Heating of porous asphalt for in-situ recycling

A contribution to the development of an Asphalt Recycling Train in the Netherlands

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Terminology

TERM	DEFINITION
AC	Asphalt concrete
Aggregates	All rock particles in an asphalt mixture whose diameter is greater than 2mm
ART	Asphalt Recycling Train
Asphalt	Homogenous mixture of coarse and fine aggregates, filler material and bitumen used for pavement construction
Binder	See bitumen
Bitumen	Black mixture of hydrocarbons with viscoelastic properties used as binder in asphalt mixtures
Compacting	Driving out voids of an asphalt mixture, rearranging particles
Course	Layer of pavement constructed from a single material
Deterioration	Declining of quality
Enthalpy	Internal energy of a system
Finishing	See paving
Mastic	Combination of bitumen, filler and sand. All particles within asphalt mixture with a diameter less then 2mm
Mortar	Combination of bitumen and filler material
PA	Porous Asphalt according to the European Union NEN standards
Pavement	All asphalt layers in a road
Paving	Levelling of asphalt mixture
RA	Recycled asphalt, conventionally gained from cold milling aged asphalt pavements
RAP	Recycled Asphalt Particles, see RA
RPM	Rotations per minute
SMA	Stone mastic asphalt,
Straight penetration bitumen	Pure bitumen without any modifications
Superheated steam	Water whose temperature is above boiling point at a certain pressure, thus above 100 degrees Celsius for atmospheric pressure
ZOAB	Porous Asphalt according to the Dutch RAW definitions

Summary

The Asphalt Recycling Train is a concept to recycle a distressed road in-situ by using multiple mobile machines which are able to recycle the asphalt. The front of the ART heats the asphalt to a temperature at which it can be loosened without fracturing the aggregates in the asphalt, after which the reclaimed asphalt is rejuvenated and paved again. Since there is no need for trucks hauling old asphalt and delivering new asphalt, this method could be more sustainable than the conventional process of maintaining a distressed road. Since over 90% of the Dutch national highways have Porous Asphalt as a surface course, which has a short lifespan of around 10 years, the aim of this research was to research the ART which can 100% recycle PA courses. There are 2 types of PA applied in the Netherlands, namely single-layered and double-layered PA, where the latter is more difficult to recycle due to the interlocking of the smaller aggregates of the top layer into the coarse bottom layer. For single-layered PA, the minimal percentage of internal voids is 20% with a maximum course thickness of 60mm. Since recycling of PA in a new PA mixture is prohibited by the guidelines, the use of an ART to recycle 100% PA should always be specified in the contract between client and contractor.

To recycle an aged PA course without devaluation, such as fracturing aggregate, the hot in-place recycling method must be used. Hot in-place recycling consists of pre-heating, loosening, reconditioning, post-heating, homogenizing, paving and compacting. Loosening of PA can theoretically be performed at 106 °C, without fracturing aggregate, where the heating step heats the PA to this temperature. Homogenizing the reclaimed PA with additives for rejuvenation and restoring the gradation if needed needs at least 100 °C. According to the circle of Sinner, a higher mixing temperature results in less need for an aggressive additive, mechanical impact or mixing time. Paving and compaction require at least 113 °C and 125 °C respectively. Since a lot of heat is lost to the base course when heating PA, an ART should be designed such that the temperature can be increased before or during the mixing phase using a drum mixer for instance to be more effective.

To determine the most effective method of heating a PA course between hot air, superheated steam or infrared, first, the thermodynamic relations and properties were reviewed for these methods. For all methods, surface area is of great importance, as the temperature difference between the infrared heater / hot gas and the PA. Since hot gas can also heat the PA in the internal voids, the surface area when using hot gas is far greater than when using infrared. Steam holds at least 2 times more energy than hot air for the same temperature, where steam releases a great amount of heat when it condenses. During condensation, the temperature of the steam stays the same, such that the temperature difference stays high between the steam and the PA, whereas hot air always cools of when transferring heat.

Modelling the heat transfer from hot gas to PA involves a great number of parameters, such that the creation of an accurate model was left out of this research. Experiments on heating bitumen showed that at low temperatures the heat transfer within the bitumen is low due to its low conductivity, where at higher temperatures natural convection increases causing increased heat transfer. A test section was constructed to test steam heating and infrared heating. Thermocouple readings registered the temperature increase over depth for both experiments. It was determined that a temperature of 70 °C was sufficient to loosen the PA without aggregate fracturing. It was observed that it took 35 minutes using steam and 54 to 84 minutes using intermitting infrared to heat the PA to a minimal temperature of 70 °C using steam, infrared and infrared, respectively.

Since it was the fasted in heating the PA course, superheated steam is observed to be the best method in heating PA taking duration into account. To determine the optimal temperature of the superheated steam, and the energy efficiency, the heat transfer coefficient of convective heat transfer for steam heating should be determined in future research. Since there is no common minimum temperature for all process steps in an ART for recycling PA, designing an ART which can heat the reclaimed PA in between or during the process steps, using a drum mixer heater for example, is favourable. Future research will involve determining the impact of construction and use on the gradation of PA and how the binder in aged PA can be rejuvenated such that the recycled PA is as good as new PA.

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1. Introduction

1.1 Project framework

Dura Vermeer is one of the major Dutch contractors specialized in infrastructure as well as construction of real estate. In 2017, 900.000 tonnes of asphalt were produced in the two asphalt plants owned by Dura Vermeer and shared plants [1]. At Dura Vermeer, the ambition is to make the construction and maintenance of infrastructure more sustainable to help clients meet their environmental goals using new methods like the 100% recycling of old asphalt courses [2]. This ambition led to internal research on the Asphalt Recycling Train concept. In 2005, an offer was made to Rijkswaterstaat, the Dutch government agency involved in constructing and maintaining all national and provincial main roads in the Netherlands, for the use of a foreign ART on the A7 highway. This offer was unfortunately rejected, where this idea was represented at Rijkswaterstaat during a so-called “attic clean-up”. In 2018, the idea of 100% recycling of porous asphalt surfaces in-situ with an Asphalt Recycling Train was used in a competition for sustainable asphalt at Rijkswaterstaat, which was rewarded with the maximum score [3]. In 2019, Dura Vermeer received 150.000- euro from Rijkswaterstaat to use for the development of the Asphalt Recycling Train in the Netherlands [4].

The idea of the Asphalt Recycling Train already exists for a long time but has only been widely implemented in foreign countries like the USA, Canada and China. [5] [6]. In the Netherlands, an ART was first used in 1979 applying the repave technique, where the surface course is recycled and paved over by new asphalt [7]. In 1988, the remix technique was first performed, where both techniques were both further researched from 1991 to 1995 by Rijkswaterstaat using the Wirtgen Remixer [8] . It was found out that the recycling process using the Wirtgen Remixer was very vulnerable to weather effects such as low temperatures, wind and moisture. The results however were promising, and further research and tests were recommended, which unfortunately did not happen.

Because of the increasing interest in more sustainable asphalt, which resulted in the sustainable asphalt competition by Rijkswaterstaat, Dura Vermeer’s aim is to further research the Asphalt Recycling Train concept to develop an implementation of the Asphalt Recycling Train in the Netherlands to achieve 100% recycling of PA courses in situ. The proposed research on the ART includes the following aspects:

- How PA courses can be heated without devaluation, such as fracturing the aggregates and short term binder aging
- The use and effect of heat in an Asphalt Recycling Train
- An actualisation of the techniques used in Asphalt Recycling Trains
- Which heating methods can be used for heating PA
- How the gradation of aggregates is impacted by construction and use of a PA course
- How the PA binder can be rejuvenated

This research will focus on the first three aspects, as further specified by this research’ aim.

1.2 Aim

The aim of this research is to contribute to the development of an implementation of the Asphalt Recycling Train in the Netherlands to achieve 100% recycling of PA courses in-situ by assessing the use and effect of heat in an Asphalt Recycling Train using a literature review. This literature review will focus on the characteristics of PA important for 100% recycling and heating, the use and effect of heat in an ART and the fundamentals of heat transfer. Also, three different heating methods, such as superheated steam, hot air and infrared heating will be evaluated and compared on efficiency and time using field tests.

1.3 Research model

The research model provides an insight and oversight of the research, mainly on the dynamic contained within the research. Furthermore, the research model helps in developing the research questions and phases of the research. In the method from Verschuren & Doorewaard, the making of such a research model is described [9]. The research model can be seen in Figure 1 . Here, ↕ means a confrontation between 2 research objects and → means drawing a conclusion from that confrontation.

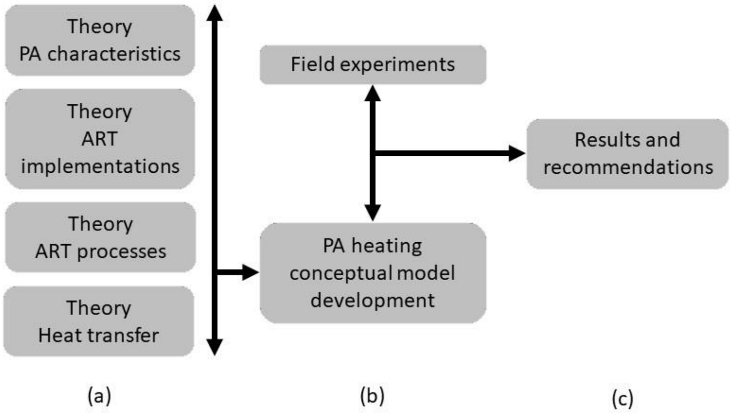

Figure 1: Research Model

Per phase, a short description will be given.
In (a), theoretical analysis will be performed on the processes within an Asphalt Recycling Train, and which influence heat has in these processes. Existing implementations for these processes will be looked after, with focus on the heating methods of asphalt courses. Important characteristics of PA such as thermodynamic characteristics and recycling requirements will also be reviewed. Finally, study will be devoted on the heat transfer fundamentals.
In (b), this knowledge will be used to develop the basics of a conceptual model which will be able to describe the heating of PA using hot air or superheated steam. Field experiments will be performed to generate calibration and validation data for the model. Furthermore, these field experiments provide a direct insight in the theoretical efficiency of these methods. In (c), the results from both phases will be evaluated and concluded, which will lead to the recommendations done on which heating method to use for PA heating in an ART of the heating methods used in this research.

1.4 Research questions

The central question of this research, resulting from the aim, can be formulated as such:
What use and effect does heat have on the processes within an Asphalt Recycling Train for recycling 100% PA in-situ, and which method for heating a PA course performs best on efficiency?
This central question will be answered by using several sub-questions, which are determined by using the research model given in Figure 1. Here, the sub-questions are split into 4 phases according to the research model.

Phase (a): Theoretical analysis

- What are the characteristics of PA important for the 100% recycling of PA in an ART?
    - What is PA according to Dutch regulations?
    - What are the requirements to the recycling of PA?
    - What are the thermodynamic characteristics of PA?
- What are the use and effects of heat on the process steps within an Asphalt Recycling Train?
    - What are the process steps within an ART?
    - How do existing implementations of an ART fill in these processes?
    - What are the use and effects of heat in each process within an ART?
- How does heat transfer from hot air or superheated steam to PA?
    - What are the thermodynamic characteristics of hot air and superheated steam?

Phase (b): Experimental analysis

- How can the heating of a PA course be described using hot air and superheated steam?
- How does the temperature increase of bitumen when heated?
- How does the temperature of the heated PA develop over depth in field experiments for steam and infrared heating?
    - At which temperature can PA be loosened without causing aggregate fracturing?

Phase (c): Evaluate and discuss

- What is the minimal temperature needed for the PA course to be recycled in an Asphalt Recycling Train?
- Which heating method uses the least time and energy to heat PA course?
- What is the optimal layout of an ART?

1.5 Research methods

In this research, 3 different strategies will be used to achieve its aim. These are a desk study, based on literature reviews. A simulation based on the developed heating model. And finally, field tests, where the heating models will be calibrated and validated. These strategies will be evaluated below on how they will be performed and what influence they have on each other.

Desk study; literature review

In the international quest to get more sustainable in using natural resources, the development of more sustainable methods in contrast to conventional methods is more than ever [10]. This quest is also present in the construction sector, though this sector is always believed to be slower in innovation than other sectors [11]. However, much research has already been done on the recycling of asphalt, since this is not only more sustainable, but also cost reducing [12] . The concept of the Asphalt Recycling Train has been along for a long time since 1930 and saw many implementations in foreign countries like the USA, Canada [5] and recently also China [6]. With this literature review, the sub-questions in the first phase as defined in Research questions will be answered. From these questions, knowledge is gained for the process steps in an ART and which influence heat has on them, as well as how a model can be developed to describe the heat transfer from hot air or superheated steam to PA courses.

Simulation; conceptual model development

In the simulation part of the research, a model will be developed to describe the heating of PA using hot air and superheated steam. This model will be developed using the knowledge gained on heat transfer in the theoretical analysis. The unvalidated model will then be used to predict the heating times for the field experiments. Using the results of the field experiments, the model will be calibrated and validated. Here, the assumptions done while developing the model will also be validated. Hereafter, the validated model can be used to run simulations to determine the efficiency and environmental impact of each method, which will be used in the conclusions of the research.

