature homogeneity during paving, and the asphalt's ultimate lifespan?** The literature study and expert interviews focuses on gaining a background understanding and theoretical understanding of the topic and phenomena at play here. Then data from two case roads (the A35 and Aziëhavenweg) will be used to find an answer to the main research question.

The literature study looks into two asphalt types which are employed in the aforementioned roads. These two types are porous asphalt and stone mastic asphalt. Porous asphalt is known for its high void percentage (often between 18 and 22%) which allows it to drain water and reduce noise from driving~~.~~ SMA, on the other hand, has a much lower void percentage (between 4 and 6%) which means that it doesn't have the same characteristics as porous asphalt. Rather, SMA is very durable in against high traffic volumes and resistant to rutting and cracking. The literature study also looked at the paving process and asphalt distress types since they are key parts of this research. Furthermore, the expert interviews aided understanding constructing and maintaining an asphalt road. Their expertise helped in gaining background knowledge.

The Empirical study focused on a 460-meter-long section of the A35, paved in 2007 with two layers of porous asphalt and a roughly 830-meter-long section of the Aziëhavenweg, paved in 2008 with an SMA top layer. During these projects data on temperature homogeneity and compaction was recorded. Now, after 12 and 11 years distress has arisen. The empirical study focuses on comparing the data collected during paving with the distress data. The Empirical study aimed to find if there are any relationships between these elements. The A35 showed quite some distress, but there was not sufficient evidence to conclude any relationships between the distress and paving data. The Aziëhavenweg also showed some signs of distress, but no solid conclusions could be made. Both of the roads were then compared, but due to the fact that both individual cases showed no real results, the comparison also did not show any relevant results.

Theoretically, there is a connection between the aspects of paving, particularly temperature homogeneity and compaction, and the distress that emerges later on. However, this study did not show this connection. Because of the theoretical basis, it is advised to look into this topic more at a much larger scale which is also statistically relevant. A type of study of this kind may be able to shine a light on what the reality is. The data collected during paving did show that there are sometimes some issues during construction which may affect the quality of the paved surface; particularly paver stops and uneven compaction. Although the research did not show this to have much of an effect, the theory suggests that it may be wise to lessen this as much as possible.

NEDERLANDS SAMENVATTING

Asfalt is het meest gebruikte materiaal voor wegen. Het is zo populair geworden omdat het sterk is, maar ook nog flexibel. Er zijn meerdere soorten asfaltmengsels waarvan elk andere eigenschappen hebben. Asfalt is in principe een mengsel van aggregaat en bitumen. Bij het ontwerpen van een asfaltmengsel is er keuze uit aggregaat type, aggregaat grootte, aggregaat verhoudingen, hoeveelheid bitumen, hoeveelheid holle ruimtes en de verschillende soorten toevoegingen die mogelijk zijn.

In dit onderzoek worden literatuuronderzoek, expertinterviews en een empirisch onderzoek gebruikt om de hoofdvraag van het onderzoek te beantwoorden: Welke relatie is er tussen asfalteren, met name verdichting en temperatuurhomogeniteit, en de levensduur van het asfalt? Het literatuuronderzoek en de expertinterviews worden gebruikt om een achtergrondkennis op te bouwen en een begrip te krijgen van de theorie die in dit onderzoek speelt. Voor het empirische onderzoek wordt er naar twee wegen gekeken (de A35 en de Aziëhavenweg) om tot een conclusie te komen.

Tijdens het literatuuronderzoek wordt eerst gekeken naar de twee asfaltsoorten die belangrijk zijn in dit onderzoek, ZOAB en SMA. ZOAB staat bekend voor het hoge percentage van holle ruimtes (meestal tussen 18 en 22%) die ervoor zorgen dat water door het asfalt de grond in afgevoerd kan worden. SMA daarentegen heeft een veel lager percentage van holle ruimtes (tussen de 4 en 6%). Dit betekend dat SMA niet dezelfde karakteristieken heeft als ZOAB. SMA is nuttig door dat het sterk is bij hoge volumes verkeer en zeer resistent is tegen spoorvorming en barsten. Gedurende het literatuuronderzoek wordt ook gekeken naar het asfalteerproces en de soort visuele schade die kan optreden op asfaltwegen. De expertinterviews hebben geholpen bij het begrijpen van hoe een weg wordt geconstrueerd en onderhouden. De expertise van de experts heeft ook geholpen met het opbouwen van achtergrondkennis.

In het empirisch onderzoek wordt er gekeken naar een 460 meter lang stuk van de A35 die geasfalteerd is in 2007 met twee lagen van ZOAB en een 830 meter lang stuk van de Aziëhavenweg die in 2008 geasfalteerd is met een toplaag van SMA. Tijdens het uitvoeren van deze projecten is data verzamelend over de temperatuurhomogeniteit en verdichting. Nu, 12 en 11 jaar later, is er schade ontstaan op deze wegen. Het empirische onderzoek vergelijkt de data dat tijdens het asfalteren verzameld is met de schade data om te zien of er relaties tussen beiden te vinden zijn die theoretisch te verwachten zijn. De A35 heeft veel schade in de vorm van rafeling, maar er was niet genoeg correspondentie te vinden tussen de schade en de data van asfalteren om te kunnen concluderen dat er een relatie is. De Aziëhavenweg was vergelijkbaar. Het verschil was dat er weinig relevante schade te vinden is op de Aziëhavenweg. Hier was het ook niet mogelijk om relaties te vinden tussen het asfalteren en de schade. Na de individuele analyses zijn de twee wegen ook nog met elkaar vergeleken, maar omdat er geen resultaten waren, was hier ook weinig relevants te vinden.

Theoretisch gezien is er een relatie tussen de kwaliteit van het asfalteren en de schade die optreedt. Tijdens dit onderzoek was deze relatie niet te vonden. Het wordt aangeraden om dit soort onderzoek uit te voeren op een veel grotere schaal met een hoeveelheid data die statistische relevantie heeft. Wat wel te zien is in het onderzoek is dat er soms problemen ontstaan tijdens het asfalteren, vooral pauzes van de asfalteermachine en oneven verdichting. Dit onderzoek heeft niet bewezen dat dit een groot verschil maakt, maar het is wel aan te raden dat dit zo veel mogelijk verbeterd wordt.

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1. INTRODUCTION

Asphalt has been commonly used in road construction for many years. Asphalt was first used in 1870, and since then the application has grown significantly (Virginia Asphalt Association, 2019). As is logical with a material used so much, various process and design improvements have taken place over the years. Additionally, various different asphalt mixture designs have been produced with different features. Although there exists a large body of knowledge on the topic, there is still the opportunity for further improvement. Optimizing asphalt usage by constructing roads which are more durable is positive for everyone. This research paper aims to add to the existing body of knowledge in a meaningful way. This will be done by compiling a literature analysis on the types of asphalt studied in this paper, employing interviews with multiple experts in the field to strengthen the research, and use two case studies to further the knowledge on asphalt processing and its effects.

This paper details the research done to understand the effects that the paving and compaction process has on the ultimate lifespan of an asphalt road. Process discontinuities, among other things, can have an impact on the quality of the asphalt mat constructed, however, the exact consequences are still uncertain. Two road sections are used to discover what the consequences of certain process discontinuities are. The first of these two case roads is a section of the A35 highway which was paved by BAM in April of 2007. Since it is a highway, the road has seen vehicles at high intensity and high speeds every day. The second case is the Aziëhavenweg; a road in an industrial part of Amsterdam. This road was paved in July of 2008 by BAM wegen. As opposed to the A35, the Aziëhavenweg sees a significantly lesser volume of vehicles which are also going a slower speed. However, the Aziëhavenweg does see a lot of freight trucks due to the nature of its location. Data on both of these very different roads is used in the analysis.

2. RESEARCH AIM

The main objective of this research is to gain increased insight into the effect that the construction process (i.e. paving and compaction) has on the quality of asphalt. Logically, an optimized construction process will improve the quality of asphalt, and a building process full of errors, mistakes, and inefficiencies will result in the opposite effect. However, that notion alone does not aid in improving the use of asphalt. Relevant information would include knowing what actions during the paving process result in negative effects later in the life of the road. Only then can processes be improved, and hopefully, optimized.

This research is done in coordination with ASPARi (Asphalt Paving Research and innovation), a research group working at the University of Twente to improve the asphalt construction process (ASPARi, 2019) (Miller S. , 2019). This is done by working collaboratively with multiple construction companies which "are collectively responsible for more than 80% of the asphalt turnover in the [Netherlands]" (ASPARi, 2019).

There are numerous factors which affect the quality of asphalt. This paper will focus specifically on two major ones: the temperature homogeneity of the asphalt mixture during paving and the compaction process. The effect that these two things have on the quality of the pavement will be analyzed. This will be done by observing the distress of roads after years of use. Comparing this distress to the existing data on the two factors will allow formal analysis to take place. If the data points towards a relation between certain factors during construction and distress, then conclusions may be derived. The conclusion will result in a recommendation to adapt the construction process.

2.1. Research question

As stated above, the objective of this research is to understand the effect that the paving process has on the quality of a road further in its lifespan. The following research question has been formulated to look at the relation between to specific parts of the construction process mentioned earlier and the pavements lifespan:

What relation is there between asphalt processing, particularly compaction and temperature homogeneity during paving, and the asphalt's ultimate lifespan?

The answer to this question will aid in understanding how paving and compaction need to be changed to achieve higher quality asphalt.

The main research question will be answered using multiple sub-questions. Throughout the process of this research, these questions will be answered. If all of the sub-questions are answered, then the main research question will also have been answered.

Asphalt damage data will be collected. To work with this data specific questions needs to be answered:

How can asphalt damage be quantified?

What does asphalt damage say about its lifespan?

After these are answered the comparison and analysis of the data collected on construction and distress can take place. During that procedure the following questions will be asked:

What effect do process discontinuities have on temperature and compaction homogeneity?

What effect do temperature and compaction homogeneity have on asphalt distress?

With answers to these questions further analysis can be done. This includes the following questions:

What is the link between certain, specific, types of asphalt damage and events during paving?

Do the different circumstances in the two cases (A35 and Aziëhavenweg) deliver similar results?

2.2. Research Method

The following methods were used in this research paper:

- Literature study
- Expert interviews
- Empirical study

The research was done in the following way. Firstly, a literature review will be performed. Background information on all aspects of the research will be compiled and used in the study. Additionally, to supplement the information from the literature study, expert interviews will be conducted. The experts are professionals that have been working in the field of asphalt and roads for many years. The literature study and the expert interviews will form a good foundation for the research. The information compiled in this process will be used in the analysis which will be performed during the empirical study.

The two roads, mentioned earlier, are used in an empirical study. Data from different phases of the road lifecycle will be collected and has been compared. Firstly, historical data from during the construction in 2007 and 2008 will be compiled. This data includes information on the asphalt mixture temperature homogeneity, compaction process, and other environmental factors. The temperature homogeneity and compaction data will be used to determine locations where there was bad temperature homogeneity and low compaction respectively. A look will be taken at the additional environmental factors to determine what effect that has on the quality of paving. To do all of this information from the literature review and expert interviews will be used. After this, the problem areas of the road can be identified.

For both roads a visual inspection will be performed. Data gathered from the visual inspection will be overlaid with the previously used paving data. The overlay images will be visually analyzed using theoretical information gathered with the literature review and expert interviews. The analysis searches for relationships between the paving data and the visual distress data. The conclusions will be based on the relationships found in the data and the information gathered during the literature review and expert interviews. Also, the conclusions for the two individual roads which will be analyzed will be compared. The recommendations will then be based on the conclusions.

Figure 1 shows this entire process. The process begins with the inputs. The actions taken during this research are also shown. Finally, this process leads to final conclusions and recommendations.

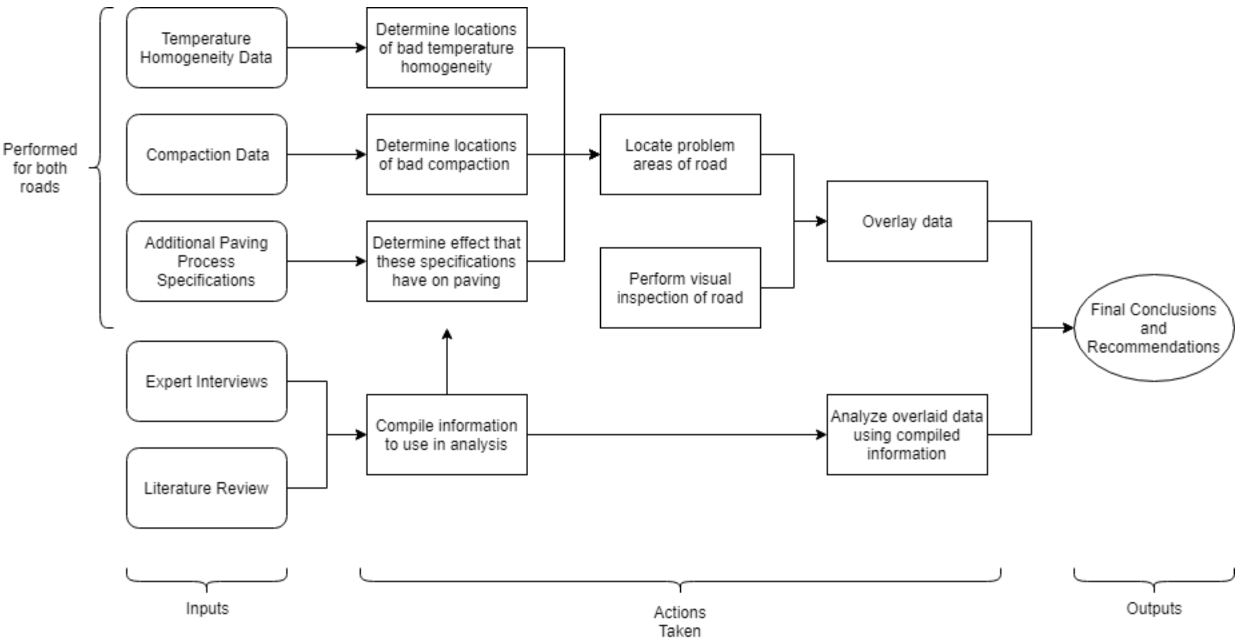

Figure 1: Visual representation Research Process

3. BACKGROUND INFORMATION AND LITERATURE REVIEW

Due to the complex nature of asphalt, new findings cannot be expected to be correct without a firm understanding of all of the phenomena at play. Understanding the properties of the asphalt types used in these roads is important when drawing conclusions from the cases analyzed in this study. Additionally, the two main parts of asphalt processing which are specifically investigated (compaction and temperature homogeneity) need to be understood. Asphalt processing is done by human beings. This makes human error and decision making a central part of the process. This will, therefore, also be analyzed and researched. Finally, the classification of various types of asphalt distress and their possible causes will be noted.

3.1. Types of Asphalt Important to this Study

Asphalt is the material that make up the surface of the majority of the roads in the Netherlands. It is the chosen material for road paving due to the fact that it better absorbs energy than concrete (Thom, 2014). Asphalt mainly consists of aggregate and binder. Depending on the mix design of a specific kind of asphalt different sizes and amounts of aggregates are used. The aggregate is then held together using bitumen, which is a residual product of oil. Two types of asphalt mixtures, porous asphalt (ZOAB) and Stone Matrix Asphalt (SMA), are pertinent to this research because they are the two asphalt types used in the case roads which will be discussed and analyzed in later chapters.

The information in this chapter was gathered by reading books and papers on the subject. Additionally, a lot of information was gained from four expert interviews. Finally, some supplementary information was gained from non-structured conversation with people well versed in the field of asphalt. Additional information which is not in the main paper can be found in Appendix section 8.1.

3.1.1. POROUS ASPHALT (ZOAB)

In the Netherlands ZOAB is the most used type of asphalt (Rijkswaterstaat, 2019). ZOAB (zeer open asfaltbeton) is a Dutch term which roughly translates to “very porous asphalt”. Porous asphalt is widely used in the USA and Europe and is becoming more popular in Asia (Yu, Jiao, Yang, & Ni, 2015). The popularity comes from its many positive qualities. The porosity of this type of asphalt allows water to be drained quickly and, additionally, reduces noise pollution from cars (see Appendix 8.1.1). Because water is drained from the road surface, aquaplaning is avoided, water spraying is reduced, glare from reflected sunlight is reduced and road markings are more visible (O'Flaherty & Hughes, 2016). Porous asphalt uses “strongly gap-graded aggregate gradations” (Huber, 2000) This means that the ratio between large and small aggregate used is skewed towards the large aggregate. As opposed to other types of asphalt which may have anywhere between 4% to 10% voids, porous asphalt has voids ranging, on average, between 18%-22% (Huber, 2000; Thom, 2014). The high void and high large aggregate content of porous asphalt is a recipe for low stiffness, high susceptibility to water damage, and a low fatigue life (Thom, 2014). For more information on aggregate choice in asphalt see Appendix section 8.1.2.

The durability of Porous asphalt is the main concern. The characteristic that makes it so attractive for road use also results in its weakness. The open mix design can cause porous asphalt to quickly lose stones from the pavement surface (MO, 2010). Porous asphalt experiences fretting and reveling as the most common form of distress (Herrington, Reilly, & Cook, 2005). The open mix design means that the asphalt is more vulnerable to aging and becoming brittle after long term exposure to atmospheric oxygen (O'Flaherty & Hughes, 2016). To counteract this enough bitumen must be used to cover the aggregate in a thicker coating (Herrington, Reilly, & Cook, 2005; O'Flaherty & Hughes, 2016). The average lifespan of porous asphalt in the right lane (the slower but more travelled lane on Dutch highways) is 10 to 12 years. Comparing this to the 18-year average that more dense asphalt mixtures have in the same situation shows that the durability of porous asphalt is significantly less (MO, 2010). In the Principles of pavement engineering book (Thom, 2014) the fatigue strength of Porous asphalt is rated at medium-low. Compared to the other asphalt surfaces listed, this was the lowest rating. Another source stated that the ultimate lifespan (the lifespan until the road has to be replaced) of porous asphalt was 7 years in the Dutch climate (O'Flaherty & Hughes, 2016).

Water is of large concern to pavement engineers (Thom, 2014). However, porous asphalt is designed to allow water to drain through it. Although this is a positive quality, it can also be reason for concern. Clogging can be a concern for porous asphalt. The pores can be clogged by dirt and pollutants such as dust and tire wear by-products (Hamzah & Hardiman, 2005). Double layer porous asphalt does, however, mitigate clogging by using a finer porous top layer and a courser, thicker bottom layer (Hamzah & Hardiman, 2005; O'Flaherty & Hughes, 2016). If clogging does occur or a layer below the porous layer becomes fatigued, then rutting can occur. This will cause water to pool when it shouldn't (Onnink, 2019). In areas where clogging occurs the noise level has been observed to increase by about 0.5 dB per year (O'Flaherty & Hughes, 2016). More on the noise reduction of porous asphalt is available in section 8.1.1.

3.1.2. STONE MASTIC ASPHALT (SMA)

Stone mastic asphalt can also be known as stone matrix asphalt is most commonly referred to as SMA. The materials used to make SMA include aggregate (both coarse and fine), filler, asphalt cement, and stabilizer (which is used to prevent draindown of the asphalt cement and consists of fibers and polymers) (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996; Asi, 2006). High quality crushed aggregate is used to more effectively interlock and increase the durability (Michael, Burke, & Schwartz, 203; O'Flaherty & Hughes, 2016). Typically, the optimal void concentration of SMA is between 4% and 6% which makes it quite dense (Antonissen, 2019; Michael, Burke, & Schwartz, 203). Some SMA types even have void contents ranging between 2% and 4% (O'Flaherty & Hughes, 2016). SMA has the coarse aggregate skeleton similar to porous asphalt, but instead the voids are filled in with finer aggregate and fines to reduce the void content (along with sufficient compaction) and provide stiffness (see Section 8.1.2 for further explanation). In Europe it has been used since the 1960's (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). SMA is still used today due to the desired qualities. The reason that it is not used more often, is because the positive qualities of porous asphalt which SMA does not have, as discussed earlier, make very effective on highways.

SMA is a very durable asphalt type to use. It provides good performance in high volume traffic areas (Brown, Mallick, Haddock, & Bukowski, 1997; Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). In the Principles of pavement engineering book (Thom, 2014) the fatigue strength of SMA is rated at medium-high. Compared to the other asphalt surfaces listed, this was the second highest rating. The primary reason it is used is for its improved resistance to rutting and high durability (Roberts, Kandhal, Brown, Lee, &

Kennedy, 1996; Asi, 2006; O'Flaherty & Hughes, 2016). SMA mixtures have also shown a low susceptibility to cracking (Brown, Mallick, Haddock, & Bukowski, 1997). Additionally, a study found that after long exposure to water (which has been called the “enemy of the pavement engineer” (Thom, 2014), SMA experiences greater durability than standard asphalt mixtures. This is due to the thicker film of binder used (Asi, 2006). A study of over 100 SMA mixtures used to construct roads in the USA found that the resistance of rutting was high (Brown, Mallick, Haddock, & Bukowski, 1997). That same study also found no raveling in any of the cases. The biggest problem when it comes to performance was found to be fat spots (see section 8.1.3 on distress types) (which are caused by segregation, draindown and high asphalt content) (Brown, Mallick, Haddock, & Bukowski, 1997).

3.2. Asphalt Paving Process

The Road Lifecycle (Figure 2) describes the five steps that asphalt takes to become an actual road (Makarov, Miller, Vahdatikhaki, & Oliveira do Santos). Firstly, the right type of asphalt is chosen based on the type of road and other external factors. A mixture which fits the specifications (such as the needed load bearing capabilities) best is *designed*. This asphalt then needs to be *produced* in an asphalt plant. The mixture is *delivered* to the construction site. Then the asphalt is *paved and compacted* to create the final product; a usable and durable roadway. This road is then hopefully used for many years and continually monitored. The last two steps of this lifecycle are of utmost importance in this research, since the phenomena observed take place in these two steps.

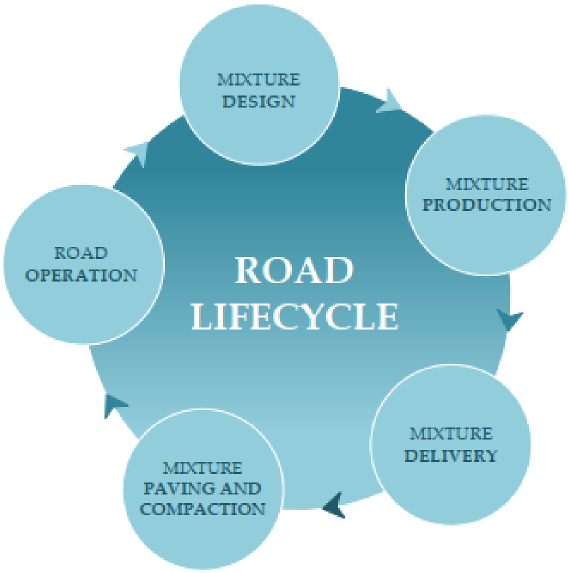

Figure 2: The Road Lifecycle (Makarov, Miller, Vahdatikhaki, & Oliveira do Santos)

The second to last step (mixture paving an operation) will predominantly be discussed in this section. The most important parts of this step for this research are the temperature of the asphalt during paving and the compaction process. There will also be a mention of the last step, road operation, because it is important to take a look at the inspection process.

3.2.1. ASPHALT TEMPERATURE

An asphalt mix is designed to be heated to an optimal temperature. Hot mix asphalt needs to be heated to make it malleable enough to be worked with. While it is hot, the paver lays down the asphalt mat. It is important that the asphalt is indeed heated to the desired temperature during construction. However, this may not always be the case.

Temperature Homogeneity

Achieving the highest degree of temperature homogeneity throughout the asphalt mat results in the highest quality asphalt. If temperature differentials are present, density differentials in the mat may be produced (Willoughby, Mahoney, Pierce, Uhlmeyer, & Anderson, 2002). This may affect the lifespan of the pavement (Willoughby, Mahoney, Pierce, Uhlmeyer, & Anderson, 2002). Temperature segregation is defined as lack of homogeneity in a hot mix asphalt mat which has a magnitude which causes a reasonable expectation of accelerated pavement distress (Stroup-Gardiner & Brown, 2000). This can occur because of uneven cooling of portion of the asphalt mix in the haul truck, along the side of the truck box and in the wings of the paver (Miller, ter Huerene, & Dorée, 2007). Temperature differentials of 20 degrees have a high likelihood of being highly segregated (Miller, ter Huerene, & Dorée, 2007). Cold spots, which are areas in the asphalt mat where the temperature is significantly lower than the surrounding asphalt, are likely a main cause for potholes in otherwise intact pavements (Thom, 2014). These cold spots become less compacted than the surrounding area which makes them weaker.

Temperature homogeneity is achieved when there are no rapid and large changes in temperature. Since a rapid 20 ^{o}C change has a high likelihood of causing segregation changes around this severity will be classified as drastically changing the temperature homogeneity for the purpose of this research. Technically, any change of temperature causes the asphalt mat to decrease in temperature homogeneity, but small changes are not very relevant and impossible to stop from happening.

In 29 paving projects monitored between 2007 and 2013 the temperature homogeneity was measured (Bijleveld, 2015). During these 29 projects, 140 paver stops were observed. The temperature drop in the asphalt mat due to the paver stops was monitored. For the 49 stops under 3 minutes (which is regarded as a truck change) the temperature dropped, on average 22 to 25 ^{o}C depending on the layer. Additionally, for the 51 stops which were between 4 to 9 minutes long (which are regarded as short paver stops) the temperature dropped an average of 33 to 40 ^{o}C depending on the layer type. Finally, for the 27 stops longer than 10 minutes the temperature dropped between 46 and 63 ^{o}C depending on the layer type (Bijleveld, 2015). The average temperature drops observed for all of the different stop lengths are significant given that temperature differentials of 20 degrees already have a high likelihood of causing segregation.

Asphalt Cooling

From the moment that an asphalt mixture is made at the asphalt factory it begins to cool down. Before it can be used for paving, asphalt needs to be transported in trucks to the build location. During transportation asphalt cools at a very slow rate (Oosterveld, 2019). This is because the trucks used to transport the asphalt are insulated and because the asphalt has little exposed surface area. Although the cooling is slow, it can still happen unevenly which may cause temperature segregation. The majority of the asphalt cooling happens once the asphalt has been paved. Then, the surface area relative to the volume of asphalt has increased greatly which means that cooling can happen much quicker. The cooling curve looks similar to the one pictured in Figure 3 (in section 3.2.2). In the next section it will be discussed how the compaction process is heavily influenced by the cooling of asphalt.