Experiment; field experiments

Using the field experiments, the models will be calibrated and validated. Using the unvalidated model, heating times for the field experiments will be predicted, which will be used to determine the measurement intervals during the experiment. These measurements can be compared with the output of the model, using the same conditions in the simulation as in the field experiment, such that the model can be calibrated and validated. Moreover, the field experiments will be used to test the assumptions done in the model. Since field experiment equipment was readily available, it was chosen to perform the field experiment directly without having a lab experiment. No literature was found on experience with superheated steam heating of PA, thus it was hard to say if a lab experiment shows the same results as a field experiment. The observations from the field experiments can be used to develop lab tests for further research.

2. Theoretical analysis

In the theoretical analysis of this research, the three research questions for phase (a) will be treated. First, the characteristics of PA important for its 100% recycling in an ART will be reviewed. Secondly, the influence of heat on process steps within an ART will be reviewed. Finally, theory about heat transfer from hot air and superheated steam to PA will be reviewed.

2.1 The use and effects of heat in an Asphalt Recycling Train

To understand the use and effects of heat in an ART, first, the procedures which can be implemented by an ART to recycle 100% PA will be reviewed. For these procedures, the process steps will be listed, where these steps will individually be analysed for the use and effects of heat on them. Finally, a review will be done on existing implementations of the ART on how these fulfil the process steps.

2.1.1 ART process steps

The Asphalt Recycling Train is a concept to perform in-situ recycling of asphalt surfaces. In-situ recycling of asphalt can be achieved in three different ways according to the Transportation Research Board [13], namely;

- Hot in-place recycling (HIR/HIPR)
- Cold in-place recycling (CIR/CIPR)
- Full depth reclamation (FDR)

HIR is applied when the majority of distresses to the pavement are limited to the upper centimetres of the surface course and there is no evidence of structural failure of the road like cracking or wheel paths. CIR is applied when more severe distresses extend further down from the surface, while FDR is mostly applied when reconstructing. Both CIR and FDR cold-mill the distressed road course, where the aggregate will be fractured, and will lead to devaluation since the gradation does not meet the requirements of a surface course after recycling. Since HIR heats the surface course to soften the mastic, the aggregate can be collected and renewed without fracturing, thus, the recycled asphalt is not devaluated by the HIR process. Therefore, only the HIR process will be studied in this research.

Hot In-Place Recycling

Shoenberger & Vollor [5] describe 4 processes in which HIR can be performed, namely:

- Reshaping
- Regripping
- Repaving
- Remixing

Reshaping and regripping will not be considered individually, since these processes are consequences of the HIR method. Repaving and remixing both involve improvement to the recycled asphalt, but to different extends. Repaving involves recycling the asphalt course after which a surface treatment or overlay with new asphalt mixture is applied. Remixing involves adding new mixture to the reclaimed asphalt where both are mixed together to gain quality improvement to the recycled asphalt and restore aggregate gradation if needed. Russel et al. [14] mentions surface recycling, which involves adding additives like rejuvenators to the reclaimed asphalt to improve the quality.
In this research, surface recycling and remixing will be considered.

Surface recycling and Remixing

Where surface recycling only allows additives to be added to the reclaimed asphalt, remixing also allows new asphalt mixture to be added to improve quality and restore gradation. Therefore, these processes are mostly the same, where they only differ on what materials can be added. Thus, for both process steps, the process steps can be described as the following:

1. Pre-heating of the asphalt surface
2. Loosening of the asphalt surface
3. Reconditioning the reclaimed asphalt
4. Post-heating the recycled asphalt mixture

5. Homogenizing of the recycled asphalt mixture
6. Paving/Finishing of the recycled asphalt
7. Compacting the recycled asphalt

A visualisation of these process steps in an ART for the remixing procedure is provided in Figure 2.

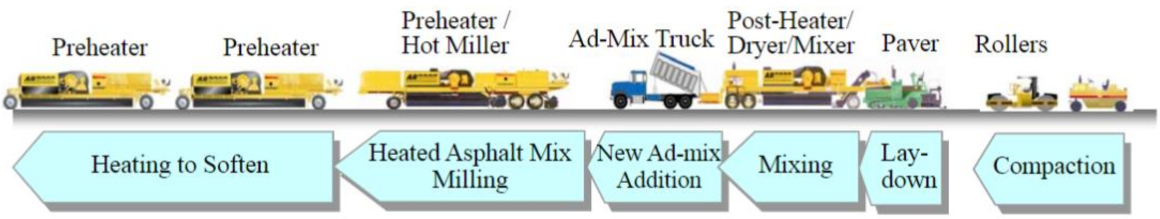

Figure 2: Martec AR2000 Asphalt Recycling Train processes

Here, the only difference between surface recycling and remixing is in step 3, but the individual processes are still the same.
Russel et al. [14] also mention the possibility for a multi-stage process, where the first two steps, heating and loosening of the asphalt surface, are performed in multiple passes to reach a greater depth. This however does not change the individual processes performed by HIR surface recycling nor remixing.

2.1.3 Existing implementations

The processes of an ART are heating, loosening, mixing, paving and compacting for both surface recycling as remixing procedures. Therefore, only ART implementations that can perform at least surface recycling or remixing will be considered.
Finlayson et al. [15] describe the development of the ART from the 1970's to 2010. These developments mainly involved heating methods used, where the first ARTs used open flames for heating, after which infrared was more commonly used where now hot air heating is used by the more innovative ARTs. In this development, propane fuel was replaced by diesel fuel, and the severe emissions from open flame heating went to minimal emissions using hot air heating. In Table 1, an overview of the reviewed ART implementations is given.

Name	Year	Procedure(s)	Pre-heating	Loosening	Post-heating	Homogenizing
Martec AR2000 [16]	1995	Surface recycling, Remixing	Hot air / low-level IR	Hot milling	Hot air / low-level IR	Twin-shaft pugmill
Marini Voyager 120 + Martec AR2000 [17] [18]	2004	Surface recycling, Remixing	Hot air / low-level IR	Hot milling	Drum mixer heater	Drum mixer Twin-shaft pugmill
Ecopaver 400 [14], [19]	2014	Surface recycling, Remixing	Propane radiant IR (multi-stage)	Hot milling (multi-stage)	None	Twin-shaft pugmill
Freetech [6]	2009	Surface recycling, Remixing	Intermittent radiant IR	Pneumatic loaded scarifying	Intermittent radiant IR	Twin-shaft pugmill
Senyuan SY4500 [20]	2008	Surface recycling, Remixing	Hot air	Hot milling	Hot air	Twin-shaft pugmill
Wirtgen Remixer 4500 [21], [22]	1991	Surface recycling, Remixing, Repaving	Propane radiant IR	Rotating scarifying	None	Twin-shaft pugmill

Table 1: ART implementations

For each process, similarities and differences on how the different implementations fill in these processes will be discussed, where also available reports on practical experiences with an implementation will be reviewed.

Pre-heating

Two of the reviewed ART's use hot air to transfer heat to the asphalt course, where the others use infrared heating. Hot air heating was first used in 1995 by Martec, as a solution to reach a greater recycling depth without overheating or aggregate fracturing and with lower emissions compared to infrared heating [16].

Using the Martec AR2000, multiple road rehabilitation projects have been carried out in different countries, where this method has delivered good results. In Italy, the AR2000 was used to recycle a 5 kilometer stretch of PA highway, where it was found out that the AR2000 was easily capable to heat the PA to an excessive 210 degrees Celsius only using 2 preheaters using 600 °C hot air [23]. The Marini Voyager and the Martec AR2000 combination presented in Table 1 uses the pre-heating and loosening technology of the Martec ART, but replaces the reconditioning, post-heating and homogenizing stages using the technology of the Marini Voyager. The technologies of the latter stages are elaborated in the following sections.

The newest ART, the Ecopaver 400, uses IR heating instead of hot air, which raises the question if hot air is better than IR heating, since most of the new implementations still use IR heating, against the trend mentioned by Finlayson et al. [15]. The Ecopaver 400 accounts for the extra emissions by using an emission incinerator on the heating units. Furthermore, the problem of overheating the top surface of the asphalt surface is overcome by performing multi-stage heating/milling, where the heated top layer of the asphalt surface is hot-milled and transported over trailing heating unit using heated conveyors. This prevents overheating the top layer and enables a greater recycling depth in contrast to single-stage heating/milling using IR heating [19].

Freetech uses the reciprocating intermittent radiant IR heating method (RIHM) in its ART in contrast to one-way continuous heating method (OCHM) which is applied by the other IR heating ART's. Huang et al. [24] performed research on comparing RIHM and OCHM, where it was concluded that RIHM was more able to heat asphalt surfaces in a uniform way without risking overheating of the top layer. However, using RIHM, there was still a 50 degrees Celsius temperature difference between the top and bottom of a 4cm Stone Mastic Asphalt 13 (SMA 13) layer in a field test at a surface temperature of 100 degrees Celsius. In lab tests, the same comparison was researched by Xu et al. where the temperature difference between top and bottom using RIHM was measured to be 87 degrees Celsius for 4cm SMA 13 at a surface temperature of 187 degrees Celsius.

Loosening

For the loosening of the heated asphalt surface, scarifying as well as hot milling can be used. Freetech uses pneumatic loaded teeth as seen in Figure 4, which are fixed over the width but able to move up and down. The Wirtgen remixer uses rotating teeth, where the teeth are fixed on a rotating drum which is able to move up and down as seen in Figure 3. The teeth rip the heated asphalt surface course loose such that it can be windrowed using a worm to be recycled. The teeth cannot be fixed at a predetermined recycling depth since this could lead to the teeth breaking when the asphalt is not

Figure 3: Freetech scarifying teeth

Figure 4: Wirtgen rotating scarifiers

sufficiently heated. Benefit of this method however is that it is less aggressive than using milling heads.
All other reviewed ART's use milling heads to loosen the heated asphalt surface. Here, drums with teeth attached over the whole width, similar to cold-milling drums, rotate at low rotations per minute to loosen the asphalt surface. This method is more aggressive in contrast to the scarifying method, which could lead to a greater risk on aggregate fracturing. For all reviewed ART's, the loosened asphalt is windrowed to the middle of the base surface using worms, such that it can easily be transferred to the following mixing stage.
Beneficial to using a milling head is that the recycling depth is fixed, since the milling head is fixed at a predetermined depth. Clumps of reclaimed asphalt plugging the mixing stage are also prevented using milling heads, since these are able to break up these clumps due to the higher rotations per minute. For the scarifiers, the depth can vary since the teeth are not fixed at a predetermined depth, where downforce is applied by pneumatic cylinders or dead weight of the scarifiers. However, both the Wirtgen Remixer as the Freetech ART use worms to windrow the reclaimed asphalt, fixing these worms at a specific height minimizing the variation in recycling depth.

Reconditioning

When the reclaimed asphalt does not fulfil the requirements on gradation and its bitumen characteristics, it needs to be reconditioned by adding new materials. These materials can be aggregate, new asphalt mix, recycling agents, new bitumen or rejuvenators. Since all researched ART's as presented in Table 1 are able to perform remixing, they are all able to perform reconditioning using all materials as specified above. For example, the Martec AR2000' miller unit is equipped with both an additive and rejuvenator tank. Both are added in front the central milling drum, increasing the dispersion of these on the reclaimed asphalt. Corrective aggregate or new asphalt mix can be added using trucks via a hopper mounted in front of the mixing unit. The hopper unloads directly above the windrow of reclaimed asphalt, where the flow of material is controlled by a computer. For the addition of aggregates or new asphalt mix, the other ART's work in a similar way, where the coarse material is always added after the loosening stage and before the mixing stage. For all ART's, liquid materials can be added during the loosening stage, where it is assumed that the milling heads / rotating scarifiers provide a good dispersion of the fluids on the reclaimed asphalt.

Post-heating

In the post-heating stage, more heat can be added to the recycled asphalt mixture when this is needed for the following stages. As can be seen from Table 1, the Wirtgen Remixer and the Ecopaver 400 cannot perform post-heating in their standard setup, therefore, all heat to the reclaimed asphalt must be applied in the pre-heating stage. For the Freetech ART, the ART is able to post-heat the windrow of reclaimed asphalt using intermittent IR, but this ART is also able to heat the base asphalt course using intermittent IR, to provide good adhesion between the base course and the recycled surface course. The Martec and Senyuan ART's both spread out the reclaimed asphalt with additives after loosening on the base course, after which it can be post-heated using hot air and low-level IR. This also heats the base course, but to less extend than the Freetech ART.
The Marini Voyager 120 uses a drum mixer heater to apply heat to the recycled asphalt mixture including additives. The asphalt collecting machine and drum mixer can be seen in Figure 5 and Figure 6.

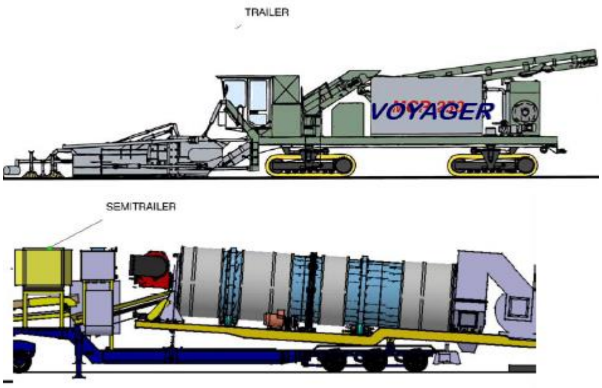

Figure 6: Pavimental collector and drum mixer [18]

Figure 5: Marini drum mixer [17]

The use of a drum mixer heater can be considered more efficient since no to little heat is lost to the base course and surroundings, and therefore, more heat can be applied to the recycled mixture resulting in less need of pre-heating and enlarging the capacity of the ART. However, in the standard setup of the Marini ART, there is no heat applied to the base course after pre-heating, which might lead to improper adhesion between the base course and recycled surface course.

Homogenizing

Homogenizing the reclaimed asphalt with new asphalt mix, recycling agents, new bitumen or rejuvenators is performed in multiple stages by most reviewed ART’s. Liquid additives are added in front of the milling units of the ART’s, where these milling units perform the initial homogenizing of these liquids with the reclaimed asphalt.
The Marini ART uses a drum mixer heater to perform post-heating of the recycled mixture including all additives. This drum mixer also homogenizes the recycled mixture to some extent.
For all ART’s, the final homogenization is performed by a twin-shaft pugmill. Here, the reclaimed asphalt is mixed with all additives, such that this results in a homogeneous recycled asphalt mixture to be paved. All ART’s but the Wirtgen Remixer collect the recycled asphalt mixture in a closed pugmill at height, after which the mixture is directly unloaded in a following paver. Since the Wirtgen Remixer is equipped with a paving screed, there is no need to collect the windrow of recycled asphalt from the base course, such that it is homogenized using a twin-shaft pugmill floating above the base course.

Paving/Finishing

For all reviewed ART’s except the Wirtgen Remixer, the paving is performed by a conventional paver which is fed with recycled asphalt mix by the ART itself. Therefore, it is possible to use these pavers not only for the ART, but also for conventional paving where the paver is fed by trucks. The Wirtgen Remixer is fitted with a built-in screed, which eliminates the need for a paver.
New innovations such as an oscillating screed, which is currently being researched at Dura Vermeer, could achieve paving without the need of compacting to reach the target density, where a roller is only needed due to the temperature shrinkage of the bitumen.

Figure 7: Oscillating screed test setup

Compacting

For all reviewed ART's, the final compacting is performed using conventional rollers. These conventional rollers can thus both be used for the ART as for conventional paving. Most conventional rollers are 2-wheel, 3-wheel or pneumatic tire rollers. The need for compacting could be eliminated using innovative paving techniques like an oscillating screed, where a roller is only needed due to the bitumen shrinkage due to the temperature drop.

2.1.3 Use and effects of heat on each process step

As the name hot in place recycling suggests, heat is needed for this procedure. However, it is important to know what the use and effects of heat are in each separate process step of HIR to determine the minimal temperature required in an ART and the maximum temperate above which the recycled PA is devalued by extreme aging / burning of the bitumen.

Pre-heating

The first stage of the HIR process is heating the PA surface course, where the temperature of the asphalt surface course is increased for the next processes. Though the required temperature of the asphalt course is mostly determined by the subsequent processes, the effect of heat on the PA surface course quality is important to consider.

When a PA surface course is needed to be recycled because of its deficiencies, it received a substantial amount of aging. Aging is caused by the oxidation of bitumen [25], where short term aging occurs during production and application of the asphalt at high temperatures [26]. Thus, short term aging will also occur when a PA surface course is heated by the ART. Yener and Hinislioglu [27] studied the influence of exposure time and temperature on the aging of bitumen, where their results can be seen in Figure 8. They concluded that bitumen ages substantially more at higher temperatures, where also exposure time makes a great difference at temperatures above 135 °C.

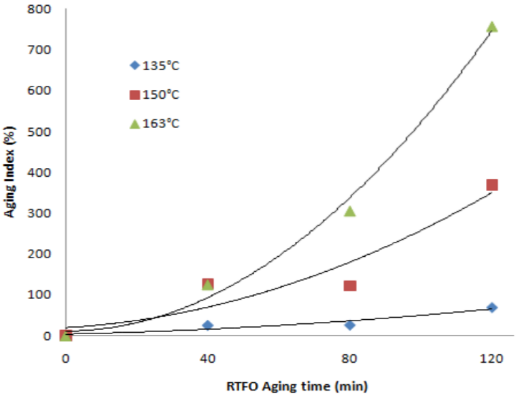

Figure 8: Effect of aging conditions on aging index

Sarnowski et al. [28] performed research on the overheating phenomenon of bitumen. Here, the temperature limit for fresh bitumen was determined around 230 °C, where the exact limit is dependent on the grading, composition and volumetric properties of the asphalt course, mastic and binder. When the binder reaches a temperature above this limit, loss of viscoelastic properties occurs in the material which can lead to loss of resistance to fatigue cracking of the asphalt course. It was found out that more open structured asphalt mixtures like SMA were less sensitive to overheating than dense mixtures like AC. Also, polymer modified bitumen were found out to have a lower temperature limit than normal bitumen.
Note that these experiments were performed on fresh bitumen, where an ART will deal with aged bitumen. There was no literature on research found on the short-term aging effects on aged bitumen without the addition of additives. Though no research was found on the exact emissions of (over)heated bitumen, it is expected that higher temperatures will result in more emissions which can have impact on the environment.

Loosening

The second stage of the HIR process is the loosening of the asphalt surface course, where the surface course is loosened such that the black aggregates can be collected for the following stages. For conventional asphalt maintenance projects, the surface course is cold-milled, but this also causes aggregate fracturing. Therefore, the surface course is pre-heated before it is loosened, such that no aggregate fracturing occurs. For the loosening of the asphalt, it is important to know what the minimal temperature needed is without causing fracturing. Though there are multiple different ART implementations applying HIR, there is no research found on this minimal temperature needed. Therefore, a simple approximation will be done on this minimal temperature.
Bitumen is a viscoelastic material, which displays viscous and elastic behaviour, depending on temperature, time and loading [29]. At sufficiently high temperatures, bitumen is essentially a Newtonian liquid, and can be described by a shear rate independent viscosity value [29]. Therefore, the shear force when loosening a surface course can be described by Equation 2.

$$F = \mu A \frac{u}{y} \quad (2)$$

Where:
F = Magnitude of force acting on the aggregate (N)
μ = Viscosity of the fluid (pa s)
A = Area of binder contact between aggregates
u = The shear speed
y = The thickness of the binder between the aggregate

Here, μ is dependent on the temperature of the PA course, where F should not be higher than the shear strength of the aggregate. u is equal to the speed of the ART if scarifiers are used. When rotating scarifiers or milling heads are used, u will be higher. The viscous fluid between the aggregate is not solely bitumen however, but mastic. Relations between the stiffness of bitumen, mortar and mastic were found, but these could not be directly related to the viscosity [30]. Therefore, the viscosity of aged bitumen will be used for this calculation. Nilsgart and Grybb [31] determined the relation between the temperature and viscosity of aged bitumen, which is given in Equation 3.

$$\log\left(\frac{\eta}{\eta_{ref}}\right) = -\frac{C1(T-T_{ref})}{C2+T-T_{ref}} \text{ [31] [32] [33] } (3)$$

Further explanation of this formula and parameters can be found in Appendix C, together with the calculations for theoretical minimal temperature for loosening PA without aggregate fracturing.
Both these relations were used to determine the minimal temperature needed for loosening a PA course with minimal aggregate fracture in Appendix C which was determined at 106 °C. Note that this

is fully dependent on the characteristics of the aged bitumen in the asphalt course, such as age, initial viscosity et cetera.

Reconditioning

In the reconditioning stage of HIR, new materials are added to the reclaimed asphalt, such as new asphalt mix, corrective aggregates, bitumen, recycling agents or rejuvenators. This stage does not prescribe a specific minimal temperature of the reclaimed asphalt nor to the added materials, but the following steps do. After pre-heating, the reclaimed asphalt is of a higher temperature, which is beneficial for the homogenizing stage. Adding new materials with a lower temperature than the reclaimed asphalt will lower the temperature of recycled asphalt mixture. However, the extend of this temperature drop is dependent on the mass percentage of the added materials to the reclaimed asphalt, combined with the specific heat capacity of the materials.

When only a small amount of new materials is added to the reclaimed asphalt, it may be beneficial to the logistics and ART design not to heat the materials. For corrective aggregates and new asphalt mix, this won't have major consequences. However, for added fluids, such as bitumen, rejuvenator or agents, the dispersion of these fluids on the reclaimed asphalt can be negatively influenced when these fluids are viscous at low temperatures. Therefore, low temperature aggregates and asphalt mix can be added if only small amounts are needed, but viscous fluids should always d be added at a temperature where they are able to disperse well on the reclaimed asphalt.

On the other hand, adding new materials with a higher temperature than the reclaimed asphalt will cause a temperature increase. Again, this increase is dependent on the quantity of new materials added and the specific heat capacities. When high quantities are added however, the need for post-heating can be minimalized, thus simplifying the ART design or increasing the capacity. However, the temperature of the new materials should not be that high such that the quality of the reclaimed asphalt and new materials is damaged.

Post-heating

In the post-heating phase, extra heat can be added to the recycled asphalt. Also, the base course can be heated to provide a better adhesion between the base course and the recycled surface course.

When post-heating is available, there is less need for extensive pre-heating. The pre-heating stage can heat the surface course to a temperature at which it can be loosened, after which the post-heating stage can heat the recycled asphalt to a temperature at which it can be homogenized, paved and compacted. Therefore, when post-heating is available, the minimal temperature needed in the pre-heating stage is determined only by the loosening phase, whereas the minimal temperature needed in the post-heating phase is set by the homogenizing, paving or compacting phase.

When post-heating is applied, the temperature of the recycled asphalt should not be too high such that the bitumen and additives are damaged.

Homogenizing

In the homogenizing stage of HIR, the reclaimed asphalt is mixed with the additives to ensure the recycled asphalt mix has better properties than the asphalt before it was recycled. The additives can be rejuvenators, recycling agents, new bitumen or new asphalt mixture, added during the reconditioning stage. When these components enter the homogenizing stage, the total mix can be considered heterogenous, whereas the goal of the homogenizing stage is to get a homogenous asphalt mixture.

To obtain a homogenous mix of the reclaimed asphalt and additives, Sinner's circle can be applied, as visualised in Figure 9.

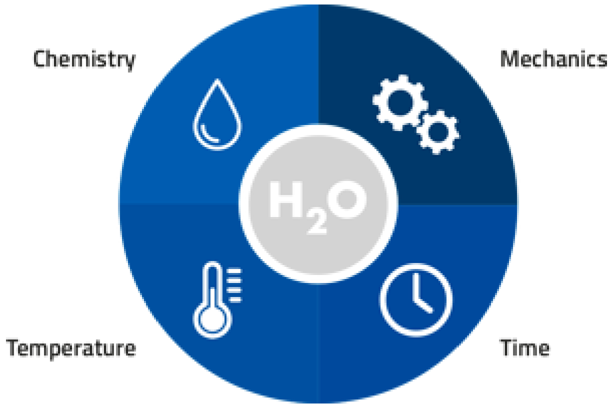

Figure 9 : Sinner's circle [34]

Though Sinner's circle is developed for use in the cleaning sector [34], it will be applied for the HIR homogenizing process in this research. From Sinner's circle, it can be deviated that not only temperature is important to obtain a homogenous mix, but also mechanics, chemistry and time. If a lower temperature is used in the homogenizing stage, the mixing needs more time, more thorough mixing or more reactive additives to obtain the same homogenous mix. Therefore, the minimal temperature is dependent on the design of the homogenising stage of the ART and additives used. Mallick et al. [35] characterized the mixing process by dispersion and diffusion, where dispersion is the distribution of the additives on the reclaimed asphalt, and diffusion is the phenomenon of the intermingling of the additives with the reclaimed asphalt mastic. Where they focussed their research on diffusion, it was concluded that there was no notable rejuvenation of the reclaimed asphalt for temperatures lower than 100 °C. It was found out that the extend of rejuvenation was dependent on the temperature, the time of mixing and the viscosity of the rejuvenator. Furthermore, it was also found out that the rejuvenation of the mastic of the reclaimed asphalt depends on the mastic film thickness, where the rejuvenation is mostly limited to the outer layer of the film, depending on the factors stated above.

Since time is one of the important factors in both Sinner's circle and the research on diffusion by Mallick et al. [35], homogenization with liquid materials which need to react with the reclaimed asphalt should be added as early as possible in the ART. However, there is one major constraint, which is that the liquids should be dispersed evenly and well throughout the reclaimed asphalt mixture. If the reactive liquids are not evenly dispersed, there is a high chance that the asphalt mixture cannot be homogenized in the final homogenization. Therefore, good immediate homogenization of the reactive liquids with the reclaimed materials should be ensured when these are added.