Weather conditions at the time of paving may affect the rate at which the asphalt cools. The optimal weather for paving is between 20 and 25 degrees temperature with low wind and no rain (Antonissen, 2019; Jagt, 2019). Temperature differences may change the speed with which the asphalt cools, although the changes are not very drastic (Antonissen, 2019). More important aspects are the wind speed. Wind will cause the asphalt to cool down quicker. This is why it is better to pave with low wind speeds (Antonissen, 2019; Jagt, 2019). Rain will also affect the cooling of asphalt. Depending on the severity of the rain and the type of paving being performed the project may need to be done at a different time. If a base layer (not a top layer) is being paved, then rain will have less of an effect. Additionally, if the rain is not very severe, then paving may still be possible (Antonissen, 2019; Jagt, 2019).

If the optimal weather is not possible there are a couple of options. Firstly, the choice can be made to pave on another date with better weather. This option may cost money upfront, however, it saves money in the long term (Antonissen, 2019; Jagt, 2019). This is because paving during bad weather conditions will result in lower quality asphalt which likely will need to be replaced much sooner. Saving a couple of thousand euros by not changing the paving date could cause millions of euros of additional costs in the future in some scenarios. The second option is to continue paving with adjusted techniques in less than optimal weather conditions. This is only an option if the weather is not extremely bad, but instead only slightly less optimal. If this is the case, then the compaction process can be adjusted to lessen the quality reduction due to the weather conditions (Antonissen, 2019; Jagt, 2019). If done well, minimal quality will be lost while money is saved by not changing the paving date. Finally, the decision can also be made to continue paving in bad weather conditions. Advisers would not advise this (Antonissen, 2019; Jagt, 2019). However, the client (often municipalities) may want paving to take place on a specific day. In this case the quality of the road will most likely be severely lower, however, if the client does not want to/has the ability to be flexible, then this is the result.

3.2.2. ASPHALT COMPACTION

Compaction is a key process during the creation of a road. After a road is paved, then the asphalt needs to go through the compaction process to reduce the concentration of voids within the concrete.

Compaction process

Essentially, compaction requires compressing the asphalt mat with heavy load to force out excess air (HAMM AG, 2010). There are two ways in which asphalt can be compacted: static compaction and dynamic compaction. Static compaction is the simplest form. During static compaction the weight of the roller is used to deliver enough compressive force to decrease the void concentration to the desired amount (HAMM AG, 2010). Dynamic compaction, on the other hand, adds an additional element to static compaction. In addition to the weight of the roller, dynamic compaction employs vibrations to provide better penetration and more efficient compaction (HAMM AG, 2010). The vibrations are created using imbalanced weights within the roller which set a drum in motion which then delivers the vibrations to the particle in the asphalt (HAMM AG, 2010). Asphalts made up of a stone skeleton should not be compacted using dynamic vibration. Two examples of asphalt with a stone skeleton are SMA and ZOAB (porous asphalt). Both of these asphalts use predominantly large/coarse aggregate which is held together with bitumen. If dynamic compaction were used the individual stones in the asphalt have a chance of breaking (Antonissen, 2019; Jagt, 2019). If, for example, a stone, which is covered in bitumen, breaks due to dynamic compaction, then the break will be a surface where bitumen does not bind the two halves of the stone (Jagt, 2019). This is a weak point. If there are many of these cases, then the asphalt is significantly weaker. Dynamic compaction, therefore, might actually do more harm than good. This is why most asphalts which are designed in this way only use static compaction. The two asphalt types pertinent to this research are both types that require static compaction.

Key to achieving optimal compaction is performing compaction at the right time. The optimal compaction time frame is decided by the asphalt temperature. The quality of the compaction process depends on the temperature of the asphalt. If the asphalt is compacted at a temperature too high, then the asphalt quality will be lower, and the matt will be compressed thinner that the designed thickness. However, if the asphalt is compacted at too low a temperature, then the compaction will have less of an effect than it is meant to. This will also result in lower asphalt quality and an asphalt mat which may be too thick. Because of this, the only window of opportunity to compact successfully is between temperatures which are too hot and too low (Miller S. , 2019). Figure 3 shows the asphalt cooling curve and how the optimal compaction timeframe fits into this. This is why cold spots (mentioned in section 3.2.1 to cause potholes) become less compacted than the surrounding area.

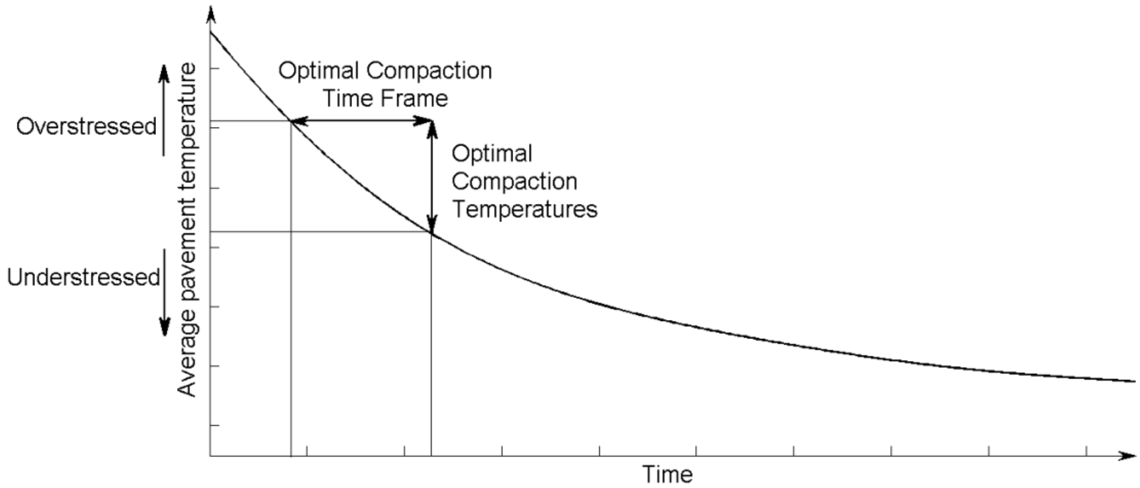

Figure 3: Asphalt Cooling Curve and the Optimal Compaction Time Frame (Timm, 2001)

Compaction influence on lifespan

Compaction, if done correctly, results in much higher quality asphalt. The fatigue life is time between initial construction and the point at which the asphalt experiences severe fatigue cracking. It was found that for every 1% more voids than optimal, the fatigue life would decrease by between 10 and 30% (Linden, Mahoney, & Jackson, 1989). A study of the effect of compaction on asphalt concrete performance used literature, a survey, and data to conclude the effect that void concentration has on the lifespan of concrete (Linden, Mahoney, & Jackson, 1989). That study states that "the rule-of-thumb that emerges is that each 1 percent increase in air voids […] results in about a 10 percent loss in pavement life…" (Linden, Mahoney, & Jackson, 1989). The 1 percent increase is above the optimal void content for that type of asphalt. For example, if a certain type of asphalt performs optimally at 6% voids, but due to insufficient compaction the asphalt mat resulted in 10% void concentration, then it can be expected that the lifespan of the pavement will be roughly 40% less than designed. However, compaction does reduce the permeability of the mix (Beainy, Commuri, Zaman, Boyd, & Alexander, 2012). Although this increases durability, it may be an issue for asphalts which are meant to be porous. It is important to remember that there are many factors which affect the lifespan of asphalt, however, void content is consistently on of the most influential factors (Linden, Mahoney, & Jackson, 1989). Lack of compaction can result in higher void content which results in a higher chance of raveling. This is also shown in Figure 4.

3.2.3. ASPHALT PAVING VARIABILITY

The paver and compactors, arguably the central parts of the crew, are operated by human beings which must work in unison to deliver a quality product. Additionally, the supervision, measurements, and other jobs are all done by human beings. Through research it has been shown that on-site factors can influence the quality of the asphalt by up to 30% (Bijleveld, 2015). Improved monitoring/tracking of the asphalt construction process and the implementation of method-based learning have been shown to improve the quality of the process (Bijleveld, 2015). The individuals that make up a paving crew must work together to create a high-quality road. In Appendix section 8.1.4, table which shows all of the elements of a full asphalt paving crew can be seen

The paver is the central part of the operation. They typically pave at about 3 to 5 meters per minute, but occasionally need to stop during the process. Stops can be planned, or accidental if there is an issue. The stops can create inconsistencies and temperature differences in the asphalt mat. Behind the paver the rollers operate to compact the freshly laid asphalt mat while the temperature is still optimal. Often multiple rollers will be working simultaneously. This means that they need to communicate and work together for optimal compaction. Roller operators attempt to compact the entire mat evenly, but that is very difficult. There are new innovations in the compaction field in the form of tracking systems called HCQ which allow the operators to see where they have compacted already. This along with their prior expertise and heat sensors in the roller attempts to further optimize the compaction process. Outside of these two main parts there are other members on site. The dump trucks bring the asphalt from the asphalt mill. The rakers make sure the sides of the mat and the excess are dealt with. The bitumen spray truck sprays joints with bitumen to bind two asphalt mats together. Lastly, the supervisor keeps the operation running smoothly. For more explanation into the roles of the Paver and the Rollers see Appendix section 8.1.4.

Although attempts are made to reduce variability during paving, the fact that it is a process done entirely by humans means that there is inherent variability. This variability means that it is not possible to ensure the same quality every single time. The first steps to lessen the variability is to understand where the mistakes are made. Then steps can be taken to lower the variability.

3.3. Asphalt Distress

Throughout the lifespan of a road, it experiences great stresses, largely from vehicles. Some roads, such as highways, experience more stresses than others. Distress in asphalt pavements results in both visible and invisible changes in the asphalt. The invisible damage is not visible with the naked eye because it is either very small or below the surface. However, many types of damage can be seen visually.

Visual inspection can be used to determine the distress that a road has experienced. This can also give an indication to the state of the road and whether or not maintenance or reconstruction is needed. There are various types of damage, including, cracking, patching and potholes, surface deformation, surface defects, and miscellaneous distresses (Miller & Bellinger, 2014). Each one of these types has sub-types of damage. Table 1, in Appendix 8.1.3, displays the distress types, a description of said type, possible causes, and the way in which they need to be measured. This table is based on the Distress Identification Manual from the U.S. Federal Highway Administration with also additional data.

Raveling is one of the most relevant type of distress to this research. This is because raveling is expected to be directly influenced by the quality of the paving process for the top layer. Raveling occurs when aggregate with a diameter of over 2 mm is removed from the top of the asphalt mat (Kennisplatform CROW, 2011). Raveling can be cause by deficient asphalt content, insufficient amount of fine aggregate matrix to hold the coarse aggregate particles together, lack of compaction, and/or excessively aged asphalt cement binder (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). Figure 4 shows that raveling correlates with air void percentage within the asphalt mat. Air void percentage is directly influenced by compaction. Clearly, compaction can therefore have a serious impact on raveling. Additionally, High severity raveling can lead to the formation of potholes (Thom, 2014).

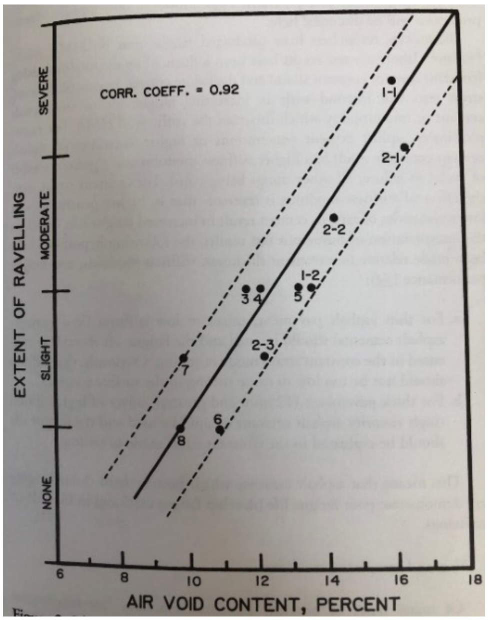

Figure 4: Raveling Extent Compared with Air Void Content (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996)

Generally, cracks are classified into two categories: load associated and non-load associated cracking (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). The main form of load associated cracking is known as fatigue cracking (or alligator cracking). This type of cracking happens when the road is repeatedly exposed to tensile loads larger than the maximum tensile strength of the asphalt (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). One of the few reasons that influence the development of fatigue cracking is the air void and aggregate characteristics in the asphalt mix (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). This means that the compaction may play a role in avoiding fatigue cracking. Non-load associated cracking is often manifested in the form of transverse cracking that come predominantly from rapid cooling of HMAs. This often happens for asphalt mixtures which have a high stiffness at low temperatures (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996). Other types of cracking, on the other hand, are not expected to be directly influenced by the paving of the top layer. Instead, cracking is caused by the internal forces which need to be supported by the lower layers. If these layers cannot support these forces, then the top layer can crack.

Quantifying whether distress to a road is serious enough to warrant repair or replacement depends on the contract that the owner and the construction company in charge of maintenance have (Flentge, 2019). It also depends on the type of road and the function it fulfills. The severity of distress depends on the type of distress and the guidelines for the area in which that specific road is located (Flentge, 2019).

Understanding what distresses are relevant and how these distresses are caused is important for the analysis which will be performed. Knowing why, specifically, raveling and cracking occur allows for more specific analysis during the empirical study. The information collected on these forms of distresses will be used extensively in the empirical study.

3.4 Conclusions Literature Review and Expert Interviews

The sections above, composed of information from many different papers, reports, expert interviews, etc., are important in this research. The information collected will be used in performing an informed analysis in section 4.

Firstly, the characteristics of the two asphalt types pertinent to this research were made known. When the analysis will be performed, these characteristics need to be known and considered. Porous asphalt has many positive qualities, but there is an increased likelihood of various forms of distress developing. SMA on the other hand is strong but lacks some of the qualities that makes porous asphalt so attractive. Then, the important aspects of asphalt paving were determined and researched. The impact that temperature homogeneity and compaction have on the final quality of the road was stated. This will play a very large role in performing an accurate analysis. A very important conclusions which can be made is that areas where the temperature changes 20 ^{o}C or more rapidly are highly likely to form segregation. This will be used to find which areas of the road are likely to have more distress. Additionally, it is established that a lack of compaction has a very large effect on the lifespan on the lifespan of a road. If asphalt is compacted 1% less than optimal, it can affect the lifespan by 10 to 30%. Therefore, the areas in which fewer roller passes, and thus less compaction, is shown are also more likely to show distress. Finally, information on the types of distress which can be expected was collected. This makes it possible to determine which types of distress can be linked to either compaction or temperature homogeneity issues. For example, raveling is partly influenced by the amount voids in the asphalt mat. The voids are influenced by the compaction and the asphalt type. Therefore, it would be expected that areas where less compaction has taken place will have more raveling. Additionally, it can be expected that Porous asphalt has more raveling in general because of the high void content.

4. EMPIRICAL STUDY

4.1. Introduction

In this section the entire empirical study will be detailed. Additionally, extra information and expanded analyses which are not found in this section can be found in the appendix. The empirical study focuses on two road sections. These two sections are the A35 Test section 3 and the Aziëhavenweg. In 2007 and 2008 BAM, together with ASPARi, paved sections of the A35 and Aziëhavenweg respectively. These two projects were the first of many in which the entire paving process would be monitored. These two roads were specifically chosen to analyze because they are the oldest projects that BAM and ASPARi have done together. The long timeframe between paving and now makes them the best subject for a study such as this one because if more recent projects were chosen then there would be very little data to use. In this section the data from the paving of these two projects, specifically the temperature contour map and the compaction coverage maps, will be compared to the current state of both of the roads. The current state of the roads will be shown by how much distress can be seen. The exact process for the entire analysis was explained in section 2.2 and is visually displayed in Figure 1. In addition to that analysis, rutting on the Aziëhavenweg will be compared to the compaction percentage and roller passes. The analyses performed in this section hopes to shine a light on some relationships between paving operations and road quality further in its lifespan.

Firstly, a comprehensive look will be taken at the data pertaining to the A35 Test section 3. Afterwards the Aziëhavenweg will be fully analyzed. After both roads have individually be assessed, they will be compared to hopefully gain an even better understanding of the relationships at play. The findings of the empirical study will play a part in the final recommendations made by this paper.

4.2. A35 Test section 3

The A35 is highway runs from Wierden, a town near Almelo, to Enschede (See red line in Figure 5) (Rijkswaterstaat, n.d.).

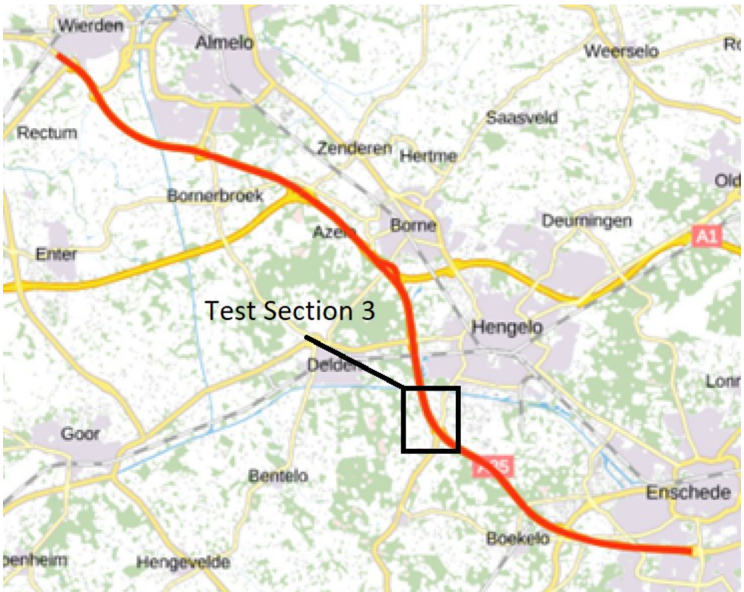

Figure 5: A35 (Rijkswaterstaat, n.d.)

In April of 2007 a part of the A35 was paved by BAM. This section (coined test section 3) was roughly 460 meters long. The challenge presented to BAM was to deliver a cleaner, quieter, and more homogeneous road (Sluer, 2007). The exact location of this section is A35 HRR 60.730 to 61.190. This means that it is the right side of the highway from location 60.730 to 61.190. The Outlines of the exact section can be seen in Figure 6 and the position of section relative to the entire highway can be seen in Figure 5. The section is located on the southwestern side of Hengelo.

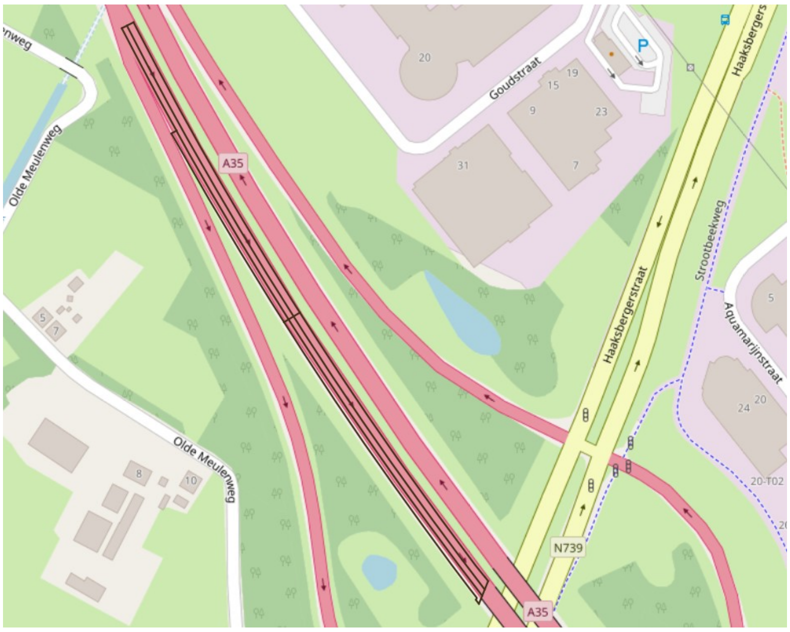

Figure 6: A35 Test Section 3

The paving of this section of the A35 was the first project in cooperation with ASPARi (Asphalt Paving, research and innovation), a research group focused on improving the asphalt construction process from the University of Twente (Miller S. , 2019; ASPARi, 2019). During this project many of the paving conditions were recorded. These conditions include temperature homogeneity directly after paving, compaction by rollers, and weather conditions. At that time this data was processed and analyzed to gain a better understanding of asphalt processing. The conclusions from that research, along with the data from the paving performed in 2007 will be used to evaluate performance of the road. This data, along with asphalt distress data will be used to understand the effect that asphalt processing practices have on the quality of the road paved.

4.2.1. BACKGROUND PROJECT

Due to the explorative nature of the project, the entire asphalt paving process was monitored more extensively than normal. Temperature homogeneity of the asphalt directly after paving, compaction coverage by rollers, weather conditions, and the GPS locations of the equipment are all important aspects of the paving process which were monitored closely (Miller, ter Huerene, & Dorée, 2007).

As is visible in Figure 6 there are three lanes for the majority of the section’s length. Lanes one and two are meant for driving and the third lane is an emergency lane. Each lane was paved separately. Because of the length of the lanes, the paving was planned to be split over two nights. The first night (Wednesday the 24th of April) lane one was paved for 230 meters, lane two was paved for 250 meters, and lane three was paved for 230 meters (Miller, ter Huerene, & Dorée, 2007). However, on the first night the first 90 to 100 meters of the first lane resulted in low quality because of operational issues (Sluer, 2007). This needed to be fixed on the second night (Thursday the 25th of April). During this night the remaining sections of lanes one and two were completed. Additionally, the low quality, 100-meter-long section of lane one paved on the first night was replaced that night. Because of the unforeseen circumstances, the second part of the third lane could not be paved that same night; thus, a third paving night was needed to complete this section. The third night took place on Friday the 26th of April. Data from the third night was not available.

One additional thing which should be considered is the traffic volume this road experiences. The Dutch Central Bureau of Statistics (CBS) shows that between 2011 and 2014 the average number of cars per hour averages between 1,000 and 1,200 cars per hour (Centraal Bureau voor Statistieken (CBS), n.d.). The graph shown on the website (Figure 7) seems to show a slight increase in the intensity over time, however, it is not reasonable to extrapolate the graph beyond 2014 because there is no way of being sure.

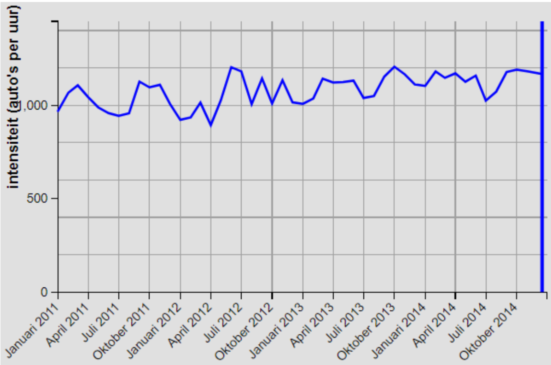

Figure 7: A35 Right Side Vehicle Intensity per Hour between Jan 2011 and Dec 2014 (Centraal Bureau voor Statistieken (CBS), n.d.)

4.2.2. HISTORICAL DATA

During the A35 project the entire section was paved with 2-layer ZOAB asphalt. Specifics of ZOAB is discussed in section 3.1.1 on Porous Asphalt. Both of the layers of ZOAB Asphalt were paved simultaneously with a special twin-lay asphalt paver, also known as the TAS (Antonissen, 2019; Miller, ter Huerene, & Dorée, 2007). The TAS could optimally lay two layers of asphalt at the same time which would also give the compaction crew a larger timeframe to work in because of the increases mat thickness (Sluer, 2007). However, the TAS was not always a success (Antonissen, 2019; Sluer, 2007).

An attempt was made to monitor the weather conditions closely using a portable weather station (See section of Weather Conditions). However, due to technical fault, the data was lost. To attempt to make up for the loss of data, data from another weather station located at the "Vliegveld (airport) Twente" (Miller, ter Huerene, & Dorée, 2007). This weather station was located roughly 10 km from the paving location. Therefore, there is reason to believe that the weather data is slightly less accurate than if it were collected on location. The actual weather data from then can be found in Appendix 8.2.1.

Temperature Profiling

During paving operations two ThermaCAM™ E320 infrared cameras were used (Miller, ter Huerene, & Dorée, Temperature profiling and monitoring of equipment movements during construction (A35: Test Section 3), 2007). These cameras take infrared photos which display the temperature of the asphalt surface mat. Every 10 meters the paver travelled; a thermal picture would be taken. The schedule for when picture would be taken was prepared based on paver speeds staying between 3m/min and 5m/min. The collection of thermal images at every 10 meters was then used to compile 2D temperature contour maps. These maps are a good visual representation of the temperature differences between some areas. One fact which needs to be noted is that during paving only about 400 of the 600 planned pictures were taken (Miller, ter Huerene, & Dorée, 2007). This may affect the accuracy of the data slightly.

In Appendix section 8.2.1 an analysis of all of the temperature contour maps (TCMs) created during paving can be found. The TCMs discussed there include the maps from all of the three lane sections paved on the first night (Wednesday the 24th of April) (Figure 24, Figure 25, and Figure 26) and maps from two lanes paved on the second night (Thursday the 25th of April) (Figure 27 and Figure 28). The lanes are numbered counting from the center line of the road. The TCMs from the second and third lane on the first night show a gradual heating up of the asphalt in the first 10 meters after paving begins. The temperature changes between 30 and 40 °C in both cases, which shows bad temperature homogeneity and gives a high likelihood for segregation to have occurred. These areas could be expected to lead to increased surface distress. The TCM for the first layer shows a large area which is significantly hotter (more than 20 °C difference) than the rest of the asphalt mat beginning at 120 meters. The transition to this hotter area also shows bad temperature homogeneity and gives reason to expect more distress. Additionally, since that area is hotter it took longer to cool down. This means that compaction processes could be affected by the temperature. It is possible that the same amount of compaction as a normal area would receive would result in more compaction in this area.

The two TCMs from the second night of paving also show some temperature differences. The TCM from the first lane shows a clear paving stop and temperature drop at roughly 140 meters. Here the temperature drops over 50 °C within 10 meters and then quickly rises back to the original temperature within 10 meters. This shows very low temperature homogeneity and a high likelihood of segregation and is definitely an area where lower asphalt quality would be expected. Both of the TCMs from the second night show a temperature drop at the end of the paving section. The drop is in both cases nearly 20 °C in less than 10 meters, so there is reason to expect some segregation within the asphalt mat. Lower quality is also expected here.