Paving/Finishing

After the homogenizing stage, the homogenous asphalt mix is paved on the asphalt base course. Poeran and Sluer [36] developed a workability test for asphalt mixtures, which can be used to determine the temperature windows for paving and compacting. A rotating paddle was used where the torque at a constant RPM was measured over the temperature of the asphalt mix. It was concluded that the workability was dependent on the temperature, the grading and the type of bitumen used. The lower workability limit temperature was determined by taking the inflection point at which the mixture agglomerated and thus became more workable according to the measurements. For PA 16 with fresh 70/100 bitumen, the lower limit was determined at 113 °C [36]. There are unfortunately no results on the workability using rejuvenated bitumen in PA mixtures. At lower temperatures the mixture is not workable enough to be well paved.

Compacting

The compaction of asphalt can be described by the rearrangement of particles while voids are driven out [37]. Bijleveld et al. [38] concluded that the temperature of the asphalt surface course is crucial to both the air void reduction for a given compactive effort, and for the overall time available for compaction. Timm et al. [39] described an optimal compaction time frame, based on the delivery temperature and cooldown rate of the asphalt, as visualized in Figure 10.

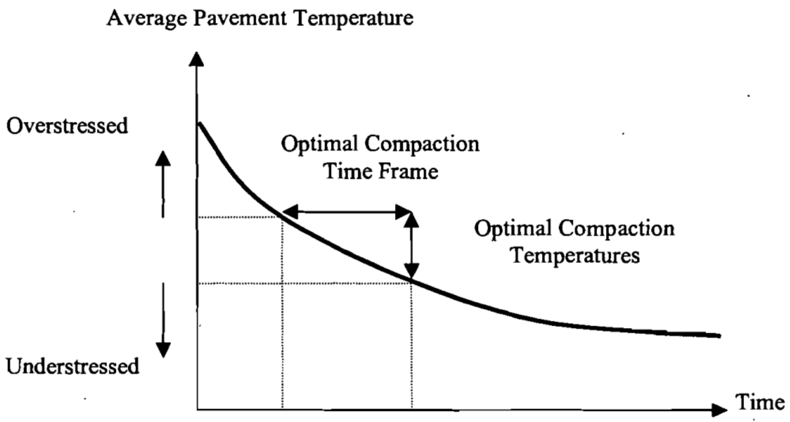

Figure 10: Pavement cooling curve and compaction time frame [39]

Chadbourn et al. [40] determined the optimal compaction temperature, i.e., the upper temperature limit of the optimal compaction time frame, to be the temperature at which the shear stress curve of the asphalt mixture reaches a minimum. Higher temperatures would lead to a higher shear stress due to the loss of the lubrication effect of the binder, where lower temperatures will make the binder stiffer thus resulting in a higher shear stress. The extend of this effect can be questioned however, since this contradicts with Figure 10. There is no documentation on how the lower temperature limit of the optimal compaction time frame is determined, however. Optimal compaction temperature for a SMA mixture with straight 85/100 penetration bitumen was determined at 125 °C.
In the research of Rijkswaterstaat on the Wirtgen Remixer [8], it was concluded that there was an important difference between compacting a conventionally paved surface course and compacting a surface course using an ART. This because the ART also heats the base course to some extent, such that the paved surface course cools down more slowly. This could make the cooling curve as visualised in Figure 10 less steep and thus enlarging the optimal compaction time frame.

2.2 Characteristics of PA

To understand what PA is according to Dutch regulations, and what requirements are stated to PA important for the 100% recycling of PA, theoretical analysis will be performed on these subjects. Furthermore, study will be devoted on the known thermodynamic properties of PA.

2.2.1 Dutch PA characterization

In the Netherlands, over 90% of the main road network within the Netherlands has a PA surface course, where PA is popularly called ZOAB (Very Open Asphalt Concrete) [41]. PA outperforms more dense asphalt mixtures on safety for road users, because of its noise reduction and water drainage which prevents splatter [41]. The consequence is that PA has a shorter life expectancy than more dense asphalt mixtures, because of its open structure, which makes it more vulnerable to weather conditions [42]. PA is a stone-skeleton mixture, due to its high percentage of aggregate which bears the load. Dense asphalt mixtures are mostly sand-skeleton mixtures, where sand is the fundamental load bearing material. In the Netherlands, there are 2 applications of PA as a surface course, namely single-layered PA and double-layered PA, where the latter performs even better in noise reduction and water drainage [43].


Figure 11: Double-layered PA drill core

The NEN-EN 13108 provides European standards for bituminous mixtures, where the NEN-EN 13108-7 focusses on PA [44]. According to this standard, PA mixtures can be identified as such [44]:

$PA \mid D \mid Binder$
Where:
PA indicates the type of mixture, in this case Porous Asphalt,
D is the upper sieve size of the aggregates in the mixture, thus the maximum aggregate diameter and,
$Binder$ indicates the type of binder used in the asphalt mixture.

A binder example is 70/100, which is most commonly used in Dutch PA mixtures. This straight penetration bitumen is indicated by its penetration test value range, which should be between 70 and 100.
In the Netherlands, the standard PA mixtures, called ZOAB, are prescribed by the RAW guidelines, published by CROW [45]. The requirements to ZOAB are derived from the NEN-EN 13108-7, with the addition of some extra requirements. In Appendix A, the specifications to ZOAB as prescribed by the RAW guidelines [44] and the guidelines for double-layered ZOAB [43] are listed.
In this specification, the minimal percentage of voids is specified for each type of PA, which is 20% except for the bottom layer of double-layered PA, which is 25%. Furthermore, the maximum thickness of a single-layered PA course is 60mm. In double-layered PA pavements, the top layer has a maximum thickness of 25mm, depending on the type used [46]. The smaller sized aggregates of the top layer will interlock between the bigger sized aggregates of the bottom layer [43], as also can be seen in Figure 11. This can cause an unjust grading when recycling the bottom layer of a double layered PA pavement. In Appendix A, the aggregate type requirement is also mentioned for the different ZOAB mixtures, which is important for the skid resistance and water drainage of the pavement [47]. For surface courses, the aggregate type for ZOAB should be 3, the highest order, where intermediate and bottom layers do not require type 3. Thus, using surface courses in intermediate or bottom layers can be considered as devaluation.
Since these are all guidelines, deviating from them is allowed, if it is specified in the contract between the client and contractor. When an asphalt mixture is used which does not comply with the guidelines, documentation is demanded by the client to guarantee that the functional properties of the non-complying asphalt mixture are just as good as for the prescribed mixtures. Since the RAW guidelines prohibit the use of recycled asphalt in PA mixes, special agreements always need to be made when recycling PA for new PA courses [45].

2.2.2 PA recycling requirements

When an aged asphalt pavement is milled, it is named recycled asphalt or asphalt granulate. The identification for asphalt granulates according to the NEN-EN 13108-8, which focusses on the requirements to asphalt granulate, is as following [48]:

$U \mid RA \mid d/D$

Where:

U is the maximum particle size, i.e., the smallest sieve size through which 100% of the asphalt granulate passes.

RA specifies the product as recycled asphalt.

d/D gives the aggregate size designation, where d is lower and D the upper sieve size of the aggregates, where D is determined by the size of the smallest sieve through which 85% of the aggregate passes.

The NEN-EN 13108-8 states requirements to the impurities of the asphalt granulate. Matter which is foreign to asphalt is split into 2 groups, where group 1 contains matter like cement concrete, bricks, subbase materials, cement mortar and metal. Group 2 contains synthetic materials, wood and plastics. RA can be categorized into 3 categories based on the impurities it contains, as described in Table 2.

Category	**Foreign matter: Group 1**	**Foreign matter: Group 2**
F_1	<1% by mass	<0,1% by mass
F_5	<5% by mass	<0,1% by mass
F_{dec}	Declared	Declared

Table 2: Recycled Asphalt foreign matter groups [48]

In the standard RAW guidelines, it is specified that for RA, category F_1 is used for intermediate and upper courses, where category F_5 is used for base courses [45]. Thus, when recycling PA, category F_1 is always used since PA is not used in base courses.

Sources of pollution on PA courses are road markings and dirt which accumulates in the PA course. Where road markings are mostly made of thermoplastic materials, these can be categorized into group 2. Dirt will probably be categorized in group 1. Van Bochove and Van Buël [49] performed research on a new technique for PA cleaning, where they found out that there was at least 55.55 kg of dirt in a 80m stretch of double layered PA. Assuming a lane width of 3.5m, the dirt pollution is 0.198 kg per square meter of highway. From Appendix B, it can be seen that at least 0.375 kg of thermoplastic road marking per square meter of highway is standard in the Netherlands.

Considering a 50mm PA 16 course with a density of 2050 kg/m3, the percentages for both foreign material groups are calculated in Table 3.

Foreign matter group	% of pollution by mass
Group 1: Thermoplastic road marking	0.37%
Group 2: Dirt	0.19%

Table 3: PA pollution percentages by foreign matter group

Therefore, it can be concluded that road markings should always be removed before a surface course can be 100% recycled, since the pollution percentage of 0.37% exceeds the limit of 0.1% by far. Though the pollution by dirt does not exceed the guidelines, it will disturb the gradation in the fine aggregates in the recycled PA if not removed. Removing dirt will also result in more cycles the PA course can be 100% recycled without exceeding the pollution guidelines.

2.2.3 PA thermodynamic properties

In this research, the components of porous asphalt are seen as visualised in Figure 12. The aggregate consists of all particles with a diameter greater than 2mm, where the mastic involves all particles equal or less then 2mm. The mastic acts as the binder between the aggregate and is composed of bitumen, filler and sand. For each level and component, the known thermodynamic properties will be reviewed.

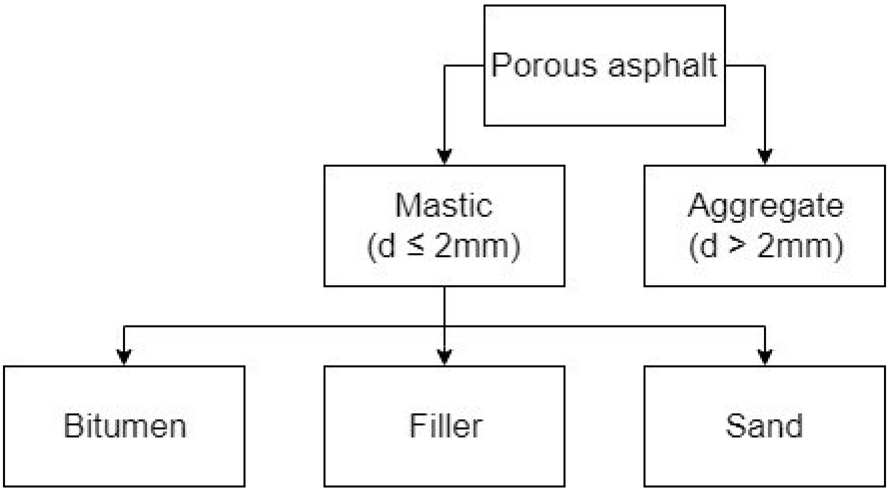

Figure 12: Components of porous asphalt

Porous asphalt

Hassn et al. [50] performed research on determining the relation between air void percentage and heat transfer through the asphalt mixture by heating the surface with infrared lamps. Using 60/40 straight penetration bitumen and limestone aggregates, the thermodynamic properties as displayed in Table 4 were determined.

Air voids (% v/v)	**Bitumen content % (m/m)**	**Thermal conductivity W/ (m K)**	**Specific heat capacity J/ (kg K)**	**Density kg/m3**
25,3	3,2	0,82	945,92	1906,10
21,5	3,3	0,90	947,11	2004, 70
17,4	3,8	0,92	953, 03	2092,65
13,2	4,2	0,96	957,77	2186,75
9,9	4,5	1,04	961,33	2256,00
5,0	4,7	1,16	963,70	2371,67

Table 4: Thermodynamic properties of PA for different air void percentages [50]

A clear relation can be seen between the air void percentage and the specific heat capacity of the asphalt mix, which shows that less dense mixtures need less energy to heat up, which is explained by the lower percentage of bitumen used. A higher void content also gives a lower conductivity of the PA course.

Aggregates

For PA mixtures, high requirements are set to the aggregates due to their skid resistance and water drainage of the pavement [47]. Only a limited amount of rock types satisfies these requirements, such as granite and greywacke. Bestone is commonly used granite rock in Dutch PA production, which originates from the Norwegian Bremanger quarry [51]. Greywacke is a variety of sandstone rock which can be found in Germany. In Table 5, the thermodynamic properties of these rocks can be seen.

Rock	Thermal conductivity W/ (m K)	Specific heat capacity J/ (kg K)	Dry density kg/m3
Granite	[52] Min: 1,25 Mean: 3.05 Max: 4.45	[52] Min: 670 Mean: 960 Max: 1550	2770 [53]
Greywacke	[54] Min: 2,41 Mean 2,79 Max: 3,17	[54] Min: 544 Mean: 627 Max: 710	2700 [55]

Table 5: Thermodynamic properties of rock used in PA

From these values, it can be seen that Greywacke requires less heat to heat 1 °C but granite is heated more easily due to its higher thermal conductivity.
To obtain these values, multiple different sources had to be used, of which none were taken from the sources of rock used for the PA production. Also, great variety exists between the minimum and maximum values measured. By comparing these values from different studies with each other, the values collected are considered as valid It must also be noted that these values are determined for pure rock, where recycled PA aggregates are black stones, having absorbed a specific amount of bitumen. There was no literature found on the thermodynamic properties of black stones.

Mastic

In PA, mastic is used as the binding material between the aggregates. When asphalt mixture is produced, a thin film of mastic will be applied on the aggregates. Apostolidis et al. [56] conducted an advanced evaluation on mastic for induction heating purposes, where the thermal conductivity of mastic was measured at 0.5 W / (m K). In this study, more filler material was used in the mastic compared to PA mixtures at the expense of sand. Mastic is not a homogenous mixture, since sand particles are unevenly distributed throughout the film. This can lead to heat bridges from the air voids to the aggregate when the air voids are filled with hot gas. Apostolidis et al. [56] determined the heat capacity of the used mastic to be between 875 and 925 J / (kg K).
The heat capacity can easily be calculated using Equation 1 when the weight percentages and heat capacities of the components of mastic are known.

$$C_{p\ mixture} = \left(\frac{m_1}{m_{mixture}}\right) C_{p\ 1} + \left(\frac{m_2}{m_{mixture}}\right) C_{p\ 2} \quad (1)\ [57]$$

Where:
C_p is the heat capacity of the indicated material and
m is the mass of the indicated material

Using the PA mix specification from Appendix D and the specific heat capacities from Table 6, a specific heat capacity of 1082.14 J / (kg K) was determined.

Sand, filler and bitumen

Sand, filler and bitumen are the basic components of the mastic used in PA. In Table 6, the thermodynamic properties of these materials are listed.

Material	**Thermal conductivity W/ (m K)**	**Specific heat capacity J/ (kg K)**	**Density kg/m3**
Crushed sand (0.063 – 2 mm)	0.25 [58]	800 [58]	2688 [53]
Filler Hydrated lime (Wigro 60K)	2.92 [59]	1214.17 [60]	2640 [61]
Fine sand	0.15 [58]	800 [58]	1600 [58]
Bitumen	0.15-0.17 [62]	1675-1800 Increases by 1.67-2.51 per 1C [62]	1030 (20C) – 921 (200C) [62]

Table 6: Thermodynamic properties of basic components of mastic

Filler material is made of hydrated lime and dust produced by the asphalt production process itself. For the self-produced dust, the properties of fine sand are taken, since these are not found for dust. As can be seen, the hydrated lime is the most conductive material in the asphalt mastic, where the bitumen acts as an isolator and has a high specific heat capacity.

2.3 Heat transfer from hot air or superheated steam to PA

Finally, the heat transfer from hot air or superheated steam to PA will be reviewed based on literature reviews, theoretical knowledge and existing models.

2.3.1 Fundamentals of heat transfer

The main fundamental modes of heat transfer are conduction, convection and radiation. When asphalt is heated using infrared heaters, radiation is the dominant mode of heat transfer to the asphalt. When asphalt is heated using hot gasses such as hot air and superheated steam, convection is the dominant mode of heat transfer. For both methods, conduction plays the dominant role in transferring the heat through the mastic film and through the aggregate.

Radiative heat transfer

Radiative heat transfer can occur through a transparent medium by means of photons in electromagnetic waves [63]. Radiative heat transfer between two grey planar surfaces can be described by the Stefan-Boltzmann equation, as seen in Equation 4.

$$Q = \frac{\sigma({T_1}^4 - {T_2}^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} A \text{ [64] (4)}$$

Where:

Q = Heat energy transferred per unit time (in W or J/s)
σ = The Stefan-Boltzmann constant (5.6704 x 10^{-8} W/m^{2}K^4)
A = Surface area
$T_{1,2}$ = The temperature of the respective surface (In °C)
$\epsilon_{1,2}$ = The emissivity of the respective surface (-)

Convective heat transfer

Convective heat transfer is the transfer of heat from one place to another by the movement of fluids [65]. In this case of heating PA with hot gasses, the gasses can be seen as fluids, where the asphalt is the surface to which the heat is transferred. There are 2 types of convective heat transfer, namely free convection and forced convection. Free convection occurs when the fluids motion is caused by varying density, resulting in buoyancy forces. Forced convection occurs when fluid is forced to flow over a surface, where the flow is created by pumps or fans. The relation for convective heat transfer is described by Equation 5.

$$Q = hA(T_f - T) \quad (5)$$

Where:
Q = Heat energy transferred per unit time (in W or J/s)
h = Heat transfer coefficient W / (m^2 K)
A = Surface area (m^2)
T_f = Fluid temperature
T = Object's surface temperature

Here, the heat transfer is mostly dependent on the heat transfer coefficient h, which depends on the fluid and flow situation. There are a lot of different methods to calculate the heat transfer coefficient for different applications.

Conductive heat transfer

Conductive heat transfer is caused by microscopic collisions of particles where kinetic and potential energy is transferred from one particle to the other, which causes the internal energy, thus the temperature, of a particle to increase [66]. The rate of conductive heat transfer through a material is described by Fourier's law, which states that the heat transfer through a material is proportional to the negative gradient in temperature and to the area. For this law, the differential form looks at the flow rates / fluxes of energy locally, where the integral form describes the amount of energy flowing in or out of a body as a whole. Here, the integral form will be used.

$$Q = -kA\frac{\Delta T}{\Delta x} \quad (6)$$

Where:
Q = the amount of heat transferred per unit time (in W or J/s)
k = the material's conductivity
A = the cross-sectional surface area of the body
ΔT = the temperature difference between the ends
Δx = the distance between the ends

For this equation, a 1-D geometry for a homogenous material between 2 endpoints at constant temperature is assumed.

2.3.2 Heat transfer in PA

In contrast to dense asphalt mixtures, PA contains a high percentage of air voids. Due to the air voids, a large internal surface area of the PA is exposed. Research from Hassan, Mahmud and Jaya [67] showed that these voids are mostly equally distributed over the depth of the PA course using CT scans, where more coarse aggregate caused more elongated voids, thus a lower number of individual voids, resulting in higher interconnectivity between the voids. In comparing gradation designs from different countries, it was concluded that both coarse aggregate and fines content influence the number of voids, thus the interconnectivity, of PA mixes. [68]. Poulikakos et al. [69] determined an average connected void percentage using the French standards NF P 98-254-2, where the bottom and sides of the specimens were sealed after which water was poured in the specimen to determine the volume of voids which can be reached from the specimen surface. Here, an average ratio of connected voids to total voids of 0.73 was determined. In Figure 13, a cross-section of 2-layered PA is shown, where a drill-core is displayed at the right and a visual representation at the left.


Figure 13: Actual and simplified representation of 2-layered PA [70]

From the visual representation, the distinction between aggregate, mastic and air voids is very clear and can be compared with the actual PA at the right. From this figure, the concept of interconnected voids can also be made clear, since there are some voids which are not connected to other voids reaching the surface, though it must be noted that this is just a 1-D view.
In Figure 13, aggregate fracturing due to compaction can also be seen, indicated by the red arrows. Aggregate fracturing can be recognised by the small cracks between the individual aggregates, when it is clear that both aggregates could have been 1 aggregate.

When the PA is heated using hot air or superheated steam, the hot gasses will fill in the interconnected air voids in the PA course, after which the heat will be transferred from the hot gas to the aggregates via convective heat transfer. However, the aggregates are separated from the hot gasses by the mastic, acting as an isolator. Therefore, Fourier's law describing conductive heat transfer can be used to describe the heating of the aggregates due to the hot gasses with the binder acting as the heat-conducting layer. Though the voids are equally distributed over the depth [67], these do not provide a direct route down to the bottom of the PA course, but more provide a random path through the PA.

Several studies have been done on determining the thickness of the mastic film on aggregates in asphalt mixtures, because of its importance for aging and stiffness of the asphalt. However, the term film thickness has also been receiving critique. In a study on determining the binder film thickness where image analysis, reflective light microscopy and scanning electron microscopy were used, Elseifi

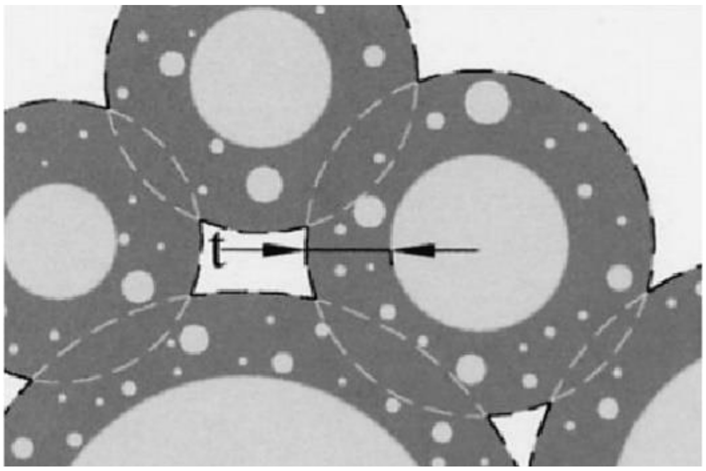

Figure 14: Mastic film thickness characterization [68]

et al. [71] concluded that the mastic film thickness can have great variations. Radovskiy [72] developed an analytical model to determine the film thickness in compacted asphalt mixture, taking the small particles such as sand and filler into account. In Figure 14, the film thickness Radovskiy proposed is visualized, from which it can be seen that small particles within the film thickness are accounted for in determining the film thickness.
Using the analytical formula given in Equation 7, the mastic film thickness can be determined.

$$a_1 t + a_2 t^2 + a_3 t^3 = \ln\left[(1-\varphi)/V_{air}\right] \quad (7)$$

Here, t gives the film thickness for a specific asphalt mixture specified by a, φ and V_{air}. Using the same parameters, the average surface area on the boundary of air voids per unit volume of pavement can be determined, as seen in Equation 8.

$$S(t) = (1-\varphi)(a_1 + 2a_2 t + 3a_3 t^2)\exp[-(a_1 t + a_2 t^2 + a_3 t^3)] \quad (8)$$

In Appendix E, the parameters of these analytical formulas are further specified. From calculations done on PA 16, as specified in Appendix D, a mastic film thickness of 33.6 mu (0.0336 mm) was determined, and a surface area of 2549.82 m^2/m^3 of pavement when 73% of the voids are interconnected. For a comparison, the optimal wet film thickness of outer paint is between 70 and 90 mu.

2.3.3 Thermodynamic properties hot air and superheated steam

Hot air and superheated steam are both gasses whose thermodynamic properties easily be compared. However, superheated steam is water with a temperature higher than its boiling point, where the boiling point of water is 100 °C at atmospheric pressure. Therefore, when superheated steam is used to heat a material whose temperature is beneath 100 °C, a phase transition will take place when the fluid is cooled beneath 100 °C which will lead to the release of the latent heat of vaporization.
Both air and water will individually be analysed for their thermodynamic properties important in heating PA at atmospheric pressure at temperatures between 20 and 130 °C.

Air

Air is a mixture of mostly oxygen and nitrogen. The exact thermodynamic properties are depended on the exact mixture composition. In Table 7, the thermodynamic properties of atmospheric air are given.

Property	**Value**	**Property**	**Value**
Boiling point	-194.4 °C	Specific heat	1006 J / (kg K)
Density (20 °C)	1.204 kg/m^3	Heat conductivity (20 °C)	0.02587 W / (m K)
Density (125 °C)	0.8868 kg/m^3	Heat conductivity (125 °C)	0.02866 W / (m K)

Table 7: Thermodynamic properties air at atmospheric pressure [73]

Since the boiling point of air is far beneath the temperature range which will occur in heating PA, there will be no phase transition when hot air is used. Therefore, the energy which can be transferred from hot air to the PA can be determined by only using the specific heat.

Superheated steam

Superheated steam is water vapour with a temperature higher than its boiling point at a certain pressure, which is 100 °C for atmospheric pressure. The thermodynamic properties of water are given in Table 8 for atmospheric pressure.

Property	Value	Property	Value
Boiling point	100 °C	Heat conductivity (20 °C) (Liquid water)	0.598 W/ (m K)
Density (20 °C)	1000 kg/m³	Heat conductivity (100 °C) (Saturated steam)	0.677 W/ (m K)
Density (100 °C)	0.598 kg/m³	Heat conductivity (125 °C) (Superheated steam)	0.026 W / (m K)
Density (125 °C)	0.550 kg/m³	Enthalpy (100 °C) (Liquid)	419 kJ / kg
Specific heat (Liquid)	4200 J / (kg K)	Enthalpy (100 °C) (Gas)	2676 kJ / kg
Specific heat (Gas)	2100 J / (kg K)		

Table 8: Thermodynamic properties of water at atmospheric pressure [73]

When superheated steam cools down to 100 °C, a phase transition takes place where the water vapour condenses to liquid water. These phase transitions together with the influence of the different heat capacities of water vapour and liquid vapour can be visualized using a water heating curve as seen in Figure 15.