During the analysis of the monitoring project after paving looked at the connection between surface temperature (what is measured here) and the temperature inside the asphalt mat. This analysis showed that the temperature inside the asphalt mat was higher than the surface, but that there is a high degree of correlation (R^2 value of 0.9) (Miller, ter Huerene, & Dorée, 2007). This means that the temperatures o the surface aren't exactly the temperature inside the mat, but the locations and degree of temperature inhomogeneity are the same within the asphalt mat as on the surface.

Compaction Profiling

Right behind the pavers, the rollers work hard to quickly compact the asphalt mat within the optimal temperature window discussed earlier. Refer to section 3.2.2 and section 8.1.4, specifically the part on Rollers, to understand how this process is handled. The GPS tracking of the paving vehicles allows a formal analysis of the compaction to take place. The GPS data can be used to accurately log how often specific areas of the asphalt mat were compacted by rollers. Using this information compaction coverage maps were made. These show the homogeneity, or lack of homogeneity, in the coverage of the entire asphalt mat.

Because the rollers compacts the asphalt directly after paving, the compaction process also took place over two nights. On Wednesday night (the first night) part of the first and second and third lane were compacted (Figure 29, Figure 30, and Figure 31). On the second night, the remaining sections of the first and second lane were compacted (Figure 32 and Figure 33), but the third lane was not compacted. For each lane a compaction contour map (CCM) was created. The full analysis of every CCM can be found in Appendix section 8.2.1.

The CCMs for the first night show that the majority of each lane experienced between 10 and 15 roller passes. The edges of the lanes we-re often roller less (between 5 and 10 times). The pattern that the end of the lane gets slightly less compacted is also visible. Some small sections of the lanes were also paved more (15 to 20 times) or less (0 to 5 times). In general, this happened very little on the first night, except for an area in the second lane where between 15 and 20 roller passes took place.

On the second night, the compaction in the first lane was considerably worse. Large sections of the right side of the lane were only rolled 0 to 5 times. The Left side of the lane was compacted much more because that side received between 10 and 15 roller passes for the majority and even 15 to 20 roller passes for some sections. It is also clear that compaction was less towards the end of the lane. The areas that were compacted significantly less will have less density and also be expected to show visual distress more often. The CCM for the second lane on the second night is much better than the first lane. Here no sections were only roller between 0 and 5 times. Large sections were rolled between 5 and 10 times, 10 and 15 times, and 15 and 20 times. It is however noticeable that the average number of roller passes drops towards the end of the lane.

4.2.3. VISUAL INSPECTION DATA

Gathering data on the quality of the road was difficult. It was not possible to personally go to the road and perform an inspection because the A35 is a heavily used highway. Because of this visual inspection images collected in 2014 and 2017 by Rijkswaterstaat would need to be used. The difficulties in attaining this data is further explained in the discussion (section 5).

After access to images of the road surface was finally attained a visual inspection was performed. Using a system similar to google maps a full view of the road could be seen. In this visual inspection each noticeable piece of distress noted. The location (width and length), the severity, the type, and the size were all recorded by hand and then redrawn in a GIS file. A full table of the distress found can be seen in Figure 34 and Figure 35 in Appendix section 8.2.1.. The location of the distress was collected using the hectometer signs which are next to the road. The Severity of the distresses found was judged using the standards created by CROW (Kennisplatform CROW, 2011). The specific specifications for each severity are listed in Appendix 8.1.3.

4.2.4. ANALYSIS

The temperature profiling and compaction data gathered during paving was compared to the road quality data gathered in 2014 and 2017. Further explanation about the individual types of data can be found in sections 3.2.1, 3.2.2, and 3.3 respectively. The full comparison and analysis can be found in Appendix 8.2.1. In this section the focus will be placed on the interesting points which show the most correspondence between data. The analysis was performed using information gathered during the literature review and expert interviews. The way in which it was determined whether there was a connection between the data or not is based on the literature. The exact specifications are explained in the detailed analysis in the appendix.

Over 40 areas of distress were located using the images from both 2014 and 2017. The majority of these areas showed some form of light or medium raveling, however, there was also some patching and cracking. As discussed in section 3.3, raveling and cracking are relevant to this research, but patching can also be interesting since patching occurs to fix previous damage. The patching encountered on the A35 was for a different purpose and therefore not used in the analysis. Because of this, none of the patching locations were used in the analysis because they were not relevant.

In the first lane (the left most lane) there were many spots where light raveling was clear. However, compared to the temperature contour maps of the road, most were situated in locations where that would not be expected. Such locations are locations where the temperature is at a good temperature and where the temperature does not change rapidly. There are, however, some areas of interest. These will be discussed. In the images shown the direction of paving was from left to right. The blue points signify every 10 meters based on the distance measurements of the highway. The temperature compaction maps use colors to show temperature and roller passes respectively. For the temperature maps red colors are high temperatures and blue colors are low temperatures. For the compaction map the blue/purple color is very low roller passes and the white/beige color signifies many roller passes.

One area of interest can be seen in Figure 8. This is an area where the temperature rose from 135-145ºC to 160-170ºC in less than 10 meters between 60840 and 60850 meters which would be cause to suspect some segregation within the asphalt mat. The green areas show raveling from 2017 and the brown is raveling from 2014. The raveling areas inside the red area would not be expected. This is because, although the temperature is higher than normal, the area is homogeneous. The two green areas outside of the red are more likely to actually cause lower quality asphalt, but both situations do not correspond exactly with the locations where the temperature rapidly changes. The first (white text 3) is on the seam between lanes. The raveling might be a result of that and not the temperature. Additionally, the temperature change is the whole width of the lane, but the damage isn't which suggests that the temperature change during construction may not be the cause of the raveling. The second area (the white text 5) is in an area where the temperature drops, but the change is not significant enough to clearly expect segregation within the mat. Because of this, both are not very good evidence.

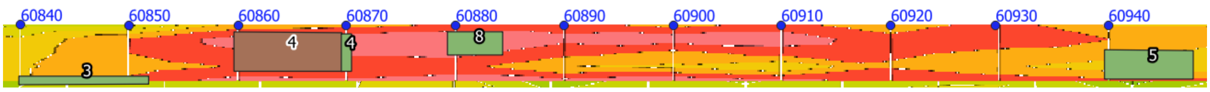

Figure 8: Temperature increase left lane A35

Figure 9 shows another area of interest. Here the temperature quickly drops from 150-160 ºC to 100 ºC and back to 150-160 ºC in 20 meters (between 61090 and 61110 meters). This significant temperature drop gives reason to expect that segregation in the asphalt mat happened. This would cause the asphalt to become damaged more quickly in the future. The two most interesting points in this image are 8 and 11. Point 8 is light raveling from 2014 and point 11 is medium raveling from 2017. Both of these areas correspond with what would be expected from such a quick temperature drop. Block 7 is not relevant distress, since it is clear that the patching there is for another purpose.

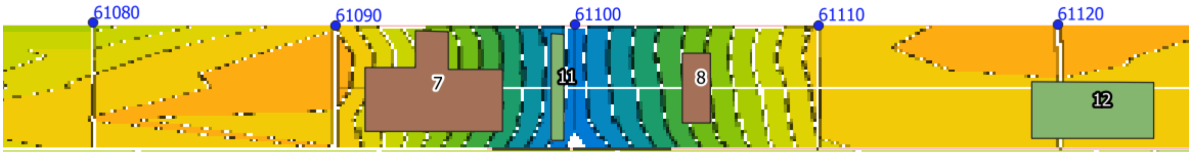

Figure 9: Significant temperature drop left lane A35

The previous images analyzed used the temperature homogeneity data. This is because this had more irregularities. The compaction maps did not show very many areas of interest; except for this area (Figure 10). Here there are significant parts of the road which only experienced 0 to 5 roller passes (blue areas). The green area with the number 12 on it is medium raveling from 2017. This area is corresponds with the area where a part of the lane width was not rolled significantly.

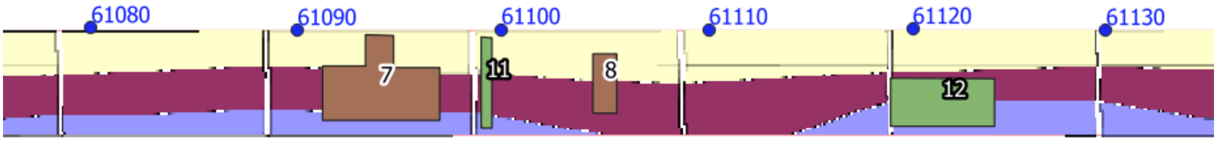

Figure 10: Low roller passes in areas of left lane A35

4.2.5. CONCLUSIONS A35

The method as explained in section 2.2 was performed fully for the A35. Firstly, the temperature data, compaction data and information on the other factors at paly was collected and analyzed. Then distress data was visually collected and analyzed. The distress data and the data from paving was compared by overlaying it in GIS and using information gained during the literature review. The following conclusions are what resulted from this process.

The analysis of the data acquired from the A35 shows some areas of asphalt distress which might have resulted because of operational problems during the paving of the A35. The 460-meter-long road with three lanes has resulted in a large number of distress areas. In the section above (4.2.4) the interesting locations were analyzed and in the Appendix (8.2.1) all of the areas were analyzed. The main question is if there is any noticeable pattern from which some relationships may be derived.

There were no clear relationships which arose in the visual analysis. This analysis, based on the literature collected in chapter 3, showed no clear increase of distress in locations where there was either bad temperature homogeneity, low roller passes, or both. Figure 36 shows a full overview of the section analyzed. In this image the distress areas are overlaid with both the temperature data and the roller passes data. As can be seen, the distress is relatively spread out over the entire area. The extensive analysis which looked at connections between individual pieces of distress and the data found no such connections. Because of the lack of evidence, it is not possible to establish cause and effect between paving practices and distress.

4.3. Aziëhavenweg

The Aziëhavenweg is a road located in an industrial area of Amsterdam. The location relative to the city center of Amsterdam can been seen in Figure 11.

Figure 11: Aziëhavenweg Location (Google, 2019)

The Aziëhavenweg is roughly one kilometer long. On this road, two asphalt mills (one belonging to BAM), two trash management plants, and one additional, small business are located. The exact outline of the Aziëhavenweg and the businesses located on the road can be seen in Figure 12.

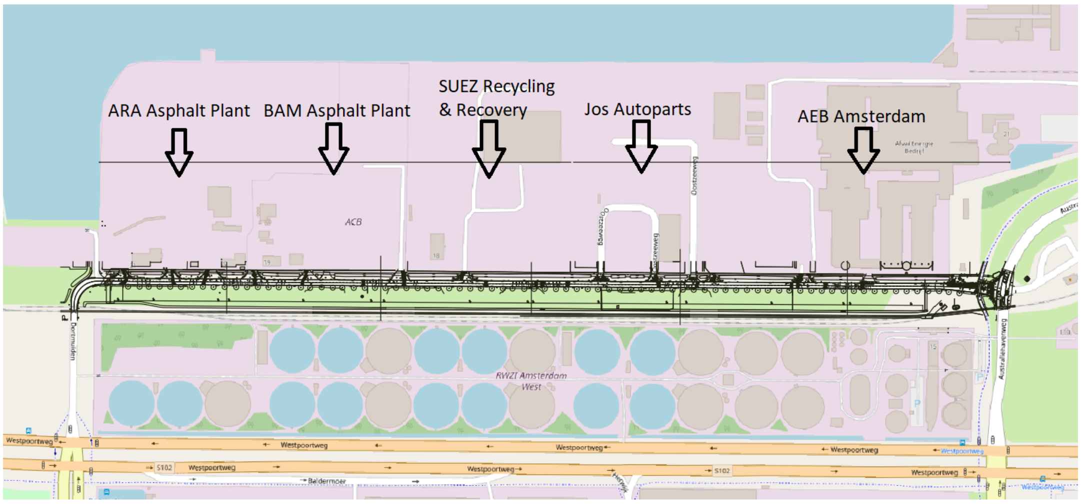

Figure 12: Aziëhavenweg Outline

Paving took place on July 5th, 2008 (Miller & Dorée, Temperature profiling and monitoring of equipment movements during construction (Aziehavenweg), 2008). A 830 meter long section of the Aziëhavenweg was paved during this project. It was the second project BAM performed in cooperation with ASPARi. Similar to the A35 project, processing conditions, such as temperature homogeneity directly after paving, roller passes, and weather conditions were recorded. However, thanks in part to the first project, the methods for monitoring the paving process were improved.

4.3.1. BACKGROUND PROJECT

The scope of this project was rehabilitation which included the removal of the existing surface layer and repaving the 7-meter-wide road with two layers of asphalt (70mm thick STAB layer and 30mm thick SMA layer) (Miller & Dorée, Temperature profiling and monitoring of equipment movements during construction (Aziehavenweg), 2008). Many specific aspects of this process (Temperature homogeneity, compaction, etc.) were monitored. The paving process was monitored by ASPARi in an attempt to improve asphalt processing capabilities and quality.

As mentioned before, two of the buildings on the Aziëhavenweg are asphalt mills. One of these two produced the asphalt used to pave this road. This is a special case in which the asphalt has practically zero travel time to the construction site. This means that there was very little chance for the asphalt to cool down before it was paved. As discussed earlier, the cooling during traveling can be a reason for temperature inhomogeneity, and thus segregation, within the mixture. The exact difference that the extremely low travel time makes is difficult to measure/quantify, but it should be considered.

4.3.2. HISTORICAL DATA

As stated, the Aziëhavenweg is constructed out of a 70mm thick layer of STAB and 30mm thick layer of SMA.

The weather conditions at the time of paving can have an influence on the quality of the finished product (see section on asphalt cooling in section 3.2.1). The weather conditions were recorded using two similar weather stations; one belonging to BAM and the other belonging to the University of Twente. The BAM weather station was mounted at the BAM asphalt plant (which is bordering on the road) and the UT weather station was positioned at the southern verge of the road (Miller & Dorée, Temperature profiling and monitoring of equipment movements during construction (Aziehavenweg), 2008). Both of the weather stations should have gotten accurate readings for the area. The actual weather data can be found in Appendix 8.2.2.

Temperature Profiling

This was the second project that ASPARi monitored with BAM. The first project was the A35 project. From that project they were able to learn and improve. Therefore, this project employed two methods the measure the temperature of the asphalt. One of the two methods employed is the same as the method used during the A35 project. This method used two ThermaCAM^{TM} E320s to take thermal pictures every 10 meters (Miller, ter Huerene, & Dorée, Temperature profiling and monitoring of equipment movements during construction (A35: Test Section 3), 2007). The thermal images are taken by hand from the side of the road 1 to 2 meters directly behind the screed (Oosterveld, 2019). This resulted in temperature data which shows the temperature of the asphalt directly after paving. In this report this method will be referred to as method one. The second method employed (method two) was slightly different. This method consisted of using an FLIR A32 camera to take images on 5 second intervals (Miller & Dorée, Temperature profiling and monitoring of equipment movements during construction (Aziehavenweg), 2008). This camera was mounted on the paver itself and pointed down at the ground behind the paver. Due to the angle needed to take good thermal images, the pictures taken are of asphalt 17 meters behind the paver (Miller, ter Huerene, & Dorée, Temperature profiling and monitoring of equipment movements during construction (A35: Test Section 3), 2007). In both cases the images taken were used to create temperature contour maps. The maps created with the first method use both distance and time on the y-axis. The second method uses only time on the y-axis, since the pictures were taken strictly with time as an indicator. A more extensive analysis of these methods can be found in Appendix section 8.2.2.

Temperature profiling was performed in the same way for both the STAB and SMA layers. For the purpose of this study only the SMA layer will be analyzed since the damage it will be compared to is strictly visible surface distress. Both the temperature contour maps for the SMA layer will be analyzed.

In Appendix 8.2.2 the full analysis of the temperature contour maps can be found. During this analysis interesting areas of the asphalt mat are pointed out. As was stated in section 3.2.1, the temperature does make a difference in the quality of the asphalt mat. Particularly, areas where the asphalt temperature changes rapidly (bad temperature homogeneity) can cause segregation which will have a negative effect on the asphalt. Both of the temperature maps created by the two different methods will be analyzed.

Firstly, the temperature contour map created by the first method is Figure 38 in section 8.2.2. On this map clear cold spots can be seen at 280, 340, 570, 670, and 790 meters. Some or all of these spots could be resulting from paver stops. In these areas the temperature drops form 150-170 ^{o}C (which is the average temperature for the rest of the mat) to 120-100 ^{o}C. Such a temperature drop means that segregation within the asphalt mat likely occurred. Therefore, these areas are potential weak spots. Theoretically, it would be expected that surface distress would first arise in these areas.

The temperature contour created by the second method is Figure 40, Figure 41, Figure 42, and Figure 43 in section 8.2.2. This temperature contour map shows very many, small, cold (purple and blue) spots. These spots can be removed since they are the back of the paver which was captured by the camera by accident at some points. Furthermore, similar to the other map, there are multiple colder areas in the asphalt mat. These cold areas are at 13:18, 13:45, 14:07, 14:19, and 14:37. These spots all coincide with paver stops. In these spots the temperature drops from 130-150 ^{o}C to below 110 ^{o}C. This means that there is a high likelihood of segregation having occurred within the asphalt mat.

As can be seen, the two different methods did deliver slightly different results. One noticeable difference is that some temperature changes cannot be seen on both maps. The largest difference is the temperature difference. The map created by the second method shows much lower temperatures than the first map. For a more extensive analysis and comparison view the appendix (8.2.2).

Compaction profiling

Following the paving operations, immediate compaction was performed. Again, only the compaction for the top layer will be analyzed. The compaction team consisted of two steel-wheeled tandem rollers and two steel-wheeled three-drum rollers (Miller & Dorée, Temperature profiling and monitoring of equipment movements during construction (Aziehavenweg), 2008). Sadly, the roller movements for one of the deadweight rollers was not collected. However, observation at the time of paving showed that the roller not recorded mirrored the behavior captured during the compaction of the bottom layer.

In appendix section 8.2.2 an extensive analysis on the compaction coverage of the Aziëhavenweg along with the paving patterns of each individual roller can be found. The compaction contour plot showing the total number of roller passes for the entire road is Figure 47 in 8.2.2. As stated, the coverage of one of the deadweight rollers was not collected, but it is stated that this roller did similar work to the other deadweight roller (Miller & Dorée, Temperature profiling and monitoring of equipment movements during construction (Aziehavenweg), 2008). Therefore, it will be assumed that the roller coverage is similar to that of the other roller that did the top half.

When you look at this map the first thing that is very clear is that the end of the road was compacted significantly less than the beginning. The red areas at the center of the lanes were rolled between 20 and 30 times. Outside of those areas the majority was rolled between 10 and 20 times (green/yellow). After the first 500 meters the coverage lessens quite a lot. Here the green areas lessen and more blue areas emerge. The blue areas signify below 10 roller passes. At the very end there are even areas which have been rolled 2 to 3 times. In theory, the compaction in these locations will be much less which will result in lower quality asphalt. It is reasonable to expect visual distress to occur first in these areas.

4.3.3. VISUAL INSPECTION DATA

On April 24th of 2019 a visual inspection of the Aziëhavenweg was performed. In the appendix (Section 8.2.2) a full list of the distresses found during the visual inspection can be found (Figure 49). This visual inspection was not performed with the modern, digital techniques. Instead it was performed using slightly older, yet still accurate techniques. To perform the inspection the following tool were used: Stonex GPS, map of the road, measuring wheel, and a high-quality camera. The entire length of the road was surveyed. Every visible form of distress was noted on the approximate location on the map. Using the Stonex, the GPS location of each distress location was recorded with 10 cm accuracy. The drawn distress on the map was linked to the points captured. Additionally, high quality images were made of each distress location.

Using this data, the distress was translated into a GIS file. As a result a layer of damage was made. Each polygon corresponds with an distress area. Additionally, specific characteristics of the damage is listed as well, such as the damage type, severity, location on the road, and coordinates. The severity of the distress areas is based on the specifications stated by CROW which are explained in Appendix section 8.1.3 (Kennisplatform CROW, 2011). The following images show the locations of damage (Figure 13, Figure 14, and Figure 15). The direction of paving was from right to left in these images. The visual inspection was, therefore, also done in this way. Each of the green points is was a location captured by GPS.

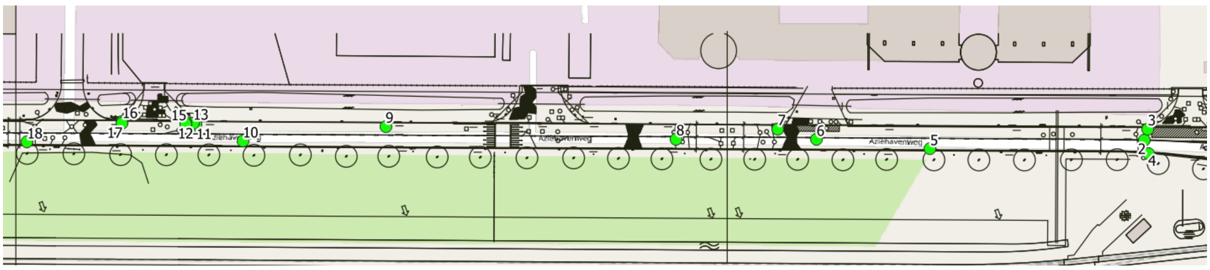

Figure 13: Damage Locations 1

In this image (Figure 13) the first third of the road can be seen. The first three points (2, 3 and 4) are the beginning point of the road. This is not necessarily damage, but a joint can be a weak point it not created properly. Points 5, 6, 7, 9, 10 and 12 are all small transverse cracks, whereas point 13 is a longitudinal crack. Points 8 and 18 are small patches of light raveling. Finally, points 14, 15, 16, and 17 are the corners of a large patch in front of the bellmouth. This shows that there must have been significant damage there. This is likely due to the fact that the joint there between the road and the driveway wore out too quickly.

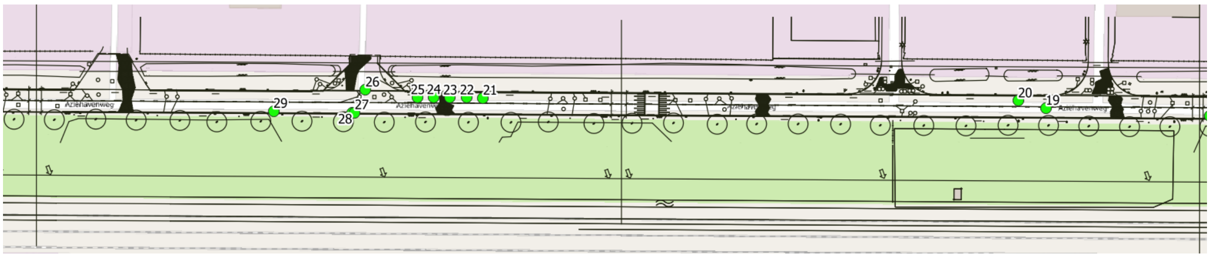

Figure 14: Damage Locations 2

Figure 14 shows the second third of the road. Points 19 and 26 are the locations of some light raveling. Points 20, 21, 22, 23, 24, and 25 are drill cores but do not display signs of damage. Finally, points 27 and 28 show the beginning and end of a longitudinal crack and point 29 is the location of a small transverse crack.

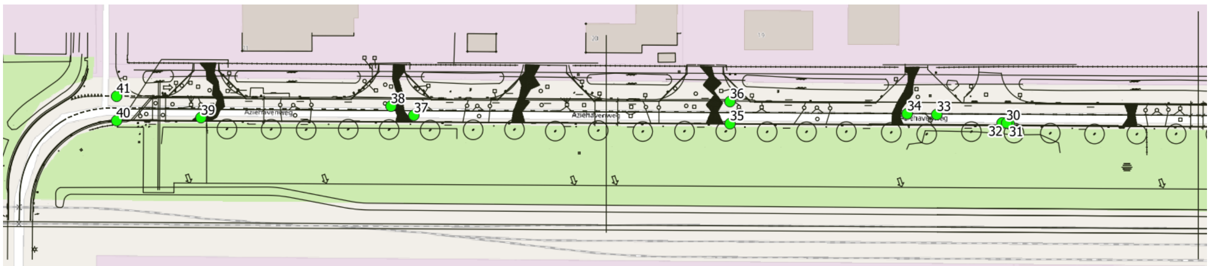

Figure 15: Damage Locations 3

This last image (Figure 15) shows the last third of the road. Points 40 and 41 show the end of the road and the joint that is located there. Points 30, 31, and 32 show the midpoint and the beginning and end points respectively of a rather large longitudinal crack. Points 33 and 34 also show the beginning and end points of a longitudinal crack whereas points 35 and 36 show the endpoints of a large transverse crack and 39 also shows a transverse crack. Finally, points 37 and 38 show the beginning of two large raveling sections of medium to high raveling in both of the lanes which seem to have resulted directly from paving mistakes.

4.3.4. ANALYSIS

The temperature and compaction contour maps, which were discussed in section 4.3.2, will be over-laid with the visual inspection data discussed in section 4.3.3. The distress found on the road consisted of cracking, raveling, and patching. In the appendix 8.2.2 the full analysis of every point is done. Here the most important areas will be highlighted and discussed. The following images which are shown are overlays of the data. The blue points signify every 20 meters of the road length. Color are used to signify the temperature and roller passes. Blue color signifies either low temperature or roller passes, and red color signifies high temperatures and roller passes. For this project paving happened from right to left.

The most common form of distress on this road was cracking. Some non-load associated cracking, known as fatigue cracking, has been found. Most of the cracks are likely non-load associated cracks. These cracks often happen because of quick cooling of asphalt that has a high stiffness at low temperatures. The weather (see 8.2.2) was quite warm at 21°C, and the wind speed was only 8km/h. This type of weather would not be expected to lead to very rapid cooling. Additionally, SMA can be made to be less stiff at low temperatures, but it is not sure if this is the case in this project. It is therefore possible that some or all of the cracks are because of this.

In Figure 16 the end of the compaction contour map can be seen. It can be seen that the end of the stretch of road that was paved was compacted considerably less. It would be logical, and supported by theory, to expect distress at this point. As can be seen, this is not really the case. The only distress seen at the end of this section is one large longitudinal crack at around 720 meters. In section 3.3 it is discussed that cracking can be caused by high void concentration (thus low compaction). The blue area pictured here (from 680 to 730 meters) has only seen between 2 and 5 roller passes. The crack observed here is quite big and exactly where it would be expected to be.