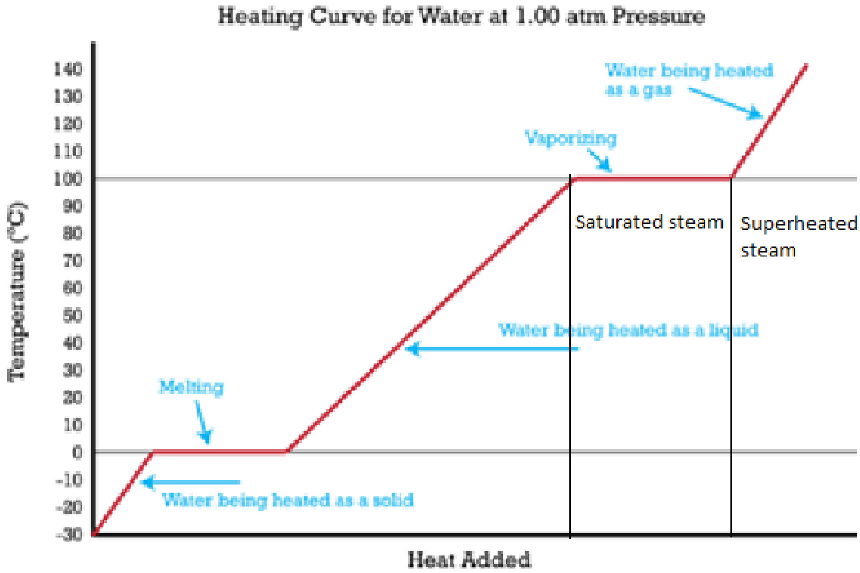

Figure 15: Heating curve for water at atmospheric pressure [74]

In the heating curve, the temperature of water is described over time, where a constant amount of heat is added per time unit. Due to the latent heat of vaporization, the difference between the enthalpy of liquid water and steam, a great amount of energy is stored in just the phase transition. This means that the condensation of steam will release a great amount of energy while the temperature is constant. From Figure 15, the difference between saturated and superheated steam can also easily be deducted.

2.4 Conclusion

In the theoretical analysis, the three research questions concerning the characteristics of PA, the use and effects of heat in an ART and heat transfer in PA have been treaded. This conclusion will provide a reflection on the findings of these research questions.

PA characteristics

Since the Dutch RAW standards do not allow recycling of PA in new PA mixtures, the use of the ART to recycle 100% PA must be specified in the contract between the client and contractor. Single-layered PA courses are easier to recycle in contract to double-layered courses due to the interlocking of aggregates in double-layered PA. The minimal air void percentage of PA is 20%, where single-layered PA has a maximum thickness of 60mm. Due to the requirements on reclaimed asphalt, all road markings should be removed before 100% recycling PA. Due to its porosity, PA is less conductive than dense asphalt courses. The stone-skeleton mixture can be characterized by aggregates covered in a film of mastic, where the aggregate is more conductive than the mastic. Due to the high weight percentage of aggregate in PA mixtures, a lot of energy is needed to heat the aggregate, where the weight percentage of mastic is much lower. Since the mastic acts as an isolator, the mastic will heat up faster than the aggregate.

Use and effects of heat in an ART

To recycle 100% PA in an ART, the hot in-place recycling method must be used. This method involves multiple processes, where surface recycling and remixing can be used to recycle PA without devaluation. These processes both involve heating, loosening, mixing, paving and compacting as process steps. Theoretical analysis on these individual processes found out that high temperatures around 130 °C are needed for compacting at the back of the ART, where PA could theoretically be loosened at a temperature of 106 °C. Most existing ART's can increase the temperature after the mixing step, which is done using a two-shaft pugmill. Using a drum mixer allows to increase the temperature during the mixing step, which theoretically needs at least 100 °C to have any effect. According to the circle of Sinner a higher temperature can be used to achieve optimal mixing in less time, where increased additive reactivity and more thorough mixing also help. Most existing ART's add the additives directly after the loosening step, but without dispersing the additives equally over the reclaimed PA, this will have little to no effect. Adding the additives just before the mixing step ensures proper dispersion and thus optimal and equal diffusion. High temperatures lead to increasingly severe aging of the reclaimed PA, thus keeping the temperature as low as needed is favourable. Temperatures should never be higher than 230 °C, due to the loss of viscoelastic properties of the binder. Existing ART's using infrared heating struggle to keep the surface from overheating, where hot air heaters are said to tackle this problem, though the air temperature used can be as high as 600 °C.

Heat transfer to PA

For each mode of heat transfer, area has a great effect on its magnitude, as does the temperature difference. When infrared heating is used, only the surface area of the PA is subjected to the radiation. Using hot gasses in PA, the area within the voids is also used, increasing the area and thus the heat transfer. Via the voids, the PA can be heated throughout the full depth of the course, while infrared heating relies on internal conduction to heat the bottom of the PA.

These voids are equally distributed throughout the PA, but provide a random path, where only 73% of the voids can be reached. The surface around the voids is mastic, which covers the aggregate. Though the mastic is not a homogenous mixture and the film can vary in thickness, a general film thickness can be calculated of around 33.6 mu. The surface area around the voids was determined at 2549.82 m^2/m^3 only considering the interconnected voids, which is substantially more than just the top surface area of a PA course which is used when heating PA using infrared.

Heat transfer from hot gas to PA can be described by convective heat transfer, where, besides the area and temperature difference, the heat transfer coefficient is also very important for heat transfer. This coefficient depends on the fluid and flow situation, which is not further treaded in this study. In comparing hot air and steam, it was found out that steam holds at least 2 times more energy than hot air. Since steam condenses at 100 °C the latent heat of vaporization is also released which is more than 100 times greater than its heat capacity for steam, while the temperature does not decrease until the steam fully condensed. When the steam is fully condensed to water, the heat capacity is 4 times higher compared to air.

Though this also means that a great amount of energy needs to be put into water to generate steam, steam is considered to be far more effective in heat transfer to PA due to its phase change and higher heat capacity for both steam and water. However, the heat transfer coefficient is also influenced by using steam or air, which should be further researched if a full comparison between steam and hot air heating should be made.

3. Experiment analysis

In the experiment analysis of this research, the conceptual model development and field tests will be treated.
First, the conceptual model will be given, from which simple calculations are done on the expected time needed to heat the PA test section to a certain temperature. Hereafter, the field experiments done will be treaded.

3.1 PA heating model

Multiple models have been made to simulate the temperature of asphalt after it has been paved, such that it can be used to determine the optimal compaction time window. PaveCool is such a model, which assumes that heat is transferred at the top of the asphalt course via convection with the atmosphere, radiation to the surroundings, solar heat absorption and conduction within the asphalt course to the base [40]. Models such as PaveCool already proved themselves useful in road construction projects, also due to its easy use as can be seen from Figure 16.

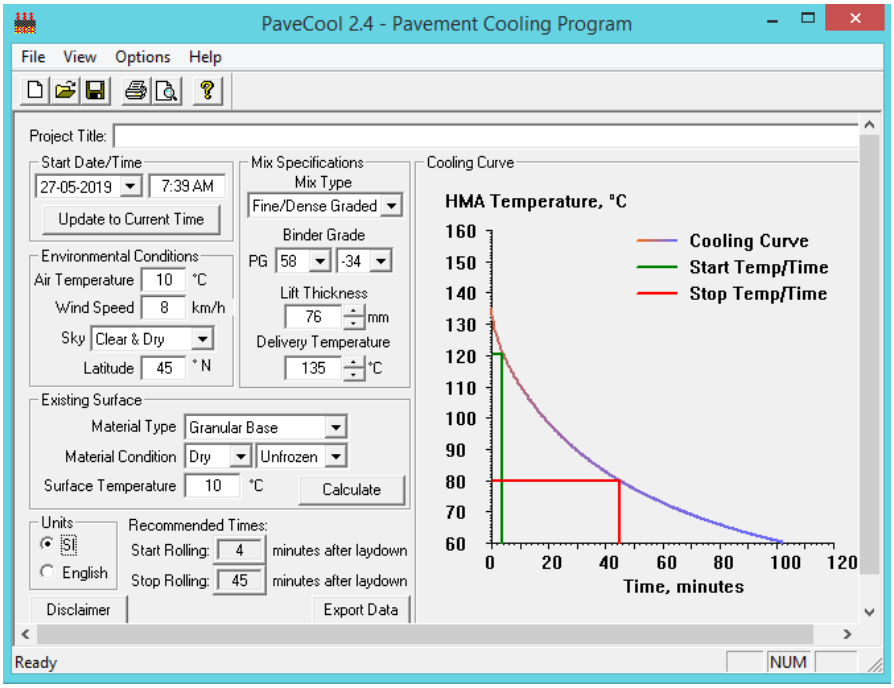

Figure 16: PaveCool 2.4 [40]

A PA heating model should be able to simulate the increase of temperature of an asphalt course, where existing models are used to simulate the decrease of temperature. However, this does not mean that existing models cannot be used to simulate the increase of temperature. PaveCool Freeze, a similar application to PaveCool, can handle air temperatures of 180 degrees, which results in an increase of 40 degrees over 6 hours.
However, the heat transfer from the air to the asphalt is simulated using free convection, where for PA heating forced convection will be applied. Therefore, the model should be adjusted when being used to simulate the heating of PA, but certain aspects of the PaveCool model could be reused in a PA heating model, such as the internal conduction of the asphalt course and loss of heat to the base.
Furthermore, PaveCool is only able to return the average temperature of the asphalt course, where the minimal and maximum temperatures over depth are of more interest in a PA heating model. Also, PaveCool considers the asphalt mix as a homogenous material, whose thermodynamic properties are influenced by the specific aggregate size and binder type used. Therefore, PaveCool cannot separately determine the temperature of mastic and aggregates.
Using the knowledge gained from the theoretical analysis and the PaveCool model, a conceptual model for PA heating is developed.

3.1.1 Conceptual model development

In the PA heating model, the goal is to simulate the temperature of a PA course over time when it is being heated using hot gas, such as hot air or superheated steam.
From the theoretical analysis, it was seen that heat transfer by convection can describe the transfer of the hot gas to the mastic. Within the mastic, the heat will be distributed via conduction, where heat will also be transferred to the aggregate via conduction. Therefore, a simplified heat transfer system can be drawn as displayed in Figure 17.

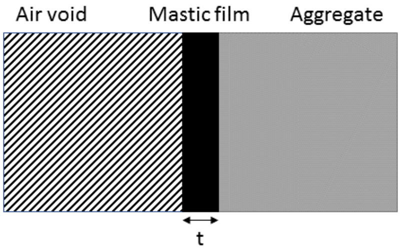

Figure 17: PA hot gas heat transfer

However, this model comes with its problems. Convective heat transfer can be described, but it is dependent on the heat transfer coefficient. Since this coefficient depends on the flow and fluid situation, this coefficient can differ throughout the PA. Since the interconnected voids provide a random path through the PA, quantifying the convective heat transfer is difficult. For the loosening of PA, the temperature of the mastic is important. This concerns the mastic which acts as a bridge between the aggregates and cannot be heated directly by hot gas from the air voids, but only by conduction throughout the mastic. Due to the low heat conductivity of mastic, the difference between the temperature represented by the simplified model can be important.
Since creating a model which can accurately simulate the heating of PA using hot gas has several challenges, which deserves its own individual research, it was decided to leave out of this research.

3.2 Bitumen heating experiment

The main goal of the bitumen heating experiment was to pour epoxy modified bitumen (EMB) over from oil drums into a tanker truck. Since the oil drums were shipped by air, the initial temperature of the bitumen was around 20 °C, such that the bitumen was too viscous to be poured over. Therefore, heating the bitumen to a temperature where the viscosity of the bitumen was low enough to be pourable was needed.
This experiment has proven to be useful for this research, since the bitumen heating experiment showed the effects of heating viscous fluids with low heat conductivity and provided a physical experience with the viscoelastic properties of bitumen.

3.2.1 Experiment setup

On the 1st of June, 1827 kg of EMB was received distributed over 9 210 litre drums. To heat the drums, 4 silicone drum heaters with a maximum output of 1500W each and 2 base plate heaters with a max output of 900W where purchased.
Temperature-viscosity data was supplied, which was used to determine the minimal temperature needed to pour over the EMB through a hose from the oil drum in a tanker. In Figure 18, the viscosity-temperature plot of EMB is compared with straight penetration 100 bitumen. From this plot, it can be seen that EMB is less viscous than penetration 100 bitumen. A rule of thumb is that a viscosity of 1000 mPa s is needed for 70/100 bitumen to be pumpable. For the EMB, this corresponds with a temperature of 93 °C.

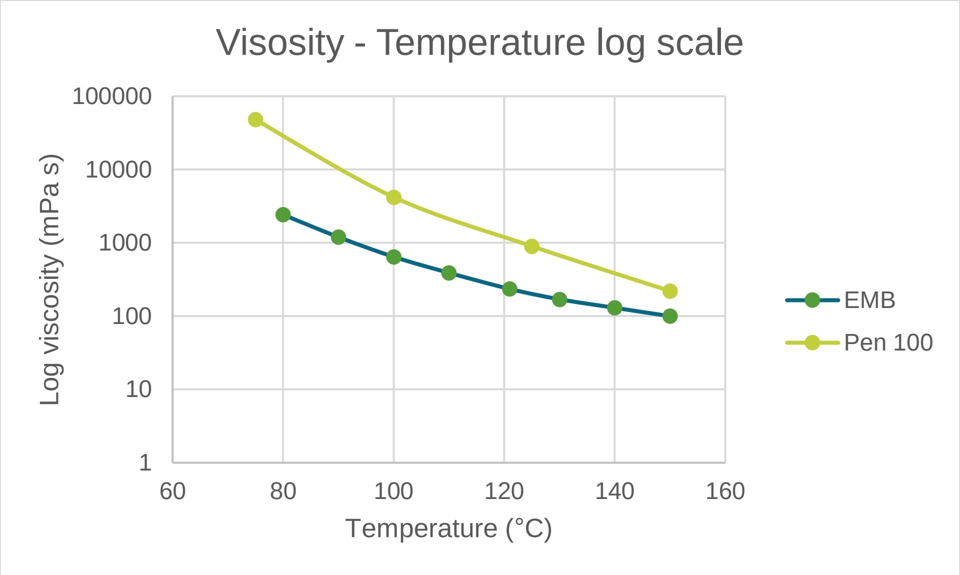

Figure 18: Viscosity-Temperature plot EMB and straight penetration 100 bitumen

To test this theoretical approximation, a heated test sample was studied. Observed was that the bitumen would flow at a temperature of 70 °C. Therefore, a target temperature of 70°C was chosen for the heating of the EMB.
Using a specific heat capacity of 1675 J / (kg K) for straight bitumen as given in Table 6, and a maximum heat input of 3900W from 2 silicone drum heaters and 1 base plate heater, a minimal heating time of 1.21 hours was determined per drum. All heating devices where fitted with a thermostat however, which allowed a maximum temperature of 150 °C for the base plate and 120 °C for the silicone heaters. Using simulation software, it was determined that the bitumen around the heaters would reach this maximum temperature fast. Due to the low heat conductivity of bitumen, the heat cannot be transferred throughout the drum fast enough to prevent the heater from turning off, which would increase the heating time needed. Since there where only 2 electric heating sets, it was decided that the remaining 7 drums would be preheated using hot sand with a temperature of around 180 °C.

3.2.2 Experiment results

The heating of the bitumen was performed at the 3th of June, where the heating of the first 2 drums using the silicone heaters and base plate heater began around 8:00. The other drums where placed in hot sand, provided by the asphalt plant. As can be seen from Figure 19, 3 drums where placed directly on the cold asphalt, where the other 4 drums where placed on a 20cm pack of hot sand. This resulted in inadequate heating of the 3 drums which where not heated at the bottom.

Figure 19: EMB preheating using hot sand

Figure 20: EMB temperature measuring / mixing

Using a long thermometer, the temperature of the first 2 drums heated using the electric heaters was measured once per 2 hours. At 11:00, it was observed that the temperature of the drums was only at 40 °C, which caused some concerns about the total time needed to heat the EMB. However, it was observed that the temperature started to increase rapidly when a temperature of around 50 °C was reached. It was assumed that due to the lower viscosity of the EMB, the natural convective heat transfer within the drums started to transfer the heat throughout the EBM, lowering the temperature of the EMB surrounding the heaters and turn them on.
Using the thermometer as mixing device, the convective heat transfer within the drums was enforced. By experiencing the drag force on the thermometer while mixing, a good estimation of the temperature could be done without looking at the thermometer. It was noticed that 70 °C was the minimum temperature needed, where there was much more drag force experienced at temperatures between 60 and 70 °C.
At around 15:00, the first two drums where poured into the tanker truck using a wheel loader and a drum turner. The bitumen was poured through a 50mm diameter hose of around 1.5m for safety. A 30mm diameter silicone hose was considered due to its smoothness and experience with bitumen, but it was observed that a 50mm diameter was needed to provide a good flow.

Figure 22: Pouring of EMB in tanker truck

Figure 21: Pouring of EMB through manhole

The sand heated drums where not at the 70 °C target temperature when the pouring began, thus it was decided to heat them using the electric heaters. Where the first 3 drums only had a temperature of around 50 °C, the last 4 drums had already achieved a temperature of 60 °C, from which it was assumed that the sand pack heating the bottom of the drum made a huge difference. This was also observed by mixing the drums, since the bottom-heated drums where easier to stir at the bottom in contrast to the first 3 drums.
During the pouring, it was noticed that with each drum, the flow decreased while the temperature was above 70 °C. It was assumed that the hose eventually got plugged by the remaining EMB which stuck to the sides of the hose, making the diameter smaller. For the final drum, a new hose was used, which had a great effect on the flow where the temperature of the final drum was almost equal to the others. This was confirmed by letting the hoses leak out after the experiment, where a great amount of bitumen was observed to have leaked out of the hose. The remaining EMB in the drums was collected by putting the drums upside down above a bucket, where these buckets where filled after just 1 day of leaking at outside temperatures. This can possibly be explained by the low softening point of the EMB, which is expected to be at room temperature.

3.3 PA heating experiment

For the PA heating experiment, a test section of approximately 6m by 15m was paved with single layered PA 16. For this asphalt mixture, the composition can be found in Appendix D. Instead of 70/100 bitumen, Shell Multiphalte HM (High modulus) 20/30 bitumen was used. With a lower penetration between 20 and 30, the Multiphalte has a higher viscosity at usage temperature and is thus less sensitive to higher temperatures [75]. Therefore, it can nearly be compared to aged PA at its end of life, whose penetration has a bandwidth between 15 and 20 [76].
The goal of the experiment was to determine the minimal temperature needed to loosen the asphalt, using a self-build asphalt rake and shovels, where thermocouples registered the temperature over depth of the PA course.

3.3.1 Construction of test section

The test section was paved at the first of May 2019 at the parking lot of the asphalt production plant "De Eem" in Eemnes. The construction started at 7:15, where it was completed at 9:15. The dense asphalt course was cleaned, and an adhesive layer of bitumen was applied. Hereafter, the asphalt was paved, where the target height of the PA 16 was 50mm and the production temperature 160 degrees Celsius. The compaction was done in 2 ways, where the south-western side was compacted using both a tandem-roller and a heavier 3-wheel roller, where the north-eastern side was only compacted using a tandem roller.
On the 14th of June, 2 cores were drilled for both sides of the test section. The average void percentages of the PA were 28% and 29% for the south-western and north-eastern side. Where the target void percentage is 20% for PA 16, both sides of the test section are more open graded than PA 16 on national roads. There is also little difference between the more heavily compacted and lighter compacted side. A reason for this is that the compacting of the asphalt began only after the whole test section was paved, including a 20m section of PA 8 for other research purposes. This may have caused extensive cooling of the PA course before compaction began, resulting in invalid compaction due to the stiffened bitumen.

3.3.2 Heating equipment

The experiment was done using 2 heating methods, steam and infrared. Much effort was done on getting equipment which was able to generate hot air at temperatures above 100 degrees Celsius, however, there was no such equipment readily available. Though it was not the goal of this research to develop a model for infrared heating, it was chosen to perform the experiment also with infrared heating to determine if the infrared heating performed worse than steam heating.
For the steam heating experiment, the following equipment was used:

- Steam roller
  Manufacturer: Berliner MaschinenBau Actien Gesellschaft
  No. 14.8872
  Year of construction: 1927
  Maximum boiler pressure: 12 bar
  Firebox heating surface area: 5.15 m^2
- 15,2m^2 steam foil 150µm
- 10m 1" steam hose

Figure 23: Steam heating setup (19-06 10:31)

Figure 24: Steam heating setup (19-06 10:40)

For the IR heating experiment, the following equipment was used:

- 3Force infrared asphalt seam heater
  Rated at 80kw maximum output
  Ceramic infrared radiation screens
  Length: 172cm, Width: 26cm

Figure 25: IR heating setup (21-06 12:00)

Figure 26: IR heating device

3.3.3 Measuring equipment

The measuring equipment used during these experiments where thermocouples and a scarifier. 4 thermocouples were placed at different depths of 4.5, 3.5 and 2.0cm by cutting slots in the PA where the thermocouples were covered with crushed sand. To record the surface temperature, a thermocouple was fixed to the surface with aluminium tape, however, after removing the steam foil it was found out that the tape did not hold and thus the thermocouple only recorded the steam temperature under the steam foil. During the infrared experiment, the upper thermocouple was fixed using a metal plate. The spacing between the thermocouples was 10cm. The readings of the thermocouples were recorded using a Voltcraft k204 datalogger, whose interval was set at 10s. A scarifier was built to intuitively determine if the asphalt could be loosened. The scarifier was build such that a load could easily be applied on the rake to force it into the PA course, where also the angle of the rake could be determined. However, during the experiments it was found out that the rake was instable and did not have a real advantage in contrast to a shovel. Therefore, the experiences with the rake are not recorded.


Figure 28: Thermocouple placement (19-06 9:45)


Figure 27: PA scarifier (19-06 10:32)

3.3.4 Experiment results
The results for the experiments will be separated in which heating devices were used. First, the results of the steam heating experiments will be shown, after which the results of the infrared heating experiments will be treaded.

Steam heating experiments

The steam heating experiments were conducted at the 19th of June 2019. The experiment as prescribed was conducted once, after which a greater area was heated again without measuring temperatures while heating, but only afterwards to determine the cooling curve of the PA after heating twice.

Just before starting the first experiment, a heavy rainstorm came over with an extreme of 10 mm/h, where temperatures dropped from 20 to 18 degrees Celsius with a light breeze of around 1.0 m/s [77]. During the rainstorm, the test section was already covered by the steam foil, but because of the PA rainwater will have penetrated the test section due to horizontal discharge. It was decided however to start the experiment during the rainstorm after the extreme around 10:30, since the boiler of the steam roller reached a pressure of 10 bar. Mild rainfall lasted until 11:00. In the beginning of the experiment, the steam discharge from the steam roller was too great, which caused a rupture in the steam foil which was resolved by lowering the discharge and provisionally closing the rupture, which caused minimal steam leakage during the experiment. The section covered by the steam foil was around 2.6m by 2.8m. The heating was stopped as soon as the boiler of the steam roller reached a pressure of 5 bar.

In Figure 29, the thermocouple measurements during the steam heating experiment can be seen.

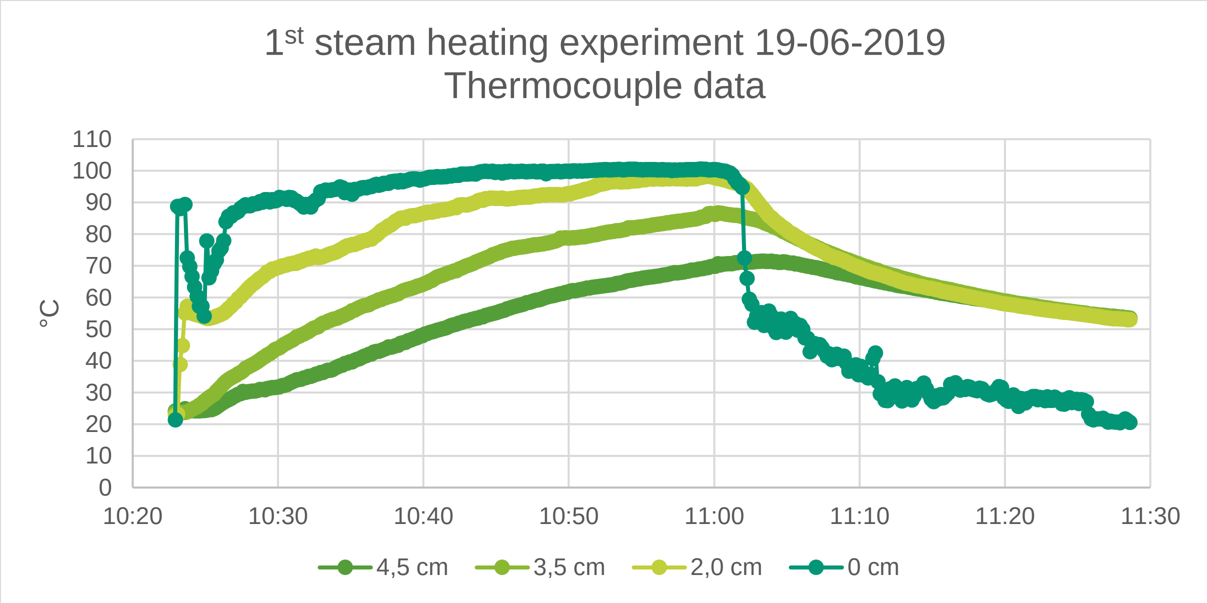

Figure 29: First steam heating experiment thermocouple data

According to the thermocouple data, there is a difference in temperature increase over depth, which can be explained by the loss of heat to the base course. The peak in the beginning is explained by the excessive steam discharge which caused a rupture in the steam foil, after which the steam discharge was stopped for a little while to close off the rupture after which the heating restarted with a lower discharge.