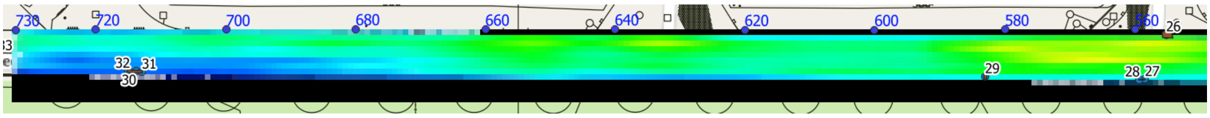

Figure 16: Compaction Contour Map End with Distress

Another interesting area is pictured in Figure 17. Here a section of the temperature contour map created with method 1 that is significantly colder than the surrounding area can be seen at the 560-meter mark. The rapid temperature drop has a high likelihood to lead to segregation, and thus weaker asphalt. Therefore, visible distress would be expected here. Points 21 through 25 are drill cores and thus not relevant. Points 27, 28 and 29 show the location of two cracks, which are located exactly in spots where there was a significant temperature drop. This suggests that there may be a connection between the data. Lastly, point 26 signifies a patch of light raveling at the beginning of the bellmouth. Although it seems to correspond with the cold area, it is difficult to connect the two. This is because there is no data on the paving of the bellmouth. The fact that this data point is not located on the road in question makes it difficult to use.

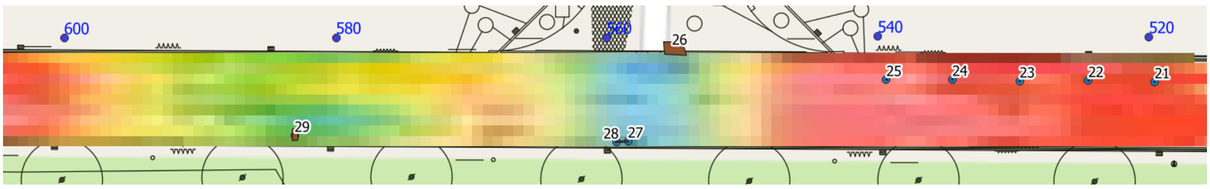

Figure 17: Temperature Contour Map (Method 1) Cold Spot with Distress

Finally, Figure 18 shows a colder area between 220 and 280 meters on the temperature contour map made with method 2. This colder area corresponds with a large patch (shown by points 14, 15, 16, and 17). This patching likely was needed to fix low quality asphalt in that location. The asphalt could have been low quality in part due to the bad temperature homogeneity. This section does correspond with the data. However, since this is also near the entrance of a bellmouth, there are also other factors at play in this area which could have resulted in this damage as well. For example, the patch is near a seam located between the main road and the bellmouth and that that area is an area where vehicles accelerate while turning. Right next to that patch two transverse and one longitudinal cracks which are connected can be seen (points 11, 12 and 13). The same uncertainties which applied to the patch apply here as well.

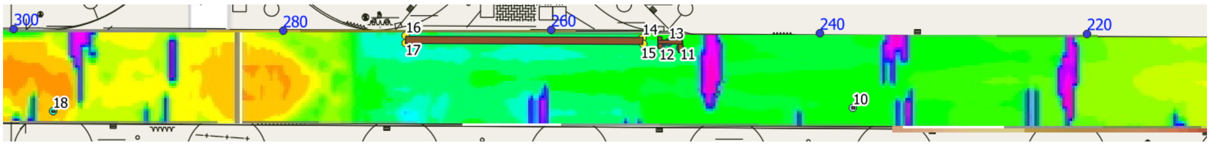

Figure 18: Temperature Contour Map (Method 2) Cold Spot with Distress

4.3.5. CONCLUSIONS AZIËHAVENWEG

During the analysis of the Aziëhavenweg data from the past was compared to newly collected data. The data from the past included temperature and compaction contour maps. These maps did show multiple points at which the paving operations did not go perfectly. These locations would be locations that distress can be expected in the future. The newly collected data was a visual inspection of the distress on the Aziëhavenweg in May of 2019. During this inspection some distress was found on the road. The distress was largely in the form of transverse and longitudinal cracking. Furthermore, there was some light raveling and patching. In the scope of this study, the raveling and patching and cracking were all analyzed. Considering that the road was paved in 2008, the amount of distress encountered was quite low. The large majority of the road was still in very good shape and could still be used for many years to come. This shows that the problems during paving that were visible in the data did not end up making a very large difference in the quality of the roadway.

As can be seen in the section above (and in more detail in Appendix 8.2.2) the distress was compared to the temperature and compaction contour maps. When comparing the compaction coverage to the distress there was very little connection between de data. The data shown here suggests that there is very little to no connection between compaction and surface distress. There is such little data that it is impossible to draw legitimate conclusions. There is much more research needed to understand this fully.

The comparison of the temperature contour maps and the distress showed slightly more of a connection. There are some areas in which distress corresponds very well with areas of bad temperature homogeneity. However, there were multiple other areas of distress which did not correspond. This gives reason to believe that the areas which did correspond were a coincidence. Additionally, most distress areas were very small compared to the entire road. The small sample size makes it almost impossible to draw any legitimate conclusions. Once again, significantly more research with a much larger sample size would be needed to understand this phenomenon better.

For both the comparisons with the temperature and compaction data it was not possible to establish any concrete connections between the data. Due to the lack of connections between the data, it is not possible to establish cause and effect between paving practices and distress.

4.4. Rutting Compared to Compaction study for Aziëhavenweg

In addition to the main analysis done for the Aziëhavenweg, the rutting and the causes will be analyzed. Firstly, the previous steps taken in this analysis will be analyzed. After that, the new data will be added to the previous work to create a full picture of the phenomena at play.

Rutting is when the asphalt surface depresses inward in the wheel path (Miller & Bellinger, 2014). This type of distress can be the result of any on the asphalt layers giving in under the weight of the vehicles which travel the road. When a layer succumbs to rutting, then all layers over it will also ben inwards to accommodate for the space made. When a vehicle drives over a road surface, the tires exert mostly a downward force on the asphalt. This force is then distributed throughout the various layers that make up the asphalt. For the top layer, the force is the highest and for the foundation and the ground underneath the whole road construction the force is significantly less. The vertical force also creates a horizontal source which is pointed outward. This force starts low at the top layer, then becomes higher until at the second o third layer when the force magnitude starts to drop of again. Both a high vertical and a high horizontal force have an increased likelihood of causing rutting. In the second layer the vertical force is still rather high, and the horizontal force is near the highest. Therefore, the second layer has the highest likelihood of succumbing to rutting.

Because the second layer has the highest chance of causing rutting to occur, the second layer (in this case the STAB layer paved in 2007) will be analyzed the most.

4.4.1. DENSITY MEASUREMENTS OF THE AZIËHAVENWEG

Figure 19 is a graph created using compaction data form during the paving process in the form of roller passes and the density of the asphalt mat created. At the 240-meter mark of the road the exact roller passes amount for 7 points in the width and the exact density of the STAB layer at those 7 points were collected and used to make this graph.

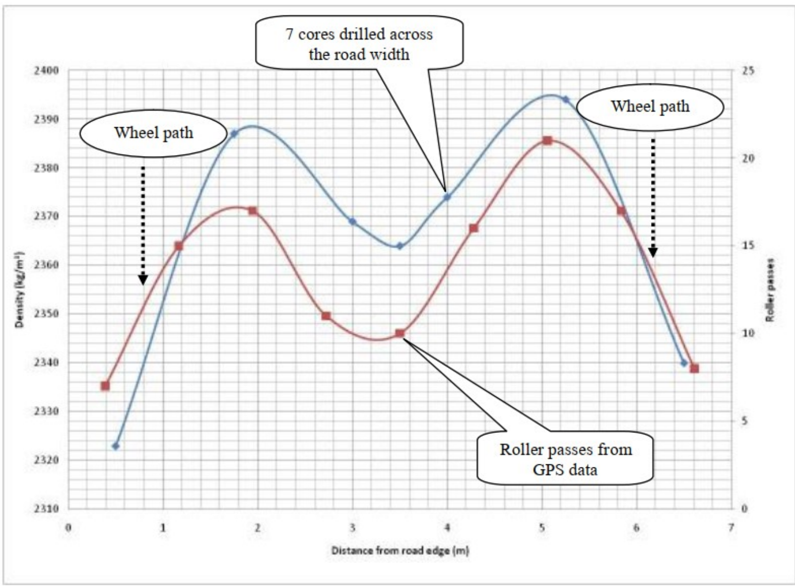

Figure 19: Comparing road density and roller passes for STAB layer position 240m (Miller & Dorée, Temperature profiling and monitoring of equipment movements during construction (Aziehavenweg), 2008)

As can be clearly seen, there is a similarity between the roller passes and the density achieved. In locations where the roller compacted significantly less, like the sides and the middle, the density is also less. It is noticeable that the rollers compact mainly in the center of each lane and neglect to compact the sides of each lane as much as the middle. Based on this evidence, it can be concluded that less compaction does result in less dense asphalt.

4.4.2. ROLLER PASSES AND DENSITY EFFECT ON RUTTING

Over the years that the Aziëhavenweg has been in use it has seen a large amount of stresses. Based on personal observation when visiting the road, it was noticeable that predominantly large freight trucks used the road. These trucks are much larger and heavier than standard cars and therefore deliver a much higher force to the road. It is logical to expect some rutting to have accumulated over the years. In 2019 Erwin van de Jagt collected rutting data from three sample locations at 240, 360, and 740 meters from the paving starting point. This data has been compared to the compaction percentage. The following graphs (Figure 20, Figure 21 and Figure 22) were made by Marco Oosterveld and show the rutting compared to the compaction percentage of both the AC-22-bind/base-Plexxipave 216-schots Graniet (the STAB layer) and the SMA-11B-Flexxipave 216-bestone (the SMA layer). Below the X axis of these graphs the approximate wheel locations on the road are shown. This aids in analyzing what the actual cause of the rutting could be. This was based off of the average width that the wheels of freight trucks are apart.

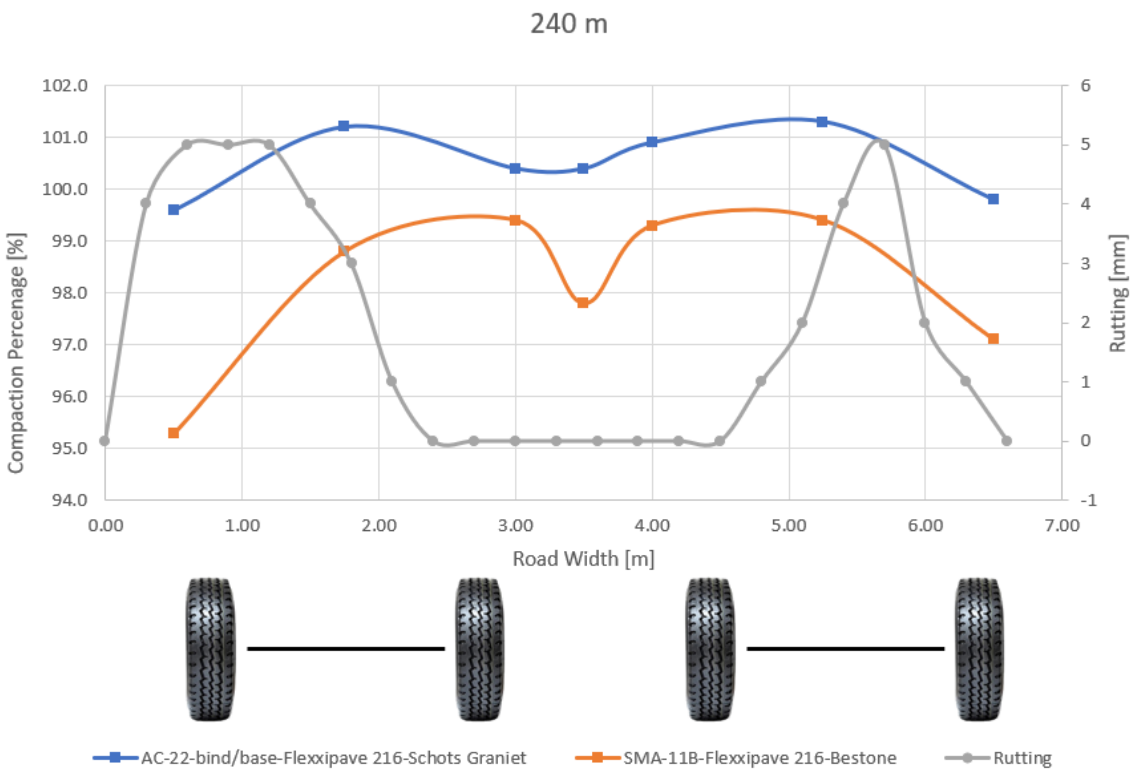

Figure 20: Compaction and Rutting vs. Road Width 240m

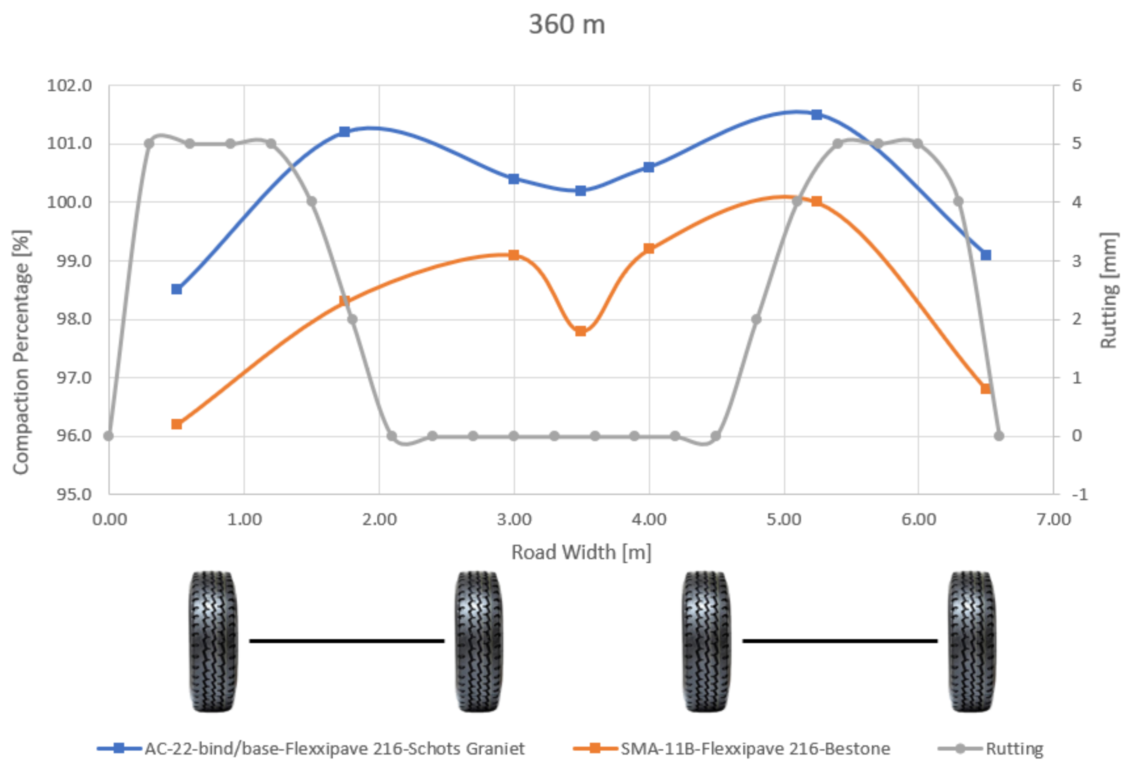

Figure 21: Compaction and Rutting vs. Road Width 360m

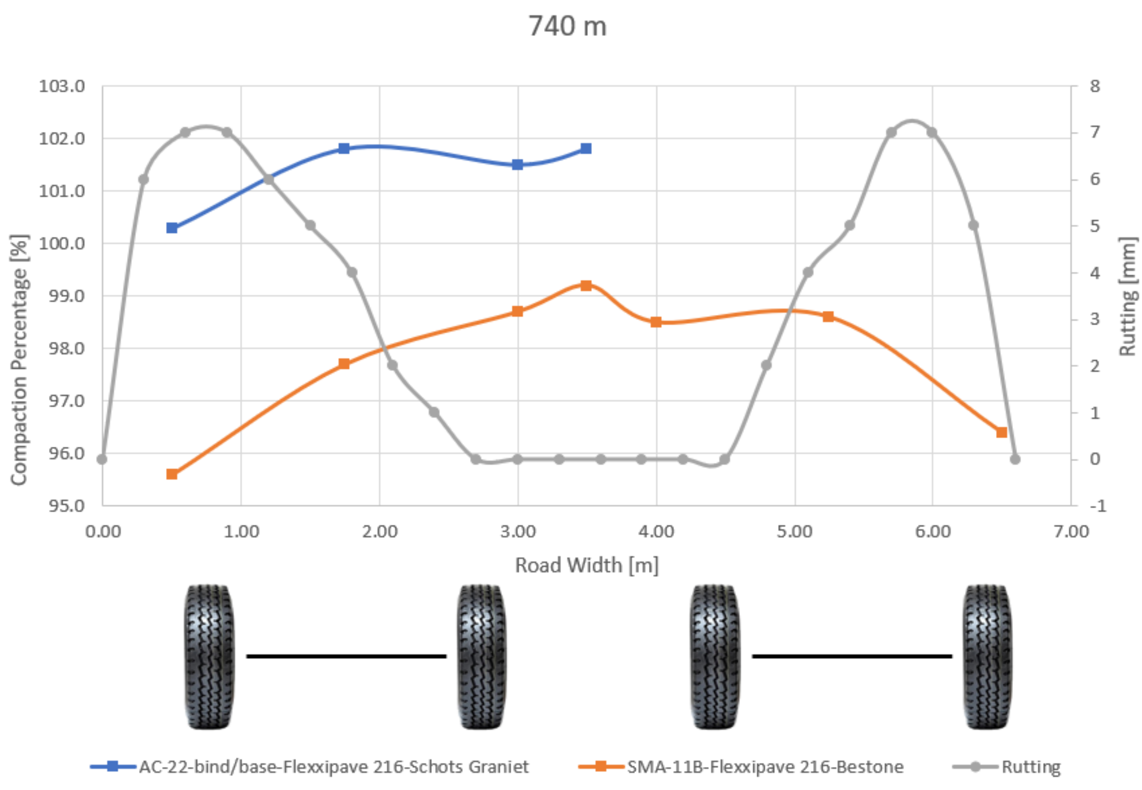

Figure 22: Compaction and Rutting vs. Road Width 740m

It is to be expected that rutting will predominantly arise in the wheel paths since that is where the forces are focused. In all these three graphs it is clear that the left wheel path for both directions has significantly less retting than the right wheel path. Every graph shows that the left wheel path going both directions has

0. Whereas in some locations the raveling is up to 7 mm in the right wheel path. This could be explained by the fact that both of the layers (STAB and SMA) for each of the location were compacted less towards the edges of the road than the middle. The left wheel path is closer to the middle axis of the road which means that the left wheel path was on asphalt which was generally compacted more. The central three meters of the road (from meter 2 to meter 5) is compacted above 98% a large majority of the time for both layers. The only place where this is not the case is in the exact center of the lane where the compaction percentage drops slightly below 98% at 240 and 360 meters. The two meters on both sides of that central 3-meter area coincidentally see a drop in the compaction percentage. In all cases the compaction percentage drops below 98% and in some cases the compaction percentage nearly reaches 95%. For the 240-meter point the average rutting in the outer two meters on each side rises 1411% compared to the central 3 meters. For the 360-meter point the average rutting in the outer two meters rises 1786% compared to the central 3 meters. Finally, at the 740 meter point the rutting in the outer two meters rises 866% compared to the rutting in the middle 3 meters. The evidence shows that sufficiently completing compaction (meaning that the mixture is compacted to 100% across the road width) is important in minimizing rutting. It is not possible to know for sure which layer was the primary reason that rutting happened. It is noticeable that in each location the SMA layer was compacted less. This does not ensure that SMA was the reason for the rutting, but it does indicate that this may be a possibility. It is difficult to say because The SMA and STAB layers react differently under forces. The SMA layer has a stone skeleton which is very resistant to such forces. However, if the stoke skeleton is not well compacted, then there may be space between the stones which means that slight rutting may develop rather quickly one loads are applied to the surface. STAB on the other hand does not have the same stone skeleton as SMA and will react to forces more gradually over time. As explained earlier, The STAB layer is expected to experience the highest forces which can cause rutting. Hence, it is also possible that the rutting seen here comes from the STAB layer instead of the SMA layer.

The evidence here suggests that the best way to reduce rutting in future projects would be to focus more on compacting the entirety of the road. It is especially advisable to focus compaction more near the outside edges of the road since that is exactly where the rutting was observed in this case.

4.5. Comparing the Results form the A35 and Aziëhavenweg

Since two case roads were analyzed in this research it is very valuable to be able to compare the findings. This comparison can shine a light on weakly concluded findings and further support other findings. In an attempt to accurately compare these very different roads the similarities and differences need to first be brought to light. Then the conclusions which can be derived from the comparisons will be discussed.

4.5.1. SIMILARITIES

In this section the similarities observed between the two case roads will be discussed. The similarities during the initial paving of the roads and the similarities found in the damage of the roads will be discussed separately.

Paving

Both of the roads have a similar age. The A35 was paved in 2007 and the Aziëhavenweg was paved in 2008. This means that they are now 12 and 11 years old respectively, which is quite similar.

Distress

When it comes to distress there are no clear similarities.

4.5.2. DIFFERENCES

In this section the differences observed between the two case roads will be discussed. Firstly, the differences in the paving operations is analyzed. Then, the differences in the distress viewed on the roads will be compared.

The first major difference between the roads is the type of road. The A35 is a highway which gets a much higher load of traffic daily. On the other hand, the Aziëhavenweg is a road in an industrial area, which means is gets a much lower volume of vehicles. However, there aver very many freight trucks that use the Aziëhavenweg, therefore the average size and weight of the vehicles is larger than that of the A35.

Paving

The road designs are also very different. The A35 has a double layer of porous asphalt. The Aziëhavenweg has a STAB layer and an SMA top layer. The characteristics of each of porous asphalt and SMA were discussed in section 3.1. The most obvious difference between the two pavement types is the fact that SMA is expected to have a longer lifespan than porous asphalt.

Additionally, there are some noticeable differences during the actual construction. The A35 was paved in three nights whereas the Aziëhavenweg was paved on one day. Additionally, the temperatures during paving were slightly different. During the one day that the Aziëhavenweg was paved the average temperature was 21 ^{o}C and the windspeed was 8 km/h. The first night of the A35 paving was not too different (17.9 ^{o}C and 4.4 km/h on average), but the second night was significantly colder with an average temperature of 13.4 ^{o}C and an average windspeed of 4.9 km/h. However, the windspeed is lower than that for the Aziëhavenweg both nights.

The location of the two roads are also very different. Normally, this would not be relevant, but in this case it is. On the Aziëhavenweg one of BAM's asphalt plants is located. This meant that the asphalt needed minimal transportation time to get to the construction site. The close proximity of the asphalt plant gives reason to believe that the asphalt had much less of a chance to cool down during transportation. The A35, on the other hand, is further away from the closest asphalt plant (Which is located in Deventer).

Finally, there are noticeable differences in the paving data. The roller passes map for the Aziëhavenweg shows that in some sections up to 30 roller passes were used. The roller passes maps for the A35 only show a maximum of 20 roller passes. A third difference between these two numbers is quite large.

Distress

These are many differences in the distress found on these two roads. First of all, the distress found on the Aziëhavenweg consisted of mostly transverse and longitudinal cracks. There was very little Raveling to be found except for a few very small areas. The A35, on the other hand, showed much more raveling. The majority of the distress found was raveling and there was very little cracking. The raveling found on the A35 was also in the form of much larger patches than that found on the Aziëhavenweg.

4.5.3. CONCLUSIONS

With the similarities and differences of this roads clearly laid out it is possible to compare the findings of these two roads accurately.

The fact that more raveling was found on the A35 and more cracking was found on the Aziëhavenweg is logical. The A35 consists of double layered ZOAB (porous asphalt) which has a much higher void content. High void content, as was discussed in section 3.3, correlates with raveling. The cracking found on the Aziëhavenweg was also to be expected. Often cracking occurs because of the roads inability to hold heavy loads. Because of the location of the Aziëhavenweg a large part of the vehicles which use it are freight trucks. Additionally, non-load associated cracking can occur because of rapid cooling of stuff asphalts. SMA can be decently stiff, which might be a reason for this cracking. The types of distresses found on the roads are clearly connected to the types of asphalt. This is also supported by the theory.

Both roads had some areas where the distress data correspond with the negative aspects of the paving data, however the frequency with which distress corresponds with paving data is not enough derive a clear relationship from it. In areas where the paving data shows positive signs, there is still damage to be found. This means that there is not enough evidence to make any relevant conclusions. More research is needed.

5. DISCUSSION

During the execution of this assignment some problems arose. That is to be expected, since very few projects are completed exactly as expected. Some of these problems may have had an effect on the conclusions reached. Therefore, they will be discussed in this section.

5.1. Past

During the initial paving of both the A35 and the Aziëhavenweg some issue arose. These issues may have had an effect on the quality of the data I had to work with.

- During the measuring of temperature homogeneity during the paving of the A35 test section 3 there were some unforeseen circumstances which caused a reduction in the number of pictures to be taken. Instead of the planned 600 thermal images, slightly more than 400 were taken. Although temperature contour maps were still created, the accuracy might be less due to the reduced thermal images to work with. This is not an issue regarding this research, but it should be mentioned.
- During the paving of the A35 the temperature homogeneity and the roller passes were not measured in some sections. The lack of temperature contour maps in some sections may be the result of the fewer pictures taken. For the second part of the third lane there is no data because it was chosen to not gather data for that section. The lack of data reduces the surface area that can be used for analysis.
- One of the deadweight rollers used for the compaction of the SMA layer on the Aziëhavenweg was not monitored. This causes the roller passes data to be incomplete. This makes it more difficult to accurately analyze this road. Some assumptions (mentioned in sections **Error! Reference source not found.** and 8.2.2) can be made, but they less accurate than the actual data.
- There were some issues gathering the weather data from during the construction of the A35. The new data is slightly less accurate. This did not really have an effect on this research, but it is important to mention.

In general, the road paving monitoring projects discussed here were the first two of its kind. BAM and ASPARi were still in the process of figuring out how to accurately monitor projects of this scale. It is natural that some issues arose. It is important to state that regardless of some slight issues, the data was well collected and recorded. Without this data this research would not be possible.

5.2. Present

During the execution of the research assignment some problems were experienced. These problems were dealt with but may still had an effect on the results.

- Some technical difficulties using GIS were experienced. Since I did not have very much experience with QGis, I had difficulty performing actions that to someone who is very knowledgeable about QGis might seem simple. Therefore, it took some time to first learnt he software and I also required significantly more time to complete the actions.
- When this project was initiated, both my supervisors and I believed that all of the data that was required to complete the empirical study was available. It turned out that that was not the case.

For the A35, it was not possible to perform my own visual inspection, so the initial plan was to get data from BAM. It turned out that BAM did not have any recent distress data from said project. After this dead end an attempt was made to get the data from Rijkswaterstaat. After some time, I was able to get access to visual inspection footage from 2014 and 2017. I hoped to be able to get this data and give it to a professional to perform an inspection. Sadly, but understandably, I was not allowed to take the footage with me. Therefore, I needed to perform a visual inspection myself. The visual inspection I had to perform had some accuracy issues. Firstly, I am not trained to perform visual inspections so there is a high likelihood that some mistakes have been made. Additionally, there was no way to measure the location of the distress very accurately. Because of that I had to use the hectometer signs which means that I cannot guarantee accuracy to roughly 5 to 10 meters.

- When performing the visual inspection on the A35 something stood out to me. The second lane from the center was replaced in 2014, shortly after the footage I reviewed was taken. However, I did not see very much data in the lane. This could be because of my inexperience as an inspector. Additionally, since it was replaced before 2017, the footage from 2017 could not be used for distress in that lane.
- The distress data for the Aziëhavenweg was collected in a visual inspection performed by myself and one of my supervisors, Marco Oosterveld. Although we attempted to be as accurate and thorough as possible, it is reasonable to expect that the accuracy is less than could be expected from a professional road inspector. However, I still believe that the data is reasonably accurate and is good within the confines of the research.

The issues mentioned above may have had an impact on the quality of this research and therefore need to have been mentioned.

6. FINAL FINDINGS AND RECCOMENDATIONS

Firstly, a look at the research questions will be taken to ensure that all parts have been answered. After that, the final findings of this research considering the literature study, the expert interviews, and the empirical study. Then finally, recommendations based on the findings of this research will be given.

6.1. Research Questions Answered

The main Research question of this paper was: **what relation is there between asphalt processing, particularly compaction and temperature homogeneity during paving, and the asphalt's ultimate lifespan?** This paper sought to answer this question answering the following questions:

- **How can asphalt damage be quantified?** There are different types of visual distress/damage which can occur on an asphalt road. The two most relevant distress types are raveling and cracking. Raveling happened when the top layer of aggregate becomes worn away. This can lead to increasingly bad road conditions and even other types of distress such as potholes. Cracking can come in multiple forms, such as longitudinal, transverse and fatigue cracking. The severity of these distress types can be quantified using the specifications stated by CROW (Kennisplatform CROW, 2011).
- **What does asphalt damage say about its lifespan?** This question was not possible to entirely answer. As stated in section 3.3, the lifespan of a road is largely determined by the contact between the owner and the maintainer of the road. In that contract it details how severe the distress needs to be before replacement is warranted or required.
- **What effect do process discontinuities have on temperature and compaction homogeneity?** Process discontinuities can cause the homogeneity of the temperature and compaction to worsen. If the paver stops then the result is often an area of significantly colder asphalt which lowers the temperature homogeneity of the asphalt mat. This was seen in both of the case roads. If the rollers do less roller passes in some areas, then the compaction is less in those areas. For the Aziëhavenweg, this could be seen in the rutting analysis. The rollers rolled significantly more in the center of the lanes and thus those sections were compacted more and became denser.
- **What effect do temperature and compaction homogeneity have on asphalt distress?** Temperature homogeneity, in theory, increases the lifespan of asphalt. Segregation, which is when there are temperature differentials in the asphalt mat cause the asphalt mat to become damaged more quickly, is reduced with increased temperature homogeneity. Compaction homogeneity is also better for the asphalt mat. Even compaction ensures that all areas of the asphalt mat have the optimal void content which has been shown to increase the lifespan of a road.
- **What is the link between certain specific types of asphalt damage and events during paving?** No link between events during paving and distress could be found. This is because the two case roads did not have enough evidence to show any type connection. Even if this was shown; this empirical study is not of a large enough scale to know for certain.
- **Do the different circumstances in the two cases (A35 and Aziëhavenweg) deliver similar results?** It is not possible to answer this question because of the findings of the two cases. Since both cases came up largely inconclusive, there is no real way to compare them.

The first 4 questions could be answered using the literature study and expert interviews. To answer the last two questions, the empirical study needed to find relationships in the data. Since de empirical study did not, it is impossible to accurately answer the papers main research question.

6.2. Findings

In the empirical study of the A35 the temperature contour maps (TCMs) and compaction contour maps (CCMs) showed interesting things. The TCMs showed multiple areas where process discontinuities resulted in hotter or colder areas. According to the theory these areas should be expected to have increase distress. The CCMs showed to a lesser degree some problem areas. On average fewer problem areas could be found, but there were still some areas where there were only between 0 and 5 roller passes recorded. These areas would also giver reason to believe that there could be more distress there. The visual inspection found multiple areas of distress. Comparing the distress showed that distress and negative paving data did correspond in some areas. However, the connection was not strong enough to signify any relationships between paving data and distress. This was in part because there was also a lot of distress found that did not correspond with the areas of bad temperature and compaction homogeneity. Thus, this case turned up inconclusive.

The empirical study of the Aziëhavenweg showed similar results. The two TCMs created using two different methods did show some paver stops which caused low temperature areas. These areas had large enough and rapid enough temperature changes to have a high likelihood of causing segregation and thus causing in increase of distress in the asphalt. The CCM also showed inhomogeneity. This map showed very clearly that the end of the road was neglected significantly compared to the beginning of paving. This would also be areas that increased distress could be expected in the future. The visual inspection, which was done by actually traveling to the road, showed very little distress. Comparing this distress to the paving data showed very little. There were only two areas of distress which corresponded with negative temperature data. Furthermore, no distress corresponded with the compaction data. Since a lot of the data did not show anything of interest, there is no way to be sure that the areas which do correspond are not a coincidence. Therefore, there were also no conclusive relationships found.

Logically, since both of the cases turned up inconclusive, comparing the two did not show anything new or interesting. The comparison also did not

6.3. Recommendations

Based on the findings of this research there are few very solid recommendations to be made.

Firstly, it is highly recommendable to look into this topic on a much larger scale. Theoretically, the connections and relationships which this paper searched for exist, but at this scale they were not noticeable. If it was possible to get historical temperature and compaction data from a very large number of roads and then also perform visual inspections for those roads, then a statistically justifiable study can be performed. The findings of that study will be more effective at building a strong argument to whether changes in the paving methods need to be made or not.

Since the first project that ASPARi and BAM have worked together on in 2007 (A35) there have been many other projects that have been monitored. Monitoring has only gotten better over the years. In the future it will be possible to use the other project to perform the aforementioned much larger study on this topic. For this to work data will need to have been organized and kept very well. Most of the data needed for this research was available to me, except for some distress data. In a larger study there will likely be the resources to get better distress data than in this project.

The paving data from both projects analyzed in this paper showed some process discontinuities which are not optimal. The temperature contour maps showed that paver stops cause colder areas in the asphalt mat which have a high likelihood to cause segregation. Minimizing these areas is very important in improving asphalt quality. Although the empirical study did not find a direct connection between this and distress, the theory points towards this relationship being true. Additionally, this research also did not disprove this connection.

It is also advisable to focus more on improving compaction homogeneity. The A35 compaction data showed a slight lessening of roller passes towards the end of some sections. However, the Aziëhavenweg compaction data showed very clearly that the roller passes were significantly lower at the end of the road. This is also supported by Erwin van de Jagt and Johan Antonissen in their expert interviews. The new use of HCQ in rollers is a large step in the right direction. Still, improvement is important.

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8. APPENDIX

8.1. Additional Background Information

In this section some additional background information is given. This information can be very effective to gain an understanding of the phenomena at play in this research. However, this information was deemed not necessary to understand the findings and was therefore cut from the main paper.

8.1.1. POROUS ASPHALT

As stated, porous asphalt has many good qualities. The noise reduction is a central reason why it is chosen over other types of asphalts. Noise pollution from cars comes from two sources, the engine and the tire/pavement interaction through vibrations (Huschek, 1990). The pavement/tire interaction depends on a number of factors (environmental conditions, speed, tire type, road type), but the asphalt type is a key factor which can be influenced (McDaniel, Thorton, & Dominguez, 2004). One study compared porous asphalt to HMA and SMA (McDaniel, Thorton, & Dominguez, 2004). This study showed that at speeds of 80 km/h porous asphalt had a 4.2 dB reduction against HMA and 5.0 dB reduction against SMA (McDaniel, Thorton, & Dominguez, 2004). On average, porous asphalt reduces noise by up to 4 dB when compared to other asphalts (Yu, Jiao, Yang, & Ni, 2015) (Liu, Huang, & Xue, 2016) (O'Flaherty & Hughes, 2016). Noise reduction can even reach up to 10 dB depending on the circumstances (HAMM AG, 2010). Regardless of the exact noise reduction, one thing is certain, porous asphalt has a significant effect on the noise generated by moving cars. Lowering the noise levels by 3 to 4 dB, as is porous asphalt can, is equal to halving the traffic flow or doubling the distance from the traffic (O'Flaherty & Hughes, 2016).

In many cities and on roadways the large surface areas which are paved make it very difficult for rainwater to enter the ground. The decrease in groundwater below cities has negative effect on the plant life (Yang & Jiang, 2003). Additionally, the soil cannot exchange heat and moisture with air which causes the temperature and humidity in large cities to rise; this phenomenon is known as the hot island city (Yang & Jiang, 2003). This is an issue which may be helped with the use of porous asphalt. Porous asphalt allows water to drain through it. This water therefore can get into to soil much easier. The quick drainage of water also reduced the spray of water when cars drive on a rainy day (Rijkswaterstaat, 2019) (McDaniel, Thorton, & Dominguez, 2004). Water spray during driving is a serious safety hazard which is almost fully eradicated with porous asphalt (Thom, 2014). In addition, when driving on a rainy day, porous asphalt can decrease the sun reflection from wet surfaces which improves the visibility for drivers (Herrington, Reilly, & Cook, 2005).

8.1.2. AGGREGATE CHOICE

In the section 3.1.1 it is stated that porous asphalt is a gap-graded mixture (O'Flaherty & Hughes, 2016). This means that that much more large/coarse aggregate is used. Many other asphalt mixtures use a mixture of coarse aggregate, fine aggregate, and even finer materials in combination with bitumen ta achieve the desired qualities. Generally, the fine aggregate and other fine materials fill the voids in between the coarse aggregate to reduce the air voids. Since porous asphalt has very low amounts of the smaller aggregate types, the high void percentages required for porous asphalt are achieved. Figure 23 shows a comparison of the aggregate compositions of different asphalt types. It can clearly be seen that porous asphalt (PA in the figure) has by far the highest void percentage and the lowest fine aggregate and fines percentage.

SMA, the other type of asphalt of interest in this paper, is very different. SMA has a much lower void percentage (4-6%) (Antonissen, 2019). It is clear to see in Figure 23 that SMA has more fine aggregate and fines than porous asphalt. This, along with sufficient compaction (see section 3.2.2 on compaction) achieves a much lower void percentage. Another noticeable thing is that SMA uses a similar concentration of coarse aggregate. The high coarse aggregate count creates a rigid skeletal structure similar to that of porous asphalt (O'Flaherty & Hughes, 2016). However, the voids in this skeletal structure are filled with the additional fine aggregate, fines, and bitumen content (O'Flaherty & Hughes, 2016).

The aggregate skeleton distributes the traffic loads evenly.

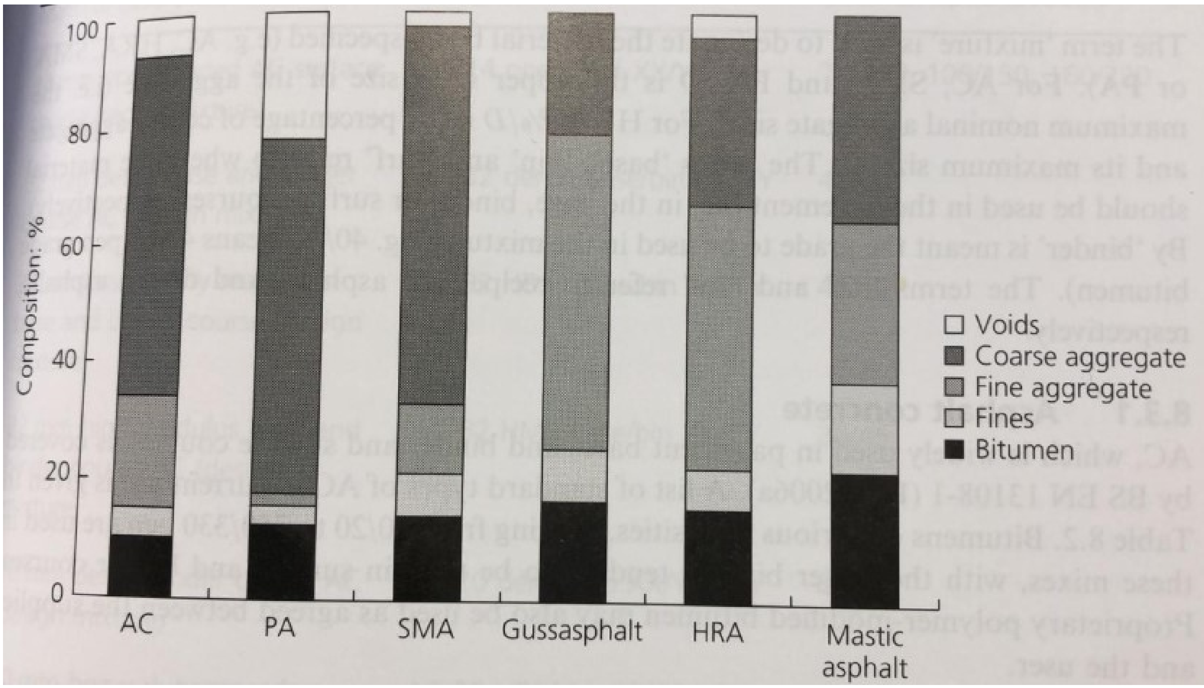


Figure 23: Aggregate Composition of Types of Asphalt (O'Flaherty & Hughes, 2016)

8.1.3. ASPHALT DISTRESS

Table 1 shows the visible asphalt distress types classified by the US Department of Transportation Federal Highway Administration (Miller & Bellinger, 2014). Information in this table not from that source will be cited to be from another source.

Table 1: Asphalt Distress (Miller & Bellinger, 2014)

Distress Type	Description	Causes	How to measure
Cracking			
Fatigue cracking	- Many-sides - Sharp angled pieces - Usually less than 0.3 m - Alligator/chicken wire pattern	- Repeated traffic loading - Inadequate pavement drainage or thickness (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996)	- Record the affected area size - Rate in severity

Block cracking	Pattern of cracking which creates approximately rectangular pieces ranging in size from 0.1 to 10m^2	- Low traffic volumes - Low temperature (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996)	- Record affected area size - Rate in severity
Edge cracking	- Only for roads with unpaved shoulders - Continuous cracking within 0.6 m of pavement edge		- Record length - Rate severity
Longitudinal cracking	- Cracks predominantly parallel to the road centerline - Often between adjacent lanes (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996)	- Low temperature - Heavy loads (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996)	- Record each crack separately - Rate in severity
Reflection cracking at joints	Cracks in AC overlay surfaces that occur over joints in concrete pavements	Variety of cracks in the underlying surface (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996)	Recorded as longitudinal or transverse cracking
Transverse cracking	Cracks predominantly perpendicular to pavement centerline	Low temperature (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996)	- Record the number and length of the transverse cracks - Rate them on severity
Patching and Potholes			
Patch/patch deterioration	Part of pavement surface (larger than 0.1 m^2) that has been replaced or has had additional pavement added later		- Record the number of patches and surface area - Rate severity of the patches - Record the distress to the patches
Potholes	Bowl-shaped holes with minimum diameter of 150mm	- Fatigue Cracking (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996) - Cold spots from lack of temperature homogeneity (Thom, 2014)	- Record the number of potholes and square meters affected - Rate severity level
Surface Deformation			
Rutting	Longitudinal surface depression in wheel path	Traffic loads (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996) - Transverse displacement of vehicles	Record the maximum rut depth to the nearest millimeter at 15.25 m intervals for each wheel path

Shoving	Longitudinal displacement of an area of the pavement surface	Braking or accelerating vehicles	Record the number of occurrences and the surface area affected
Surface Defects			
Bleeding	Excess bituminous binder on pavement surface		Record surface area affected
Polished aggregate	Surface binder worn away to show the coarse aggregate		Record surface area affected
Raveling	Wearing away of pavement caused by loosening of aggregate particles	- Deficient asphalt content - excessively oxidized (brittle) binder (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996)	Record surface area affected
Miscellaneous Distresses			
Lane-to-shoulder drop-off	Road surface is higher than outside shoulder		
Water bleeding and pumping	Water seeping from cracks		Record number of occurrences with minimum length of 1 m
Fat spots **(Pavement Tools Consortium, n.d.)**	Isolated areas in the mat where excess asphalt binder is visible on the surface May lead to shoving and rutting and reduce skid resistance (Pavement Tools Consortium, n.d.)	- Excessive moisture in the HMA - Construction (Pavement Tools Consortium, n.d.)	

Severity Distresses

In this section the method used to assign a severity to the distress areas recorded with the visual inspections will be explained.

The severity of the raveling and cracking found was judged as is explained in the visual inspection guidelines from CROW (Kennisplatform CROW, 2011). Raveling judged by the percentage of the surface area that shows raveling. It is also different for porous asphalt than for other, denser type of asphalts. The severity is judged in the following way:

Table 2: Raveling Severity

Asphalt type	Light	Medium	Heavy
Dense asphalt	5 to 20% of area shows raveling	20 to 50% of area shows raveling	>50% of area shows raveling
Porous asphalt	5 to 10% of area shows raveling	10 to 20% of area shows raveling	>20% of area shows raveling

Cracking is more complicated. Cracking severity is judged by a variety of factors including width, height difference between sides of the crack, length, and other factors. The severy was judged in the following way:

Light	Medium	Heavy
- Longitudinal with height difference between side <10mm - Width <5mm - Filled crack	- Multiple cracks parallel - Branching longitudinal cracks - Longitudinal with height difference >10mm but <15mm - Width >5mm but <10mm	- Longitudinal and transverse cracks connected to each other - Longitudinal cracks with height difference >15mm - Width >10mm

8.1.4. ASPHALT PAVING CREWS

Table 3 shows all of the parts of a typical asphalt paving crew. Additional explanation on pavers, rollers, and inspections will be given below

Table 3: Parts of a Paving Crew (Antonissen, 2019)

Core Paving Crew members	Specifics
One or more pavers	Machinist/operator
	Screed Operators
Two or more rollers (typically two or three)	Tandem and driver
	Deadweight and driver
	3-drum and driver
	Pneumatic tire roller and driver
Dump trucks	Driver
Bitumen spray truck	Driver
One or two rakers	
Supervisor	
(Potentially) Technologist	

Pavers

The process of paving a road on the surface seems quite simple, but in reality, it can be very complicated. The foundation of the road has been prepared before a paving crew comes to pave the road. One or more pavers are lined up to pave the road. The amount is based on the width of the road, the type of paving done, and additional factors. A paver can, in general, pave a section as little as 1.9 meters and as large as 5.5 meters because the screed can be extended (Oosterveld, 2019). This means that if a road 9 meters wide needs to be paved, then either two or three pavers can be used. The distinction between two or three pavers is that the seam between the two paved mats will be in different locations. Since the seam is potentially weaker, it is smart to plan that the seam will be in a location which receives less loading. The pavers do not drive side by side, but instead are staggered because otherwise they will collide (Oosterveld, 2019). The pavers typically pave with a speed of 3 to 5 meters per minute.

Rollers

Directly behind the paver, the rollers compact the freshly laid asphalt mat to the required void content (Antonissen, 2019). The rollers consider the optimal window of compaction (see section 3.2.2) and attempt to reach the optimal compaction level within this timeframe. Because of the nature of asphalt cooling this timeframe may be short (which requires the rollers to work quickly and be close behind the paver) or long (which gives the rollers more time and means they don't need to be as close to the paver) (Antonissen, 2019). The choice of how to do this exactly is left up to the roller operators. The choices they make are often based on years of experience (Antonissen, 2019) (Jagt, 2019). Additionally, some roller operators will look at the asphalt color and use that to decide whether compaction can continue (Jagt, 2019). Also, most rollers have a temperature sensor which they use to know if they are compacting at correct asphalt temperatures.

Compaction is a team effort since there are often two or three rollers working at the same time, communication is key. It is better if the entire asphalt mat is equally compacted. The roller operators need to work together to achieve this (Jagt, 2019). In many cases the different types of rollers play to their strengths. IF a roller causes a piece of uneven compaction, another roller may come and fix that (Antonissen, 2019). This can be quite difficult without proper communication. A new, innovative, roller uses GPS to track where the roller has already compacted (HCQ). This provides roller operators with another tool to compact the road more evenly.

It has been observed that some roller operators tend to neglect the end of the road. This is because they are tempted to finish compaction quickly after the paver crew is finished (Jagt, 2019). This may lead to the end of the road being considerably less compacted and may lead to weaker pavement. This is an issue which is entirely human error and could easily be fixed if more attention was paid to the rolling operations.

Inspections

After a road is paved, it will be used and maintained. Although this seems obvious, this is not always the case. Many roads which are paved are never looked at again (Jagt, 2019). These roads are mostly roads which are not very busy and therefore do not display distress quickly. Most popular roads, however, need to be inspected regularly to ensure quality and safety. The frequency with which roads are inspected is often based on the contract with the client. Sometimes the client may have very strict quality needs which means that the road also needs to be inspected more often; the opposite is also possible. In most cases the client is the municipality or another government body. For an average contract the road will undergo an in-depth visual inspection every year (Flentge, 2019). However, for area contracts, contracts which cover all of the roads, tunnels, buildings, etc. in a specific area, visual inspections may only be performed every two years (Flentge, 2019). In addition to visual inspection, drill core samples can be taken from the roadway. This is normally only done when there is a specific reason to do so (Flentge, 2019). This may be done when there is damage suspected which is not visible at the surface or when adjustments need to be made to the road (Flentge, 2019).

Due to the importance of inspections in maintain quality infrastructure, they need to be performed accurately. In the past the damage was physically drawn onto special 100 meter road maps (Flentge, 2019) (Jagt, 2019). With modern technology, this process has been streamlined to be more efficient and even more accurate. To achieve this, BAM works with a company called Horus. This company drives over the road with a car mounted with three HD cameras which show a roughly 140 degrees view of the road at the front, and one HD camera mounted in the back. The footage from these cameras can be viewed and edited in a program called the Horus movie player (Flentge, 2019). In this program the road distress which is visible in the footage can be marked, quantified, and given a severity level. The finished product can be exported as a shapefile which can be displayed in 2D using Gis (Flentge, 2019). All of the inspections for a specific road are then saved in this manner. Based on the severity of the distress, the decision can be made to do nothing in the case that the damage does not exceed the amount specified in the contract and in the national standards (Flentge, 2019). If the damage does exceed the amount acceptable, then the decision can be made to fix/replace all or part of the road (Flentge, 2019).

8.2. Additional Information A35 and Aziëhavenweg

In this section information pertinent to the two case roads which are analyzed will be given. This information, while still useful, was not deemed necessary enough to put in the main paper.

8.2.1. A 35 TEST SECTION 3

The following sections detail the historical data gathered during the paving of the A35 (weather, asphalt temperature, and compaction). After that comes sections detailing the distress found with the visual inspection and the analysis performed with the data. This is the extended version of the analysis discussed in section 4.2.

Weather Data During Paving Operations

Weather data was collected for each of the two paving nights. On Wednesday night the average temperature was 17.9 °C and the average windspeed was 4.4 km/h. Thursday night the average temperature was 13.4 °C and the average windspeed was 4.9 km/h (Miller, ter Huerene, & Dorée, Temperature profiling and monitoring of equipment movements during construction (A35: Test Section 3), 2007). In addition to temperature and windspeed, the wind direction and the humidity were also collected. Table 4 shows all of the weather data.

Table 4: Weather Conditions A35 (Miller, ter Huerene, & Dorée, 2007)

Vliegveld Twente Weather Station		Temp (°C)	Windspeed	Wind direction	Humidity
Night 1	Max.	21.0	6.9	135.0	82.0
Wednesday	Min.	13.0	1.2	0.0	53.0
	Range	8.0	5.7	135.0	29.0
	Average	17.9	4.4	81.7	65.6
	St. Dev.	2.4	1.7	45.8	8.4
Night 2	Max.	23.3	6.9	90.0	87.0
Thursday	Min.	9.0	3.5	0.0	25.0
	Range	14.3	3.4	90.0	62.0
	Average	13.4	4.9	49.7	67.1
	St. Dev.	5.0	1.1	37.2	19.0

Temperature Contour Map Analysis

Wednesday Night Paving

As mentioned earlier, the road was paved over two nights with multiple pavers. For each of the lanes and each night a temperature contour map (TCM) was made using the thermal images. The first night (Wednesday), the following three TCMs were made (Figure 24,Figure 25, and Figure 26). The temperature homogeneity of these TCMs will be assessed in this section. The definition of temperature homogeneity used in this paper was defined in section 3.2.1.

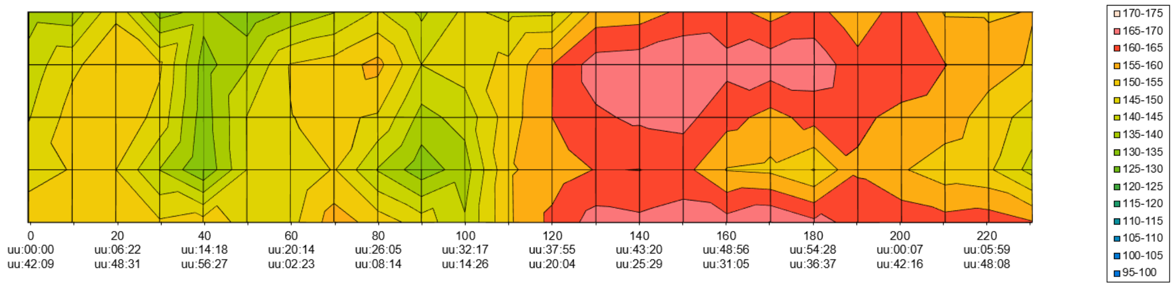


Figure 24: Temperature Contour Map Wednesday Lane 1

The temperature homogeneity of the asphalt mat laid on Wednesday night in the first lane can be seen in Figure 24. As can be observed, for the first 120 meters, the asphalt temperature is relatively homogeneous. The temperature stays around 140 to 150 °C and only dips to around 130 °C at two points (40 m and 90 m). From roughly 120 to 210 meters the temperature rises. The average temperature for that section lies somewhere between 160 and 170 °C. Towards the end of the asphalt mat, the temperature decreases again.

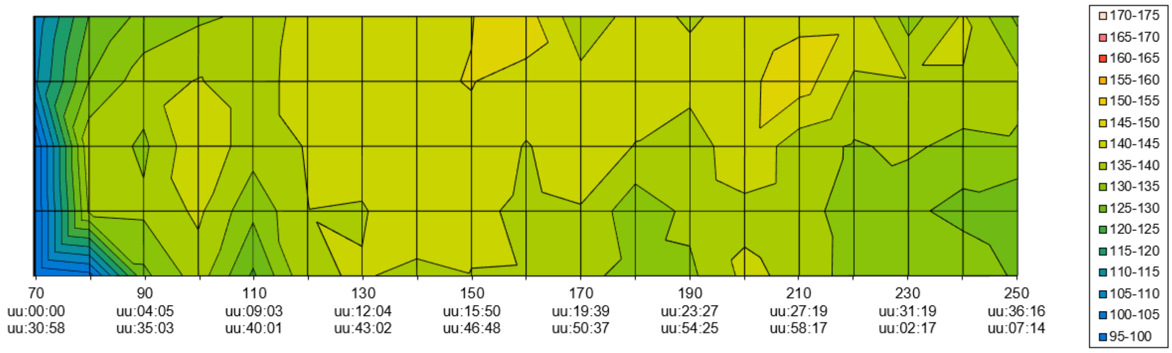


Figure 25: Temperature Contour Map Wednesday Lane 2

The temperature contour map for the second lane paved on Wednesday night can be seen in Figure 25. This map starts at 70 meters in because there is no data available from the first 70 meters. The start of the paving is very cold relative to the rest of the temperature contour map. The average temperature of the first 10 meters (70-80) is 95.8 °C. After this issue the temperature quickly rises to between 130 and 140 °C for the remainder of the entire section paved. Other than roughly the first 10 meters, the rest of the mat has a very good temperature homogeneity.

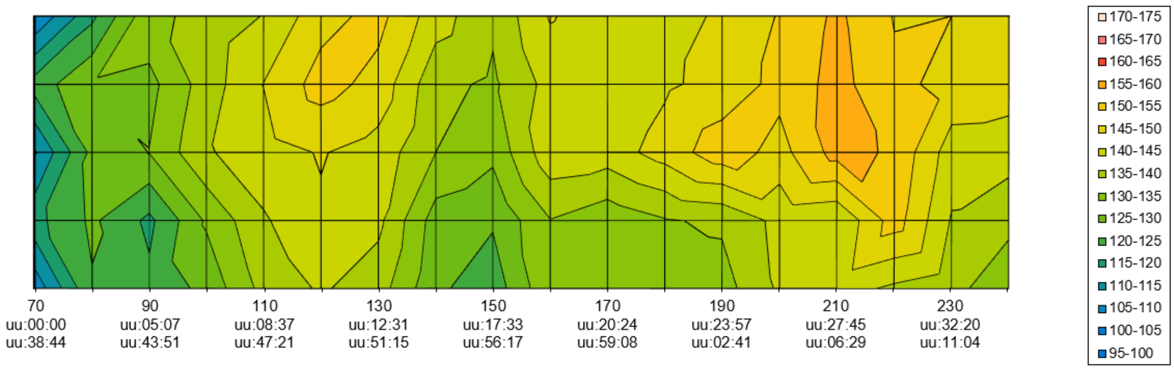


Figure 26: Temperature Contour Map Wednesday Lane 3

The temperature contour map for the third and final lane paved on Wednesday night can be seen in Figure 26. Similar to the second lane paved, the first 10 meters is significantly cooler than the rest of the contour map. However, the temperature difference is less severe than observed in lane 2. Also, similar to the second lane, this temperature contour map starts at the 70-meter mark. In this case that is because the lane does not start until 70 meters after the begin point of the other lanes. The average temperature at the 70-meter mark is 112.4 °C. After that the temperature rises to between 130 and 140 °C. At 210 meters is the only point that the temperature rises to above 150 °C. Except for the beginning, the rest of the mat has a good temperature homogeneity since there are no large and rapid temperature differences.

Thursday Night Paving

Paving the road resumed on Thursday. On the second night only the first and second lanes were paved. Based on the thermal images made during the paving temperature contour maps were made (Figure 27 and Figure 28).

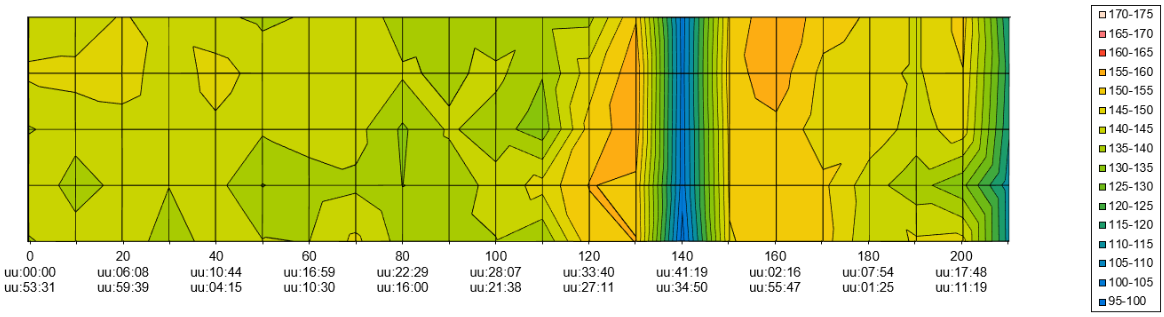


Figure 27: Temperature Contour Map Thursday Lane 1

In Figure 27 the temperature contour map for the first lane paved on Thursday night can be viewed. Roughly the first 110 meters shows very good temperature homogeneity with temperature ranging between 140 and 150 °C. At around the 120-meter mark a paver stop occurred. The temperature first rises slightly (to 156.2 °C at 130 meters) and then drops extremely quickly. At the 140-meter mark the temperature has dropped to only 101.4 °C. At 150 meter the temperature has risen again to 151.3 °C. After that, from about 150 to 200 meters, the temperature stays decently high and only fluctuates within a range of 10 °C. At the end of the paving operations the temperature drops rapidly again to 114.4 °C at 210 meters. Compared to other temperature contour maps, the temperature homogeneity is quite poor. The first section (0-110 meters) is good, but the large temperature dip at the 140-meter mark, and the smaller, but still significant, temperature dip at the 210-meter mark are negative.

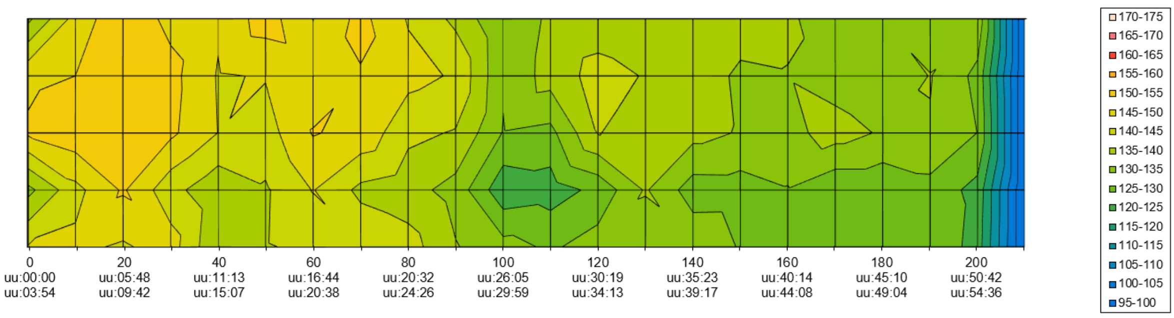


Figure 28: Temperature Contour Map Thursday Lane 2

The final temperature contour map is Figure 28 and shows the paving operations in the second lane paved on Thursday night. The first, roughly, 90 meters of the asphalt mat shows temperatures between 140 and 150 °C. After that the average temperature drops to the mid to low 130's. At the 200 meter point the average temperature is 127.6 °C. Then, the temperature drops to an average of 75.6 °C in 10 meters. At this point the paving operations are done. The temperature homogeneity of the most of this asphalt mat is quite good with only slight temperature differences between the first (0-90 meters) and second (90-200 meters) sections. However, the end has bad homogeneity since the temperature drops very quickly to very low temperatures.

Compaction Contour Map Analysis

Wednesday Night Compaction

Three sections were compacted on the first night. These are the first part of lane 1, the first part of lane 2, and the first part of lane 3 (Figure 29, Figure 30, and Figure 31 respectively).

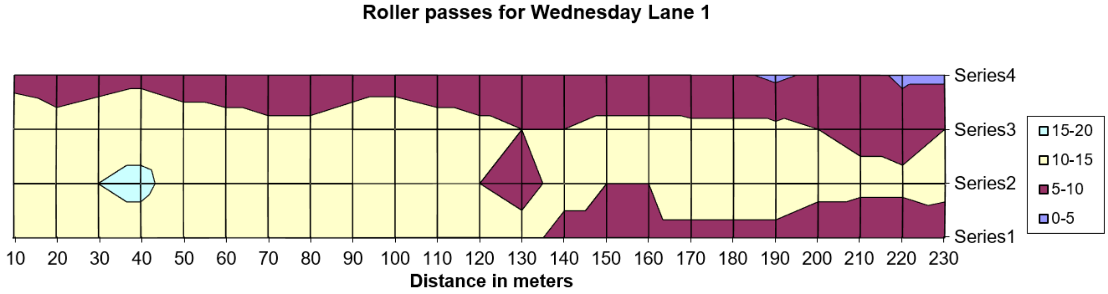


Figure 29: Roller Passes Map Wednesday Lane 1

The amount of roller passes over the asphalt mat laid on the first night in lane 1 can be seen in Figure 29. The majority of the asphalt mat was rolled between 10 and 15 times. There is one small section which was rolled slightly more (15 to 20 times) and there are two smaller areas which seem to have been largely forgotten since those areas only got rolled between 0 and 5 times. It is noticeable that the center of the lane was, on average, rolled more than the outside edges.

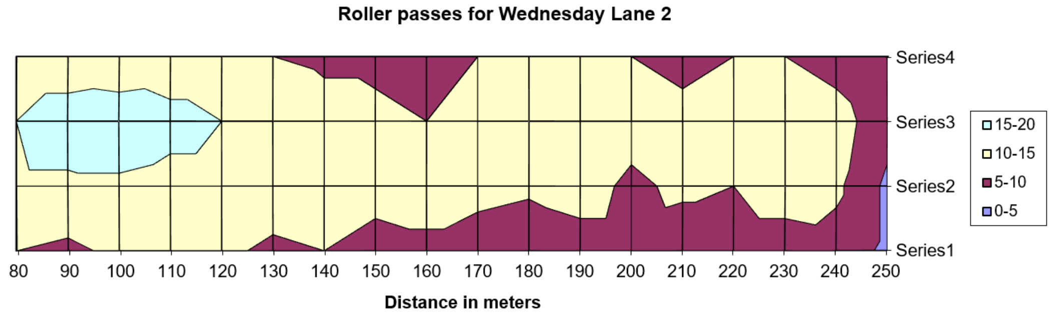


Figure 30: Roller Passes Map Wednesday Lane 2

Figure 30 Shows the roller passes for the section of lane 2 which was paved on the first night. Similarly, to lane 1, the majority of the section was rolled between 10 and 15 times. Large parts of the edges of the lane were rolled slightly less (5 to 10 times). Additionally, a large section at the beginning of the lane was rolled more (15 to 20 times). There is one small section at the very end of the asphalt mat which was neglected and received only between 0 and 5 roller passes.

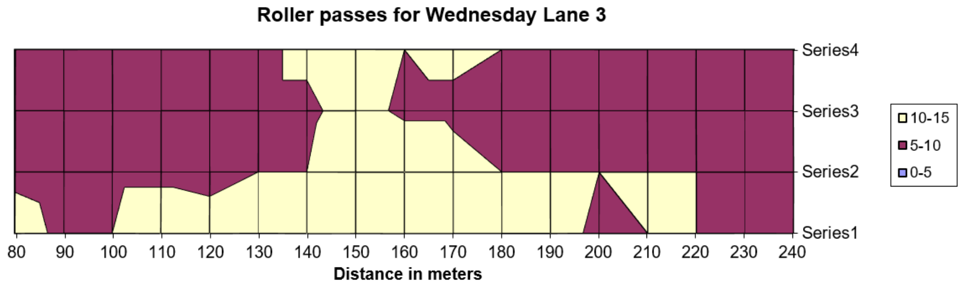


Figure 31: Roller Passes Map Wednesday Lane 3

The final section paved on Wednesday night was lane 3. The roller passes for that section can be seen in Figure 31. The majority of this section was rolled between 5 to 10 times. In the middle there is a large section where it was rolled slightly more at 10 to 15 times.

Thursday Night Compaction

On the second night both lanes 1 and 2 were finished (Figure 32and Figure 33)

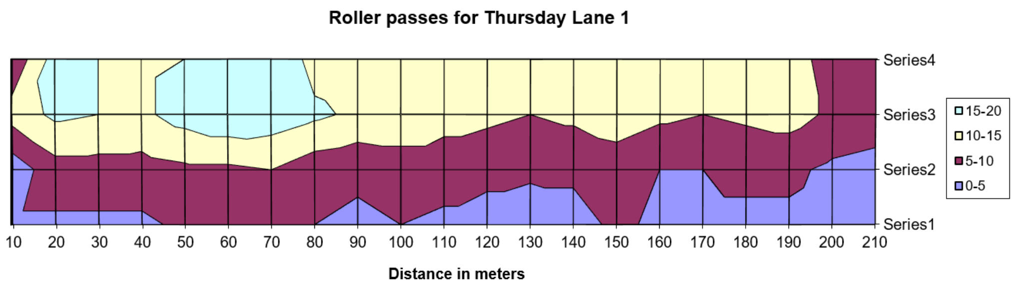


Figure 32: Roller Passes Map Thursday Lane 1

In Figure 32 the roller passes on the second part of lane 1 can be viewed. This roller passes map shows clearly that the bottom/southern side of the road was compacted considerably less than the opposite side. For much of the bottom half the asphalt mat has only be rolled 0 to 5 times or 5 to 10 times, whereas the top half is largely rolled 10 to 15 times and even has areas that were rolled 15 to 20 times. This shows neglect for even coverage of the entire road.

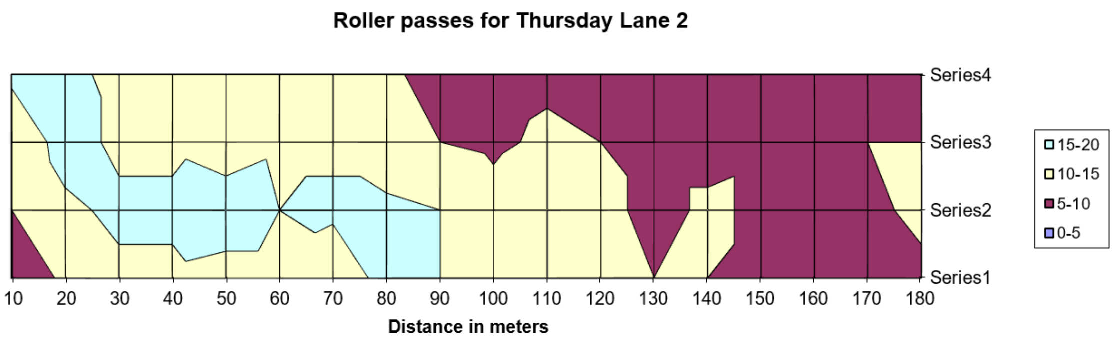


Figure 33: Roller Passes Map Thursday Lane 2

The roller passes for the second half of lane 2, completed on the second night, can be seen in Figure 33. AS can be seen, the first half of the section, roughly speaking, was paved much more than the second half. The large majority of the first half has been rolled 10 to 15 times and 15 to 20 times. The same can't be said for the second half. For that section the majority of the asphalt mat was rolled between 5-10 times and sometimes 10-15 times. This suggests, as discussed in the section on compaction, that the roller drivers are often tempted to end the compaction process before it was truly finished.

Visual Inspection Findings

Figure 34 and Figure 35 show tables of all of the distress found with during the visual inspection of data from 2014 and 2017 respectively. The table from 2017 is noticeably smaller, because the distress which had not changed much from 2014 was not noted twice. Hence, the table from 2017 shows mostly new or worsened distress.

1	Raveling	Light	2 to 3 meters in length	Left side left lane	60770
2	Raveling	Light	2 meters in length	middle left lane	60820
3	Raveling	Light	5 to 6 meters in length	middel left lane	60822
4	Rutting	light (both wheel paths)	10 meters in length	Both wheel paths	60860
5	Raveling	Light	7 to 8 meters in length	right side left lane	60970
6	Raveling	light	40 meters in length	Between first and second lane	60990
7	patching	Light		Middle of left lane	61095
8	Raveling	light	1 meter in length	middel left lane	61105
9	Patching	light		right and middle of left lane	61155
10	Raveling	Light	1 meter length	middle left lane	61180
11	Raveling	Medium	0.5m	Whole width left lane	61190
12	Raveling	medium	3 meters long	reight side of second lane	60770
13	Raveling	medium	0.5 meters long	whole 2nd lane	60800
14	Longitudinal Cracking	Light	0.2 meters long	right side of 2nd lane	60808
15	Raveling	Light	tiny	right side 2nd lane	60890
16	Raveling	light	tiny	right side 2nd lane	60940
17	Pathing	light	one line	whole width 2nd lane	61160
18	Raveling	light	4m lengt	2nd lane whole width	61190
19	Raveling	light	40 meter length	middle of right lane	60920
20	Raveling	medium	5 meters long at seam	seam between 2nd and 3rd lane	60980
21	Raveling	light	25 meters long	center right lane	60980
22	Patching	light		whole 2nd lane	60095
23	Patching	light		whole right lane width	60095
24	Raveling	light	21 meter length	left side right lane	61130
25	Patching	light	small	left side right lane	61165
26	Raveling	light	3m long	left side right lane	61175
27	Raveling	Light	4 metrs long	whole right lane	61185
28	Raveling	Medium	Whole seam to bridge	whole seam to brdige	61190

Figure 34: Table Distress 2014

1	Raveling	medium	2 meters long	Middle of left lane	60825
2	Cracking	light		whole lane width	60835
3	Raveling	light	12 meter length	right seam left lane	60840
4	Raveling	light	1 meter length	middel left lane	60870
5	Raveling	light	8 meter length	right side of left lane	60940
6	Raveling	Light	3 meter length	right side of left lane	60960
7	Raveling	medium	10 meter length	Right side and seam of left lane	60980
8	Raveling	light	5 meters in length	left side of left lane	60880
9	Raveling	light	3 meters long	righ side of left lane	61005
10	Longitudinal cracking	light	2 meters in length	right side of left lane	61040
11	Raveling	medium	short but wide	middel of left lane	61100
12	Raveling	medium	5 meters long	right side of left lane	61120
13	Raveling	medium to high	4 meters long	entire left lane width	61190
14	Raveling	medium to high	8 meters long	whole right lane	61190

Figure 35: Table Distress 2017

The distress in these two tables will be compared to the paving data previously discussed and analyzed (in Section 4.2.4). Raveling, which is explained in section 3.3 to be one of the most important distress types in this research, will be used the most in the analysis. Patching of large areas (not only crack like in some cases here) is also useful since the patching most likely occurred because of damage such as raveling.

In-depth Comparison Analysis

Each point of interest will be compared to both the compaction and temperature homogeneity data. A connection with points of interest in the data will be given in the following ways: No connection with the data, possible connection with the data, connection with the data. If there is, or is possible, connection with the data then an explanation will be given. Whether the data corresponds or not is based on the literature study. For example, as discussed in section 3.2.1, temperature differences of 20 ^{o}C within the asphalt mat have a high likelihood of causing segregation. Therefore, if distress is located near a rapid temperature change of 20 ^{o}C or more, then the data corresponds with each other.

No connection will be determined if:

- the distress is in an area where there are not noticeable temperature homogeneity changes or
- if it is located in an area where there was good roller coverage (20 to 10 roller passes)

Possible connection will be determined if:

- the distress is in an area with temperatures which are not desired, but not in a temperature transition area or the temperature transitions are small or gradual
- the distress is in an area with sub-par roller coverage (10 to 5 roller passes)

Connection will be determined if:

- the distress is located on an area which saw a significant temperature homogeneity change (>20 °C)
- the distress in in an area which was roller very little (5 to 0 roller passes)

Table 5: A35 Temperature Homogeneity and Compaction Comparison with Distress

Distress location	Temperature Contour Map	Compaction Coverage
Wednesday night lane 1		
Light raveling (2014 ID: 1)	No connection	No connection
Light raveling (2014 ID: 2 and 3)	No connection	No connection
Medium raveling (2017 ID: 1)	No connection	No connection
Light raveling (2017 ID: 3)	Possible connection - Near an area where the temperature rises from 140 to 160-170 °C, but not in a location where this would be expected to lead to raveling	No connection
Light raveling (2017 ID: 4)	No connection	No connection
Light raveling (2017 ID: 8)	No connection	No connection
Light raveling (2017 ID: 5)	Possible connection - In an area where the temperature drops, but not significantly rapidly and much (only about 10°C temperature difference)	Possible connection - part of the section was not well rolled (only 5 to 10 passes), but another part was rolled better
Wednesday night lane 2		
Wednesday night lane 3		
Light raveling (2014 ID: 19)	Possible connection - Area of distress has temperature differences of 15°C but the temperature differences are gradual and small (below 20 °C)	Possible connection - Majority of the distress area is in an area where there were only between 5 and 10 roller passes
Thursday night lane 1		
Light raveling (2017 ID: 6)	No connection	Connection - Vast majority of the distress section is in an area where there was only rolled between 0 and 5 times
Light raveling (2014 ID: 5)	No connection	Possible connection - Vast majority of the distress area is in an area where there were only between 5 and 10 roller passes
Light raveling (2017 ID: 7)	No connection	Possible connection - Majority of the distress area is in an area where there were only between 5 and 10 roller passes and even some areas where there were between 0 and 5 roller passes

Light raveling (2014 ID: 6)	No connection	Possible connection - Majority of the distress area is in an area where there were only between 5 and 1o roller passes
Medium raveling (2017 ID: 11)	Possible connection - The distress is near a rapid transition of temperature, but not exactly on it	No connection
Light raveling (2014 ID: 8)	Connection - The distress area is in a location where the asphalt temperature changes rapidly form 150-160°C to 100°C	No connection
Medium raveling (2017 ID: 12)	No connection	Connection - The majority of the distress is in a location where there were only 0-5 roller passes and the other part is in a location with 5-10 roller passes
Light raveling (2014 ID: 10)	No data	No data
Medium to high raveling (2017 ID: 13)	No data	No data
Thursday night lane 2		

As can be seen in Table 5, there was quite a lot of data found; specifically, for the first lane (left lane). The visual inspection of the 2014 footage of the second lane (right driving lane) showed less distress and it was not possible to gather distress data from 2017 for that lane since at that point the entirety of that lane had been repaved. The third lane (the emergency lane) also showed les distress. Also, the second half of that lane has no available paving data (both temperature homogeneity and compaction) which made analysis impossible.

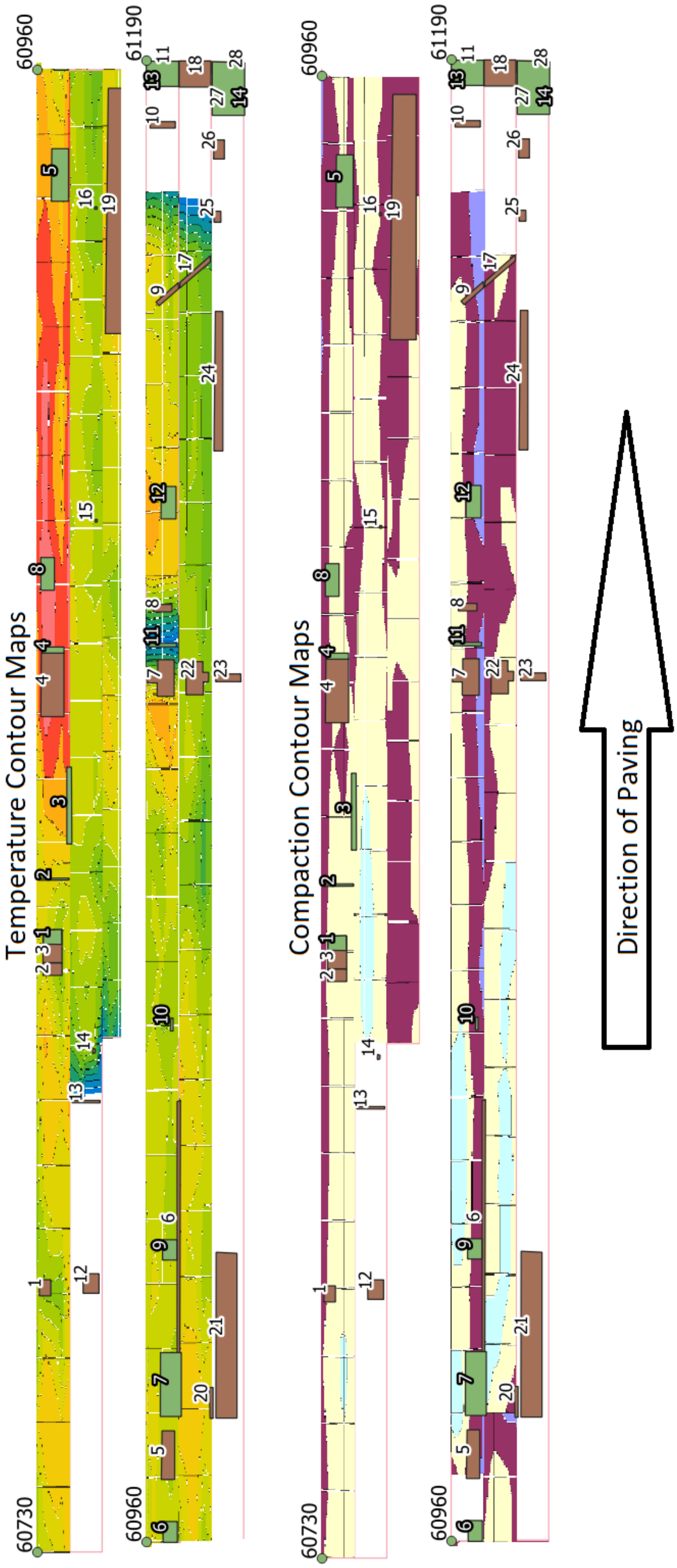


Figure 36: Temperature and Compaction Contour Maps Overlaid with Distress on A35

8.2.2. AZIËHAVENWEG

The following sections detail the historical data gathered during the paving of the Aziëhavenweg (weather, asphalt temperature, and compaction). After that come sections detailing the distress found with the visual inspection and the analysis performed with the data. This is the extended version of the analysis discussed in section 4.3.

Weather Data During Paving Operations

The weather conditions were quite close to the optimal weather conditions for paving. An average temperature of 21 °C and an average windspeed of 8km/h were observed (Miller & Dorée, 2008). The humidity and the solar radiation were also recorded. Figure 37 Shows each of the weather factors over the time that the paving took.

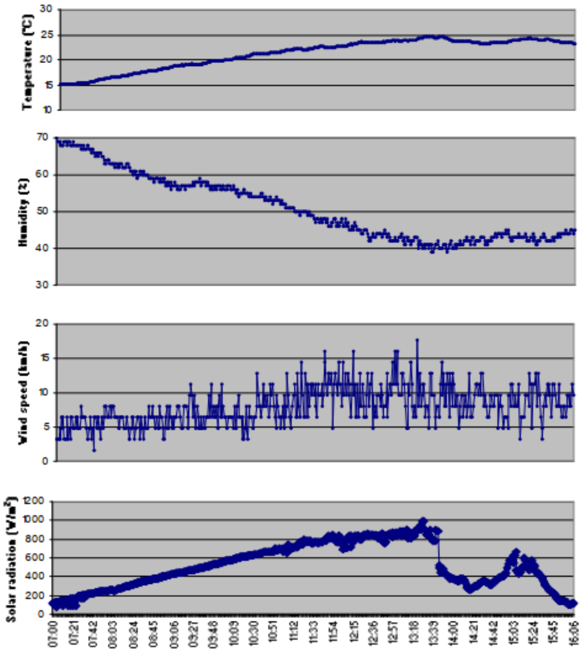


Figure 37: Weather Conditions Aziëhavenweg (Miller & Dorée, 2008)

Temperature Contour Map Analysis

Method 1: ThermaCAM^{TM} E320 camera images taken every 10 meters

The first method produced one temperature contour map for the entire road since it was all paved in one go (Figure 38). A graph showing the average temperature over the length of the road was also generated (Figure 39).

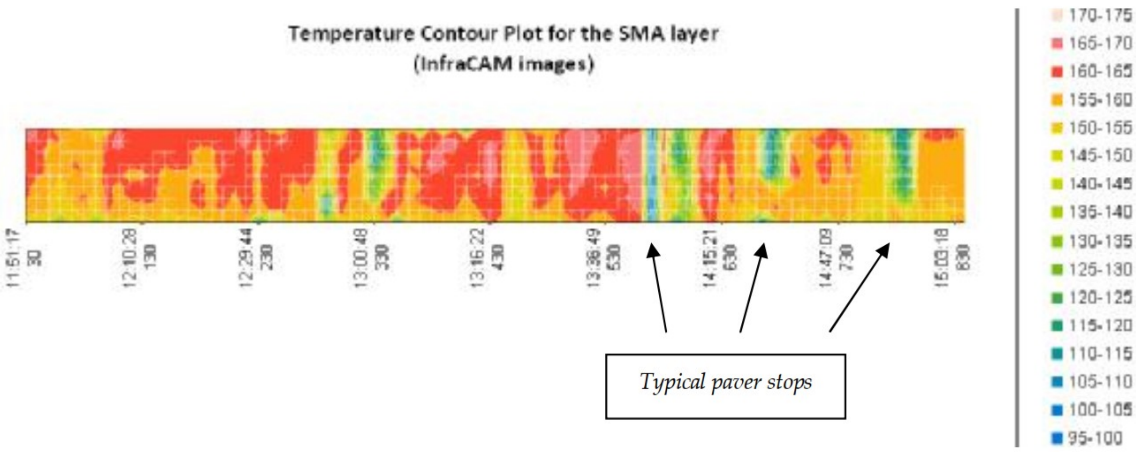


Figure 38: Temperature Contour Map Aziëhavenweg Method 1

The image above (Figure 38) displays the temperature contour map made of the Aziëhavenweg using the first method discussed. It is clear that a large majority of the asphalt mat had temperatures between 150 and 170 °C. There are smaller areas which deviate slightly and a couple of areas which deviate greatly. An example of the slightly deviating areas is that some of the dark red areas also have light pink areas which are above 170 °C. The areas which will be most likely to cause problems are the area which have very different temperatures than the rest of the asphalt mat. Refer to the section on Asphalt Temperature for an understanding as to why this is such an issue. The areas that might pose a problem are the paver stops. When the paver stops that area of the asphalt mat cools down. There are three stops clearly visible at roughly 570 meters, 670 meters, and 790 meters. These have also been pointed out in the image. Additionally, there are cold sports at roughly 280 and 340 meters. The temperature drops of the asphalt mat can be seen clearly in Figure 39. From this image it can be clearly seen that most of the cold sports have a similar low temperature; around the low 130's and 120's °C. However, the cooler area which is also most visible in the temperature contour map, is much cooler. That area had a low temperature of just below 100 °C.

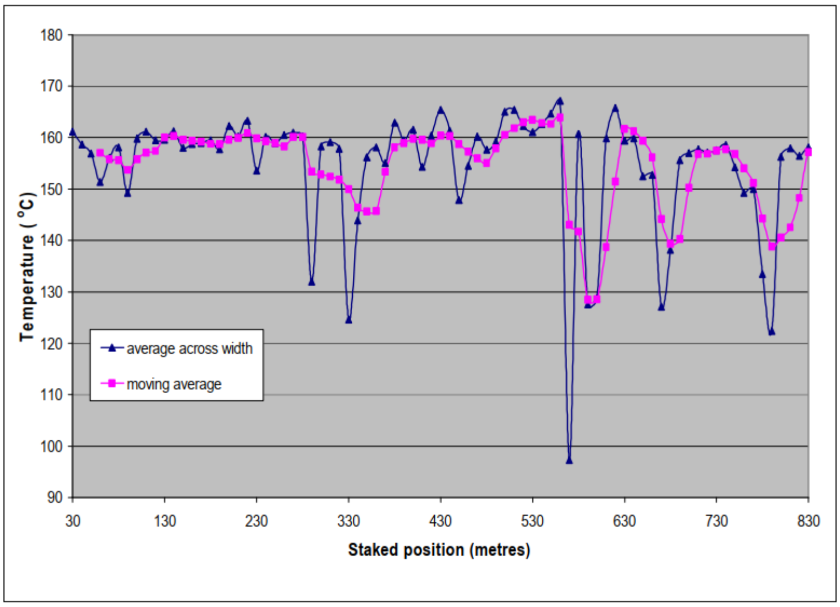


Figure 39: Asphalt Temperature vs. Distance

Method 2: FLIR A32 camera images taken every 5 seconds

The Temperature contour maps made using the second method are split up per hour. Because the paving operations took more than 3 hours there are 4 map sections (Figure 40, Figure 41, Figure 42, and Figure 43). In these figures clear lines of purple and blue can be observed. These are not very cold sports in the pavement. Rather, they are cases in which the back of the paver was accidentally captured in thermal images (Oosterveld, 2019). Because the paver is much cooler than the asphalt this creates the appearance of very high and rapid temperature differences. These sports can be ignored.

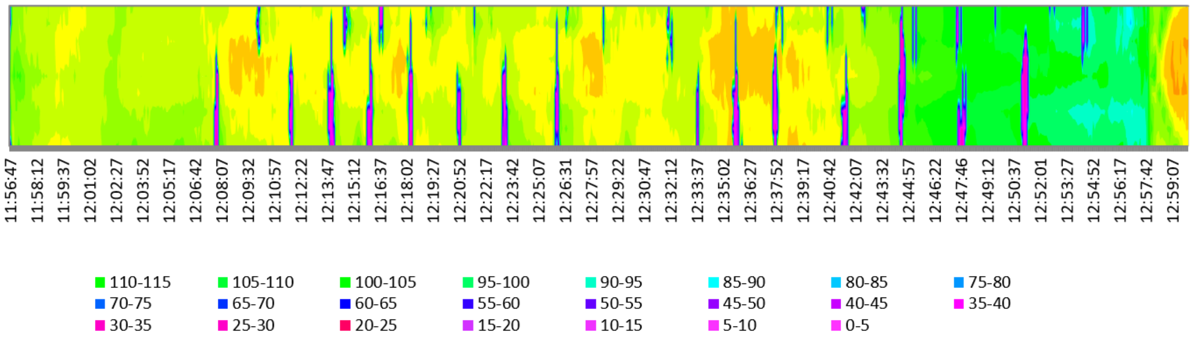


Figure 40: Temperature Contour Map Aziëhavenweg Method 2 hour 1

The larger part of the first hour (Figure 40) shows good temperature homogeneity. The temperature is shown to be roughly between 130 and 150 ºC. At 12:41 a stop was needed which caused the temperature to drop to slightly below 100 ºC. At the end of this hour the quick change in temperature after the stop can be observed. After the paving resumes, the temperature rises quickly back to between 135 and 155 ºC.

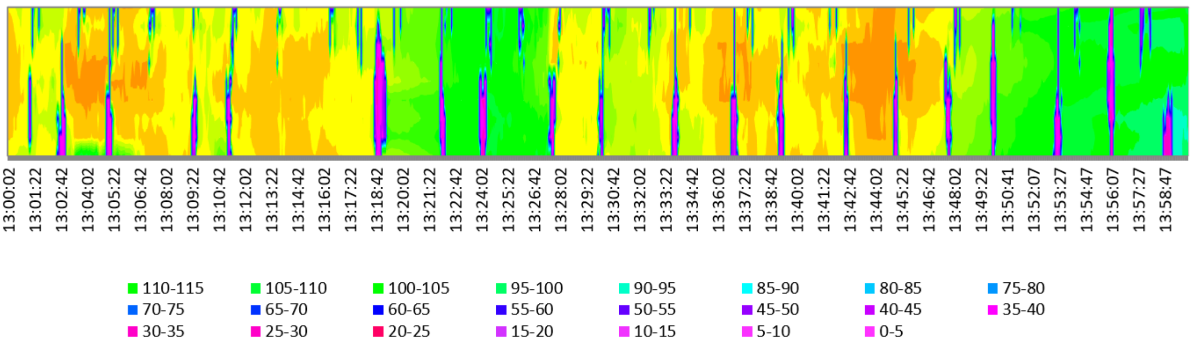


Figure 41: Temperature Contour Map Aziëhavenweg Method 2 Hour 2

The temperature stays within this range achieved at the end of the first hour for the majority of the second hour (Figure 41) except for one stop halfway and one stop at the end. The stop halfway starts at 13:18 because of a break for the workers. The temperature then seems to drop to around 100 ºC. The final stop in the hour starts at 13:45 and, again, causes the temperature of the asphalt mat to drop considerably a few minutes after.

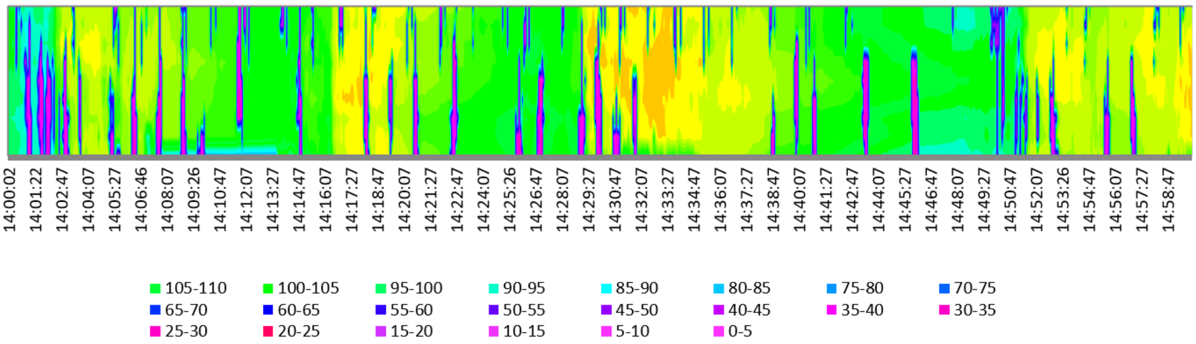


Figure 42: Temperature Contour Map Aziëhavenweg Method 2 Hour 3

The third hour of paving (Figure 42) sees four cold patches. The first stop witnessed began in the second hour. After that, three additional stops take place at 14:07, 14:19, and 14:37. During these three stops the temperature dropped to around 100 °C. In between the stops the temperature was roughly between 125 and 150 °C.

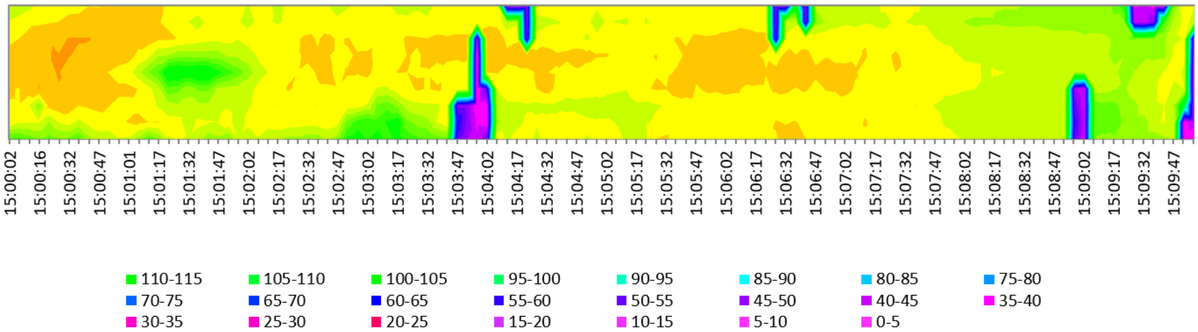


Figure 43: Temperature Contour Map Aziëhavenweg Method 2 Hour 4

The final roughly 9 minutes of paving (Figure 43) gives little insight into the entire process. The temperature homogeneity during this section is good, staying between 130 and 150 °C.

In the temperature contour maps created using the second method the areas in which the paver had to stop can clearly be seen. A log was created which noted the times of stopping and the reasons for the stop. The cumulative time of the stops recorded equaled 25.3% of the total construction time. The stops are the following (Table 6):

Table 6: Stops Aziëhavenweg Construction

Begin time	End time	Reason
12:41	12:54	Waiting for completion of the bellmouth paving
13:18	13:24	Short break for workers
13:45	13:59	Waiting for completion of the bellmouth paving
14:07	14:13	Waiting for completion of the bellmouth paving
14:19	14:25	Waiting for completion of the bellmouth paving
14:37	14:48	Waiting for completion of the bellmouth paving

Comparison Methods 1 and 2

The two methods employed to observe the temperature homogeneity deliver similar results. That is to be expected, since they are only slightly different methods observing the same situation. However, there are some differences which are noticeable.

First of all, the first temperature contour map generated using the second method (Figure 40) shows a large cool area staring at 12:41 that was created by the first stop. Coincidentally, this is one of the longest stops experienced. However, the temperature contour map generated with the first method (Figure 38) shows very little temperature change at this point. There is a slight indication of some cooling, but not nearly the severity that the other method would suggest.

Secondly, there is quite a discrepancy in the temperatures reported by the two methods. When observing the temperatures observed using the first method it is very evident that the temperature of the asphalt is, on average, between 150 and 160 °C when there are no additional complications (Figure 39). This is different from the temperatures reported using the second method. The temperature contour maps show a light green to yellow color (Figure 40, Figure 41, and Figure 42). This means that the average temperature of the asphalt mat when there are no other complications is, at best, between 130 and 150 °C. This difference is directly caused by the different gathering techniques. Since the first method take images directly behind the paver, the asphalt is still at the temperature that it was directly when being first paved. The second method has a time delay between the time when the asphalt is paved and when it can be measured. This time delay is because it takes 17 meters before the road can be fully viewed by the camera mounted on the paver. Paver move at, on average, 5 meters per minute. Therefore, the asphalt has had between 3 and 4 minutes to cool down. This explains the 10 to 20-degree difference in the measurements.

Compaction Contour Map Analysis

Figure 44, Figure 45, and Figure 46 show the roller passes for each of the individual rollers and Figure 47 shows the total compaction of the top layer (SMA) excluding the one roller which was not recorded.

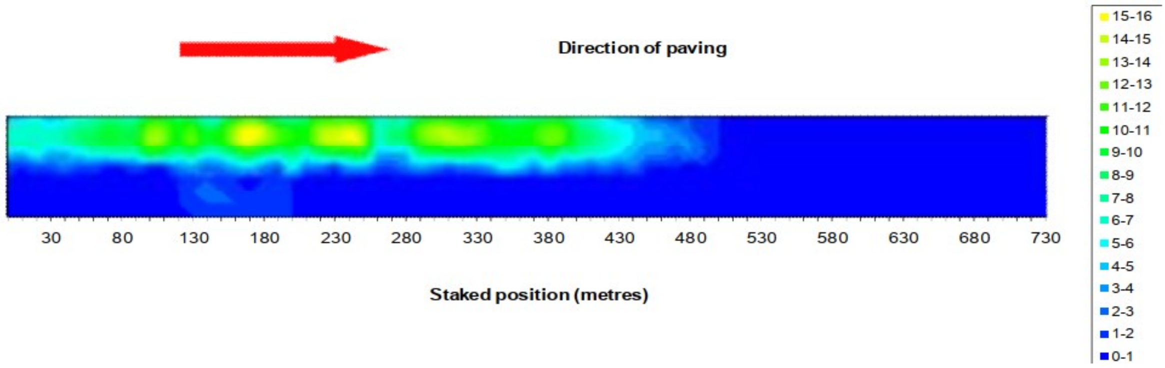


Figure 44: Roller passes Deadweight Roller 1

The roller passes displayed in Figure 44 show the first deadweight roller. There were two deadweight rollers working together, but the other one was not recorded. As can be seen this roller focused on predominantly the top half of the first 450 meters of the asphalt mat. The sections not focused on by this roller seem to not have been rolled over at all based on the legend. The area this roller did roll was covered in between 5 (the teal on the edges) and 16 times (the yellow in the middle). This shows that the coverage of this area still lacks consistency.

There is reason to believe that the roller not recorded covered the other half (bottom half) of the asphalt mat. First of all, in the report it is stated that the deadweight roller was observed to have behaved as it did for the bottom layer (STAB). From the roller passes recorded for the bottom layer it is clear to see that the two deadweight rollers worked together to achieve a more even compaction (Miller & Dorée, Temperature profiling and monitoring of equipment movements during construction (Aziehavenweg), 2008). This is also logical since it is known that roller operators often work together in this way (Jagt, 2019). Because of these reasons, it is expected that the deadweight roller which was not recorded did act in this way. However, this does not explain why the end of the asphalt mat was compacted significantly less.

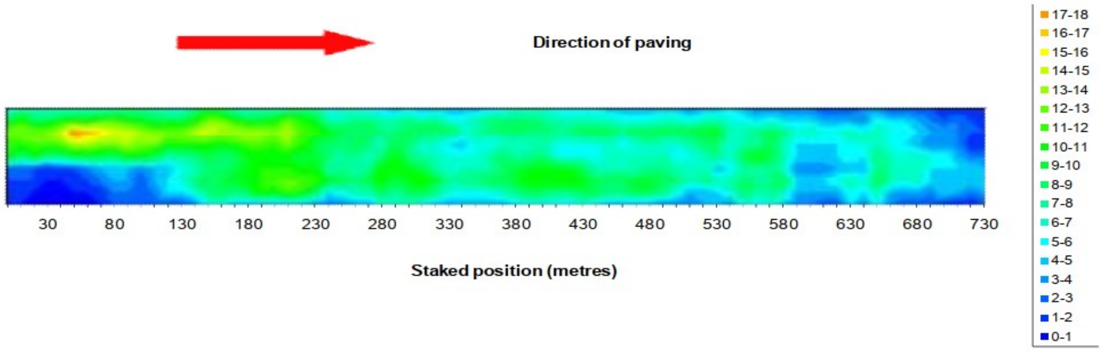


Figure 45: Roller Passes Tandem Roller 1

The first tandem roller's roller passes (Figure 45) are significantly more spread out over the entire asphalt mat than the passes recorded for the deadweight rollers. There are visible locations in which the roller did little to no compaction. These areas are the bottom left corner and some sections at the end of the asphalt mat. The largest part of the asphalt mat was evenly covered. The majority of the areas were rolled between 5 to 6 times on the edges and 13 to 14 times in the center. There is only one area where the asphalt has been rolled visibly more (around 17 to 18 times); located in the top left corner.

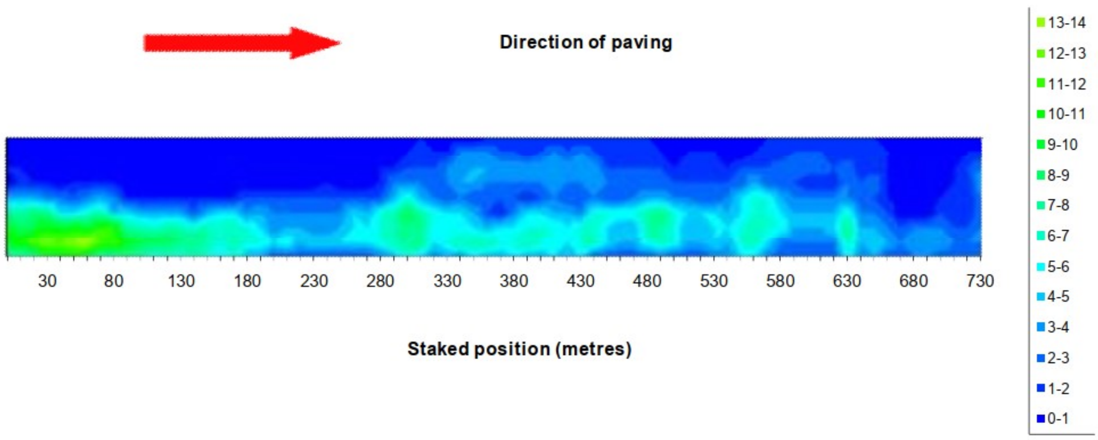


Figure 46: Roller Passes Tandem Roller 2

The second tandem roller shows much less compaction than the first one (as can be seen in Figure 46). The majority of the asphalt mat was not rolled by this roller. It is clear that there was some coordination between the roller operators because the major area neglected by the first tandem roller was hit the most by this tandem roller with between 5 to 6 passes on the edges and 12 to 14 passes in the middle. The other large area not rolled by the first roller, the end of the asphalt mat, was also largely neglected by the second roller. Because of this, the first roughly 600 meters was covered much better than the last 130 meters.

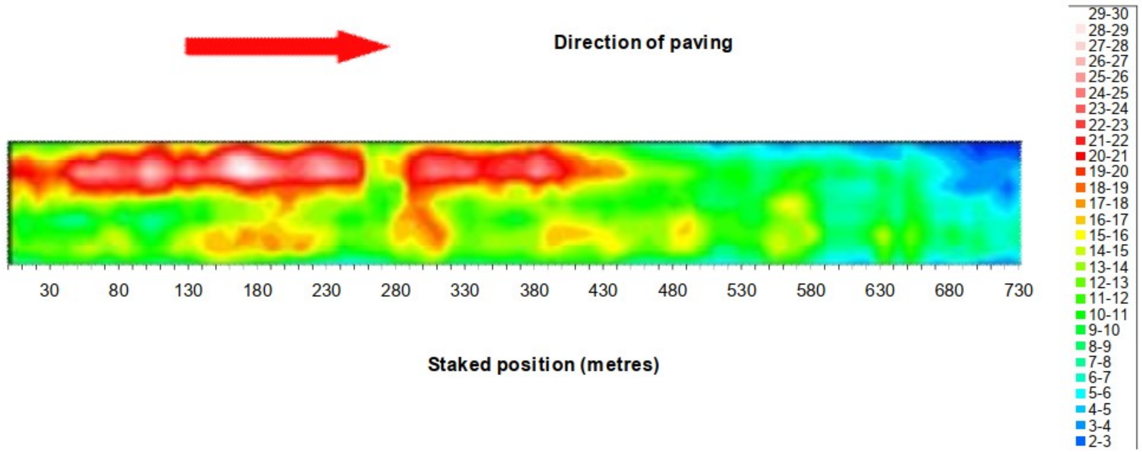


Figure 47: Overall Roller Passes (excluding one deadweight roller)

Combining the previous three figures generates Figure 47. This figure shows the entire compaction of the top layer on the Aziëhavenweg. As is expected, the end of the asphalt mat was significantly less compacted than the beginning. From about 480 meters onward sections that were rolled significantly less, to none begin appearing. The end (from about 660 to 730) was compacted even less. This section is almost entirely neglected. A very probable reason for this is human error and the roller operators' tendency to quit compaction relatively soon after the paver is done (Jagt, 2019). On the other hand, the first part of the asphalt mat was compacted significantly more. It is clear that the top half shows more roller passes than the bottom half. Again, this is because the roller passes for one of the deadweight rollers was not recorded. S explained earlier, there is reason to believe that the second deadweight roller did compact the bottom half which would, roughly, even out the compaction in that sense. There is no reason to believe that the second deadweight roller did more rolling at the end of the asphalt mat, so that is not expected.

Some small parts of the asphalt mat were roller up to 30 times (in white). These parts are at the center of areas which were rolled between 20 and 25 times (red). Furthermore, the majority of the asphalt mat was covered in 8 to 14 roller passes (green) with small sections having been rolled up to 17 or 18 times (yellow/orange). As stated, the end of the road was only rolled between 2 to 8 times (blue and teal).

A low number of roller passes means that the asphalt does not become as compressed as it should be. Figure 48 shows that the nuclear density of the asphalt is influenced by the number of roller passes. Clearly, and logically, more roller passes increases the nuclear density. The areas where there

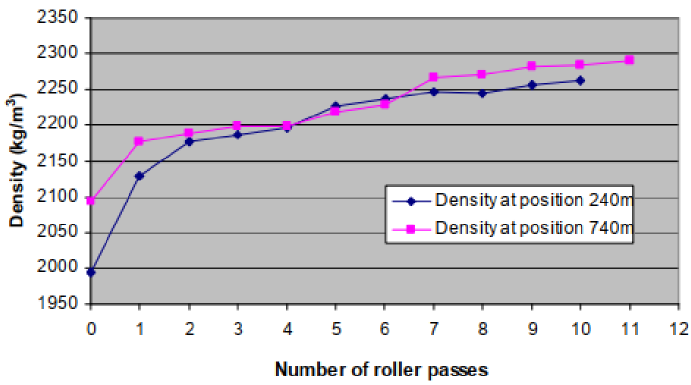


Figure 48: Nuclear Density of SMA mix depending on Roller Passes (Miller & Dorée, 2008)

was very little compaction are likely less dense than the rest of the asphalt mat.

Visual Inspection Findings

The following (Figure 49) is a table showing the types of distress observed on the Aziëhavenweg during the visual inspection which was performed on the 24th of April, 2019.

fid	Damage Type	Severity	Road Location (width)
1	Perpendicular Joint / Transverse Cracking	High	Entire width
2	Transverse Cracking	low	Left side of left lane
3	Transverse Cracking	light	Left of center line
4	Transverse Cracking	light	Right side of right lane
5	Raveling	Light	Left of center line
6	Transverse Cracking	medium	Right side of right lane
7	Physical Damage	light	Left lane
8	Transverse Cracking	Heavy	Right side of right lane
9	Transverse Cracking	Heavy	Right side of right lane
10	Longitudinal Cracking	Heavy	Right side of right lane
11	Patching	medium	Right side of right lane directly infront of bellmouth
12	Raveling	light	Left lane
13	Raveling	Light	Left of center line
14	Hole	light	Middle of right lane
15	Boorkern	light	Middle of right lane
16	Boorkern	Light	Middle of right lane
17	Boorkern	Light	Middle of right lane
18	Boorkern	Light	Middle of right lane
19	Boorkern	Light	Middle of right lane
20	Raveling	Light	Bellmouth
21	Logitudinal Cracking	Light	Left side of left lane
22	Transverse Cracking	Light	Left side of left lane
23	Longitudinal Cracking	Light	Left side of left lane
24	Longitudinal Cracking	medium	Center line
25	Transverse Cracking	Light	Full width
26	Raveling	Medium	Left lane
27	Raveling	Medium	Right lane
28	Transverse Cracking	light	Left side of left lane
29	Perpendicular Joint	light	entire width

Figure 49: Distress observed on Aziëhavenweg

In-depth Comparison Analysis

Table 7 shows each distress area of interest and the comparison with each of the different data sets: Temperature contour maps (TCM) from both the methods and the compaction coverage. Connection with points of interest in the data will be given in the following ways: No connection with the data, possible connection with the data, connection with the data. If there is, or is possible, connection with the data then an explanation will be given as stated for the analysis of the A35, whether the data corresponds or not is based on the theory collected during the literature review.

No connection will be determined if:

- the distress is in an area where there are not noticeable temperature homogeneity changes or
- if it is located in an area where there was good roller coverage (30 to 20 roller passes)

Possible connection will be determined if:

- the distress is in an area with temperatures which are not desired, but not in a temperature transition area
- the distress is in an area with sub-par roller coverage (19 to 10 roller passes)

Connection will be determined if:

- the distress is located on an area which saw a significant temperature homogeneity change (>20 °C)
- the distress in in an area which was roller very little (9 to 0 roller passes)

Table 7: Distress and Paving Operations Connection Comparison

Distress Location	**TCM method 1**	**TCM Method 2**	**Compaction Coverage**
Point 5, 6, 7 and 9: Light Transverse Cracking	No connection with the data	No connection with the data	No connection with the data
Point 8: Light Raveling	No connection with the data	No connection with the data	No connection with the data
Point 10: Light Raveling	No connection with the data	Possible connection with the data - within an area that s significantly cooler than desired (110 °C), but not near a homogeneity change	No connection with the data
Points 11, 12 and 13: Connected Heavy Longitudinal and Transverse Cracking	Possible connection with data - Near, but not on, a temperature transitions area	Possible connection with the data - In a low temperature area	Possible connection with the data - the cracking is in an area where only 10 roller passes were experienced. Additionally, cracks are connected
Points 14-17: Patching	Connection with the data - within an area where the temperature drops from 150-160 °C to 110-120 °C	Connection with the data - in an area where the temperature is significantly lower (90-100 °C) and near a transition from cold to hot (90 °C to 140-150 °C)	Connection with the data - in an area with low compaction coverage on map (7-5 passes)
Point 18: Light Raveling	Connection with the data	No connection with the data	No connection with the data

	- in an area where the temperature changes rapidly from 150-160 ºC to 110-120 ºC		
Point 19: Light Raveling	No connection with the data	No connection with the data	Possible connection with the data - in an area with roughly 15 roller passes
Point 26: Light Raveling	Possible connection with the data - Slightly off of the TCM, but next to a location with a severe stop/cold spot (<100 ºC)	No connection with the data	No connection with the data
Point 27 and 28: Light Longitudinal Cracking	Connection with the data - Exactly in a cold stop area where the temperature changes from 150-160ºC to under 100ºC	No connection with the data	Connection with the data - On the side of the road where this is located very few roller passes were used (5-6)
Point 29: Light Transverse Cracking	Connection with data - In an area where temperature changes from 150ºC to 120ºC	Possible Connection with data - In a colder are, but not near a transition	Connection with the data - On the side of the road where this is located very few roller passes were used (5-6)
Points 30, 31 and 32: Light Longitudinal Cracking	No connection with the data	Possible Connection with data - In a colder are, but not near a transition	Connection with the data - On the side of the road where this is located very few roller passes were used (<5)
Points 33 and 34: Medium Longitudinal Cracking	No connection with the data	Possible Connection with data - In a colder are, but not near a transition	No data available

The previous analysis was performed by overlaying the distress data with the paving data. The following images show the relevant data for each of the areas discussed above:

- Point 5, 6, 7 and 9: Light Transverse Cracking

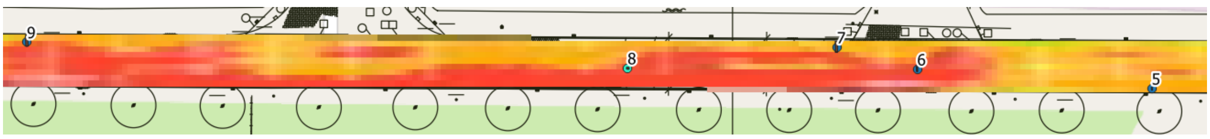


Figure 50: Point 5, 6, 7 and 9 TCM Method 1

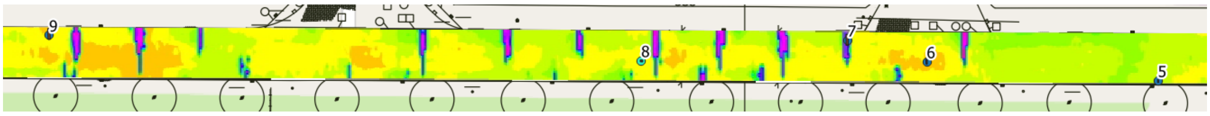


Figure 51: Point 5, 6, 7 and 9 TCM Method 2

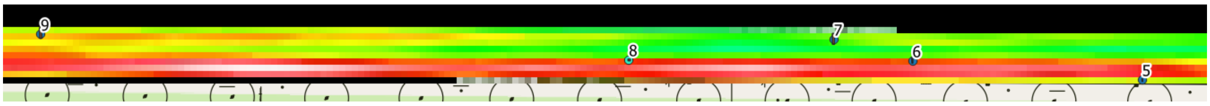
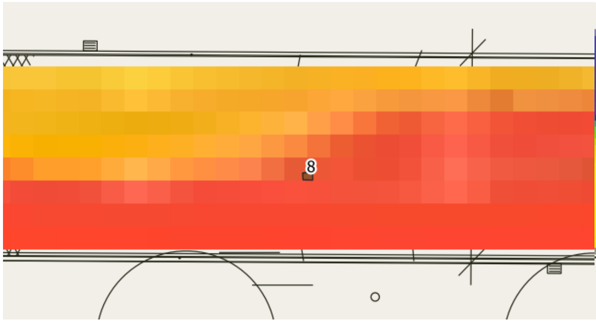


Figure 52: Point 5, 6, 7 and 9 Roller Passes Map

- Point 8: light raveling



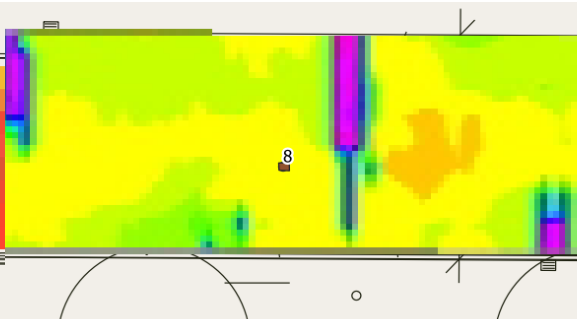


Figure 53: Point 8 TCM Method 1

Figure 54: Point 8 TCM Method 2

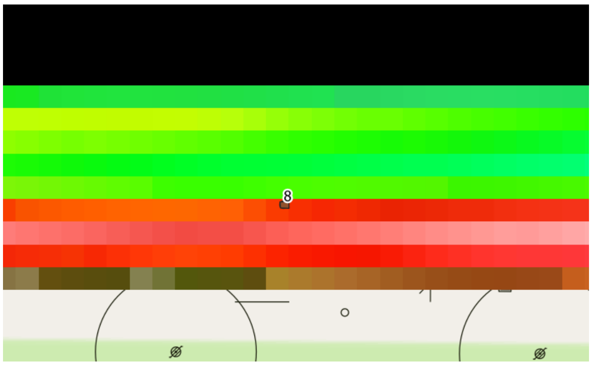
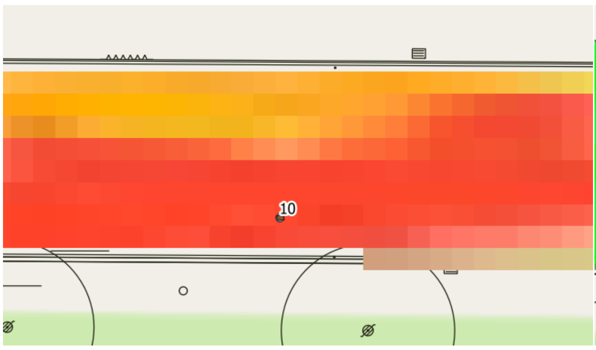


Figure 55: Point 8 Roller Passes Map

- Point 10: light raveling



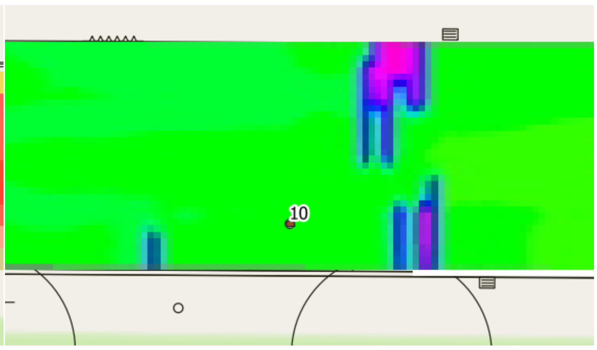


Figure 56: Point 10 TCM Method 1

Figure 57: Point 10 TCM Method 2

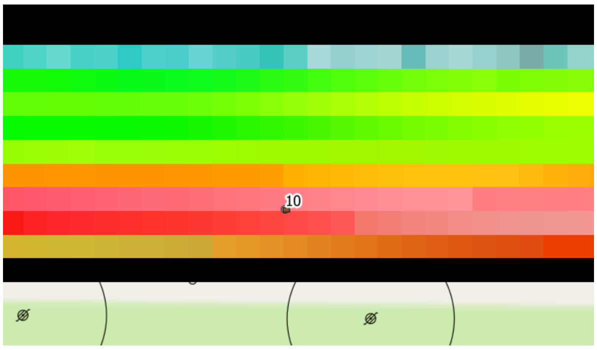
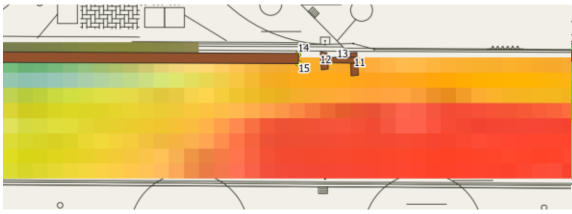


Figure 58: Point 10 Roller Passes Map

- Points 11, 12 and 13: Connected Heavy Longitudinal and Transverse Cracking



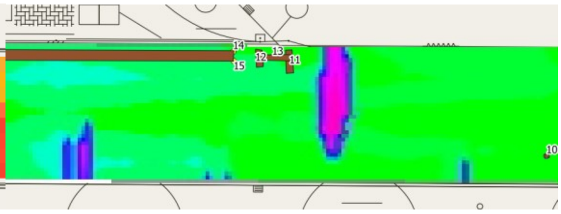


Figure 59: Points 11, 12 and 13 TCM Method 2

Figure 60: Points 11, 12 and 13 TCM Method 1

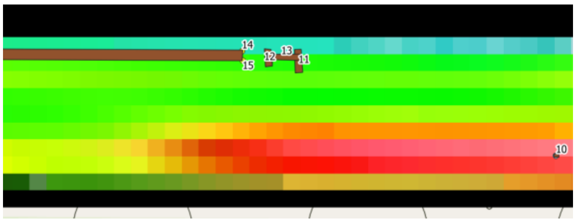
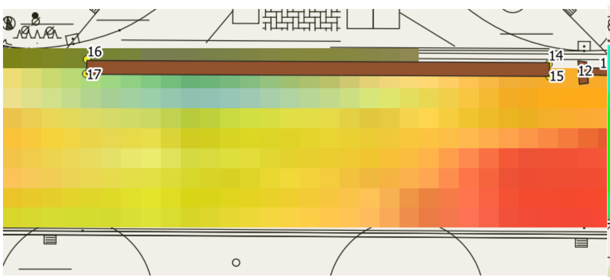


Figure 61: Points 11, 12 and 13 Roller Passes Map

- Points 14-17: patching



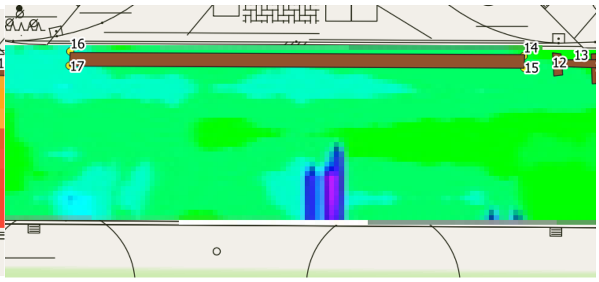


Figure 62: Points 14-17 TCM Method 1

Figure 63: Points 14-17 TCM Method 2

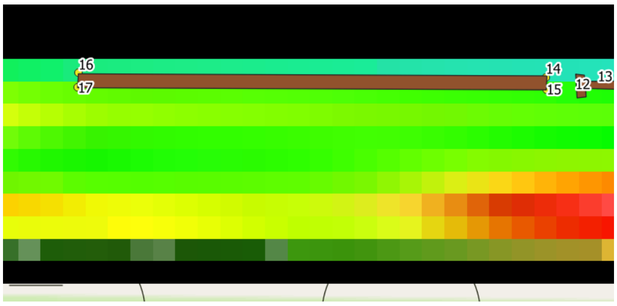


Figure 64: Points 14-17 Roller Passes Map

- Point 18: light raveling

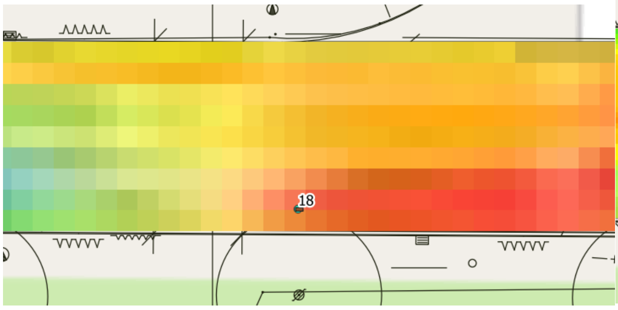


Figure 65: Point 18 TCM Method 1

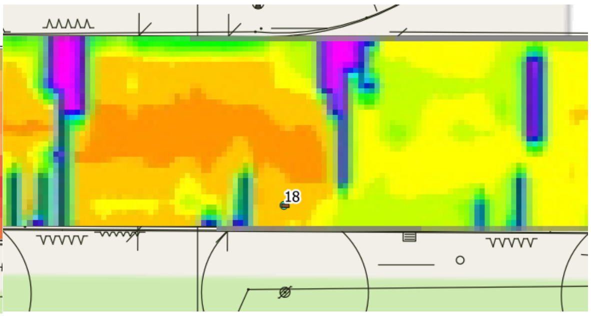


Figure 66: Point 18 TCM Method 2

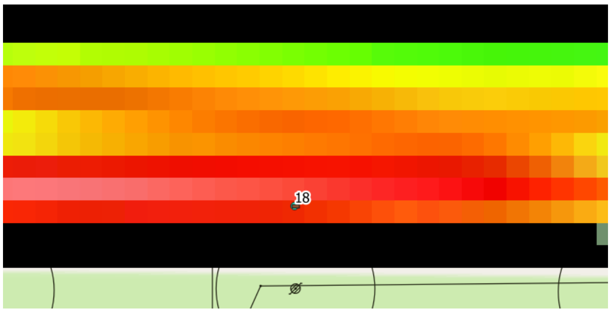


Figure 67: Point 18 Roller Passes Map

- Point 19: light raveling

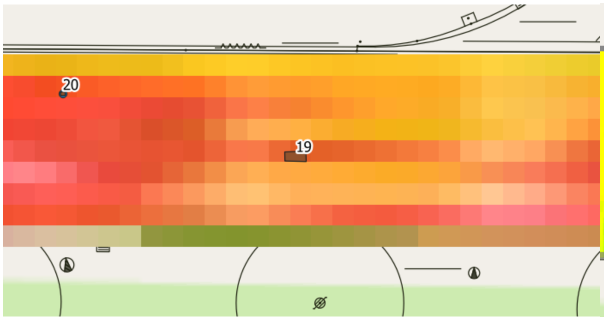


Figure 68: Point 19 TCM Method 1

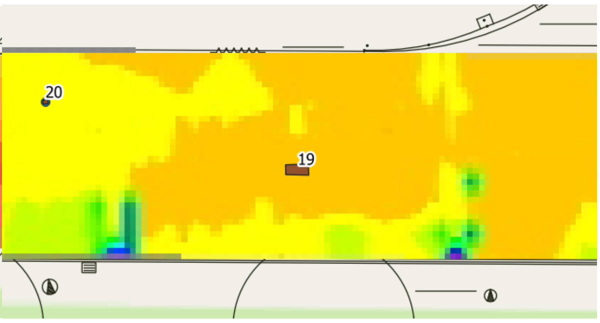


Figure 69: Point 19 TCM Method 2

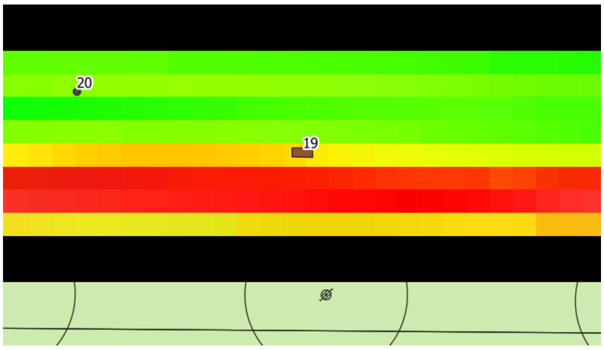


Figure 70: Point 19 Roller Passes Map

- Point 26: light raveling

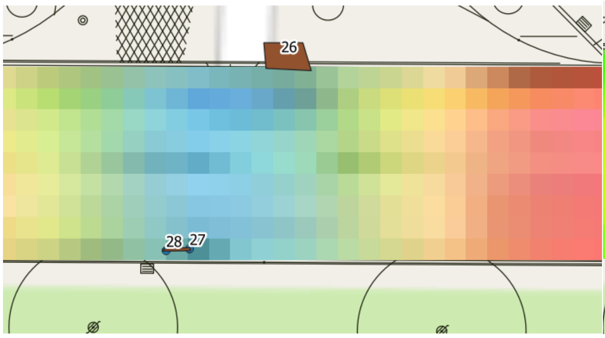


Figure 71: Point 26 TCM Method 1

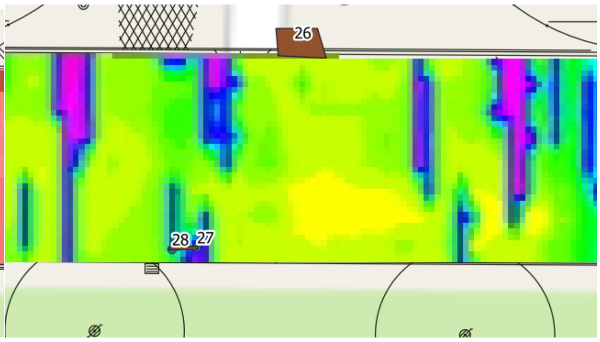


Figure 72: Point 26 TCM Method 2

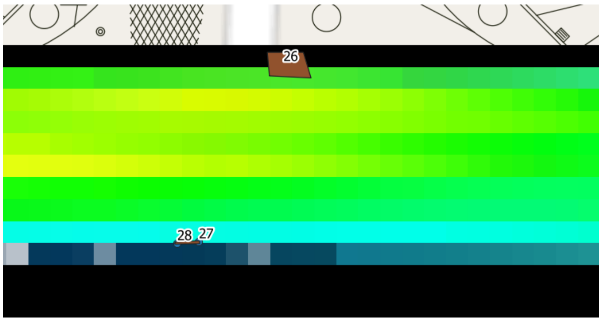


Figure 73: Point 26 Roller Passes Map

- Point 27 and 28: Light Longitudinal Cracking

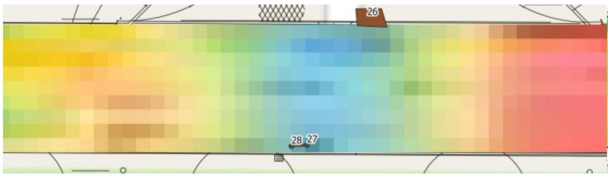


Figure 74: Point 27 and 28 TCM Method 2

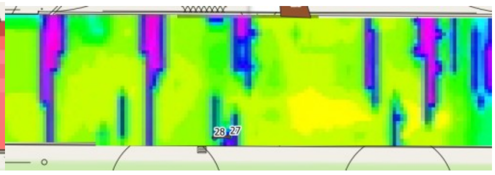


Figure 75: Point 27 and 28 TCM Method 1

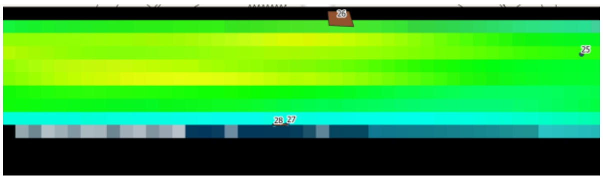


Figure 76: Point 27 and 28 Roller Passes Map

- Point 29: Light Transverse Cracking

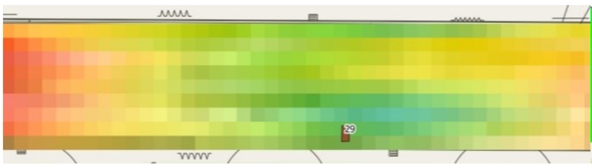


Figure 77: Point 29 TCM Method 2

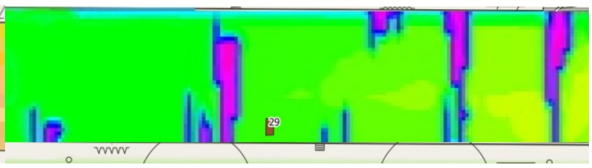


Figure 78: Point 29 TCM Method 1

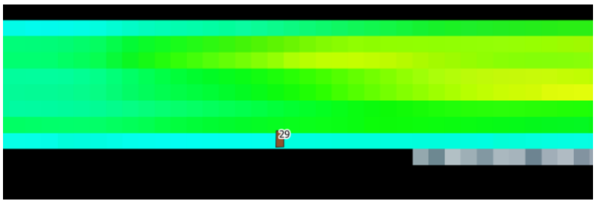


Figure 79: Point 29 Roller Passes Map

- Points 30, 31 and 32: Light Longitudinal Cracking

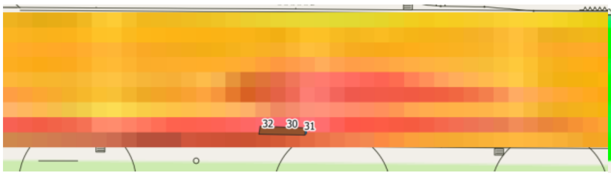


Figure 80: Points 30, 31 and 32 TCM Method 2

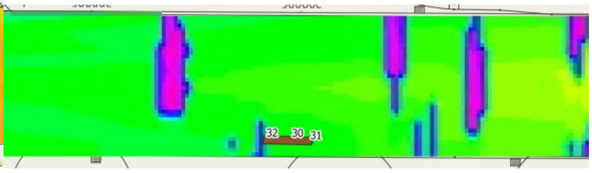


Figure 81: Points 30, 31 and 32 TCM Method 1

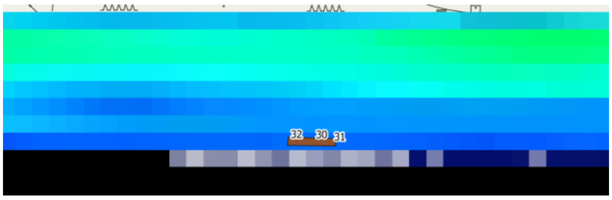


Figure 82: Points 30, 31 and 32 Roller Passes Map

- Points 33 and 34: Medium Longitudinal Cracking

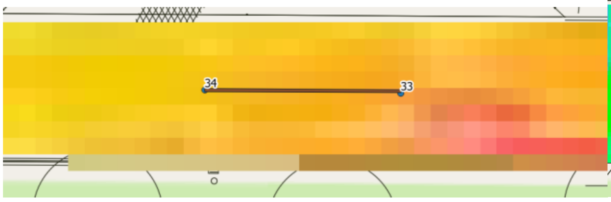


Figure 83: Points 33 and 34 TCM Method 2

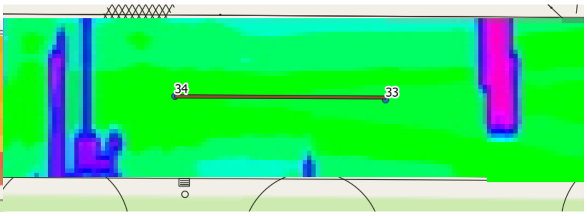


Figure 84: Points 33 and 34 TCM Method 1