After the test section was heated for 35 minutes, the steam foil was removed to test if the PA could be loosened. The maximum temperature at 4.5cm reached 71.5 degrees Celsius, after which the PA course began to cool of rapidly. The upper part of the PA course cooled of more rapid than the lower parts, where after just 10 minutes the PA reached a general temperature for all depths where the rate of cooling decreased. While the PA was cooling of, loosening was performed using the asphalt rake and shovels. From this, it was determined that 70 degrees Celsius is sufficient to loosen the asphalt to a degree that the individual aggregates could be separated. It was also noticed that the PA could be separated easily from the base course. At temperatures between 60 and 70 °C, the loosening resulted in chucks of PA which could be separated by applying light crushing force. No visible aggregate fracturing occurred during the loosening.

Figure 31: Shovelled heated PA (19-06 11:10)

Figure 30: Shovelling PA (19-06 11:24)

After the test section was cooled down to a degree that it became more difficult to loosen and the steam roller came back to a pressure of 11 bar, a greater area of 3.8m x 4m was heated for half an hour, including the previously heated section. No temperature recordings were done during this heating cycle, since the thermocouples where covered by the steam foil. After 35 minutes of heating, the recording of the thermocouples was started again after removing the steam foil which resulted in the cooling curve as seen in Figure 32.

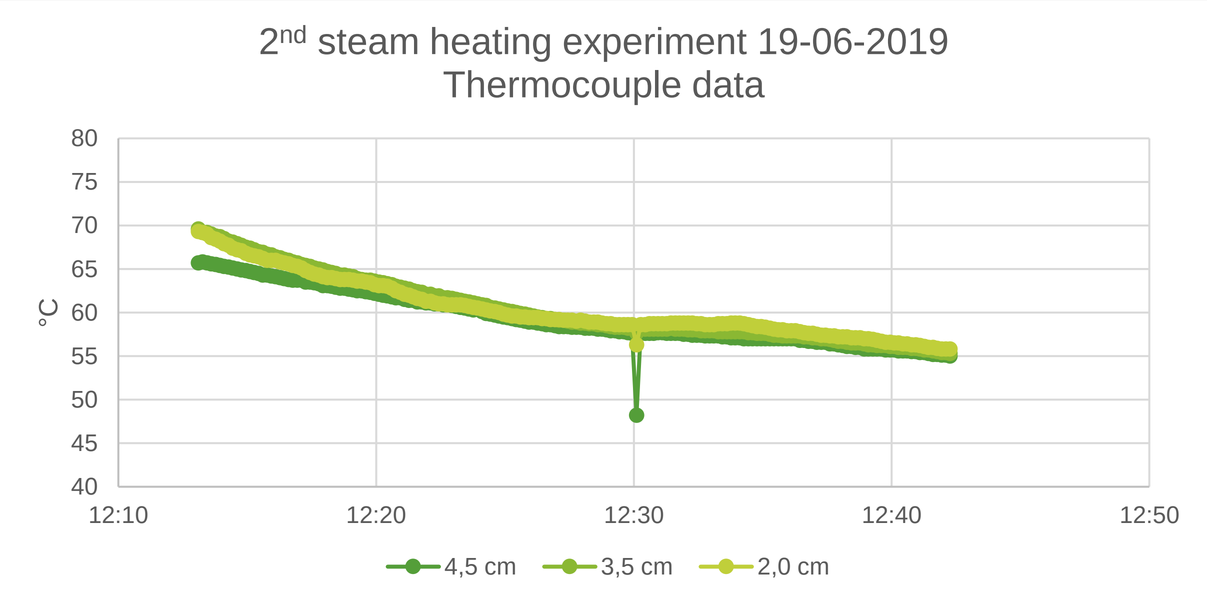

Figure 32: Second steam heating experiment thermocouple data

Comparing the cooling curve from the first experiment in Figure 29 and the cooling curve from Figure 32, it can be determined that the rate of cooling is lower for the second heating cycle. An explanation for this could be that the aggregates in the PA are not heated to the same degree as the mastic around the aggregate after 35 minutes of heating, which causes rapid cooling due to the cold aggregate after the first heating cycle. Another effect noticed is the rapid cooling of the top of the PA course in contrast to the bottom. This indicates that the heat loss of the PA course to the open air is greater than the loss of heat to the base course when not covered / heated.

Infrared heating experiments

The infrared heating experiments were conducted at the 21th of June. Here, the experiment was performed twice, where once the same test section used at the steam heating experiment was used. During the second experiment, some light rainfall occurred twice for small periods, where the temperature was around 15 degrees Celsius when the first experiment started after which it gradually climbed to 19 degrees Celsius at the end of the second experiment. During the experiments, there was a light breeze of around 1 to 2 m/s [77].

For the first experiment, the thermocouples had to be put into the slots again. Because of a large rainstorm which occurred after the steam heating experiment, some sand was lost into the voids of the PA, where extra crushed sand was added to cover the thermocouples. It was determined that the infrared heating would be applied intermittent, where the heater would be turned off when the surface temperature was 200 degrees Celsius and turned on when the surface temperature reached 100 degrees Celsius again. The thermocouple readings can be seen in Figure 33.

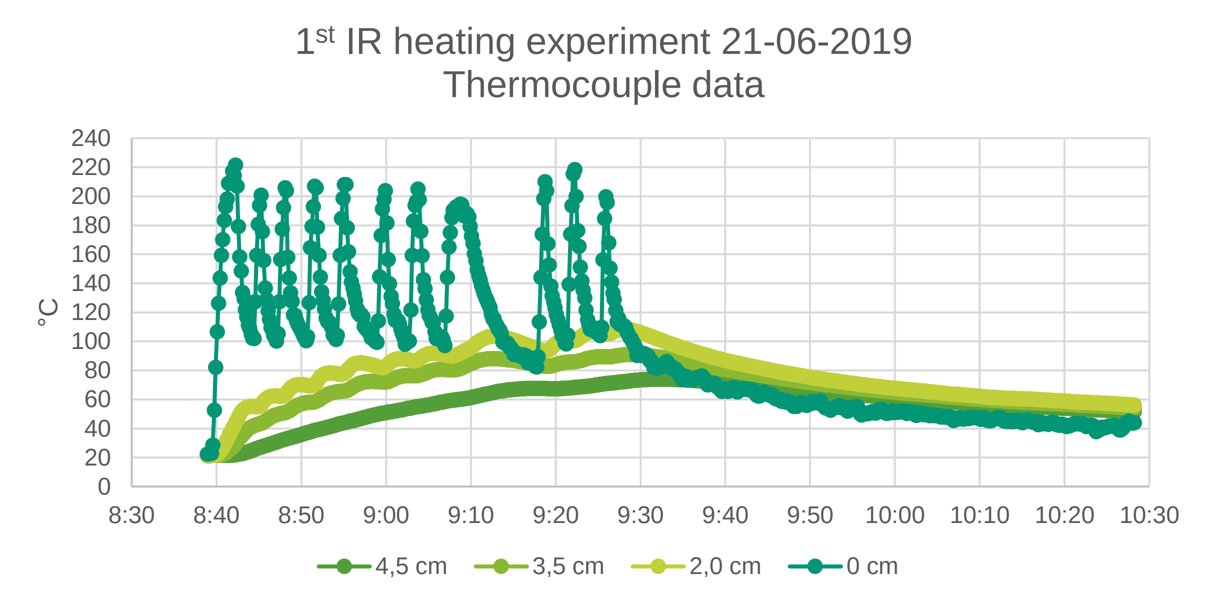

Figure 33: First IR heating experiment thermocouple data

In total, 11 heating cycles were needed to obtain a temperature of 74.1 degrees Celsius at a depth of 4.5cm in the PA, which took in total 54 minutes. The eighth heating cycle differs from the others because of the propane tank being empty, where it was switched with a full tank during the experiment. After the last heating cycle, the surface cools of the fastest, where the temperatures within the PA course reach a general temperature and have almost the same rate of cooling. Here, the same effect with the top cooling faster than the bottom to reach a general temperature is seen as with the steam heating experiment. The decrease of the rate of cooling over time can again be explained by the colder aggregates absorbing heat till the heat is evenly distributed.

The second experiment took place at a section which was not used by the steam heating experiment. The temperatures recorded by the thermocouples are displayed in Figure 34.

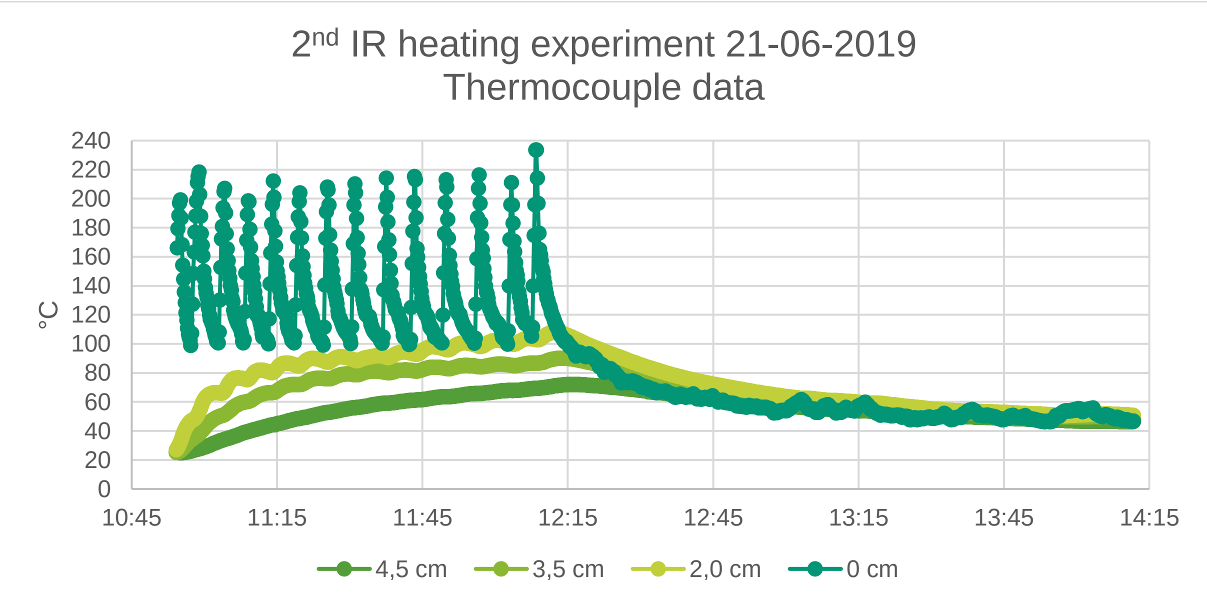

Figure 34: Second IR heating experiment thermocouple data

For this experiment, 14 heating cycles were needed to obtain a temperature of 72 degrees Celsius at a depth of 4.5cm, which took 1 hour and 22 minutes. Due to a wrong connection order to the data logger of the thermocouples, the first minute was not recorded. The second experiment took around 30 minutes longer than the first experiment to reach a temperature above 72 degrees at the deepest part measured, which can be explained by the filling of the voids with crushed sand for the first experiment.

3.4 Conclusion

In the experimental analysis, the two research questions involving heat transfer in PA will be treaded. First, the conceptual model creating will be treaded, after which the results of the experiments will be treated.

PA heating model

In the development of a PA heating model, many challenges were faced in quantifying the heat transfer from hot gas to PA, and how this heat distributes within the PA. Therefore, it was decided to leave the development of a PA heating model to a next research, where this research can provide a template on how to develop such a model. Important for a PA heating model is to determine the mastic temperature, since this this temperature determines when the PA can be loosened, and not the average temperature of the PA course. For simple calculations, like for Life Cycle Analysis calculations, the energy input can be calculated using the specific heat capacities for PA and hot gas.

Bitumen heating experiment

From the bitumen heating experiment, the effects of heating a viscoelastic fluid with low heat conductivity was seen. When the bitumen is cold, and thus has a high viscosity, conductive heat transfer is dominant. When the fluid reaches a higher temperature and a lower viscosity, convective heat transfer due to natural convection starts to take over as a dominant mode of heat transfer. This can be helped by mechanical input causing forced convection.
This answers the question on how temperature is distributed by the bitumen when heated. Now, this has consequences for the increase of temperature of bitumen. Since bitumen is not able to distribute its heat well at low temperatures, the directly heated bitumen will increase in temperature while the indirectly heated bitumen, which is only heated from the bitumen it is surrounded by, will only heat up slow. Therefore, the temperature difference between the heating surface and the bitumen at their contact point will decrease, resulting in less transfer of heat since all modes of heat transfer are dependent on this difference. During the increase of temperature, the bitumen is able to distribute its heat faster, leading to a lower temperature difference at the points of contact and thus in faster heating.
Note that these observations where done in heating bitumen in a drum with a diameter of 53cm. It is not certain if these effects are also of great importance in thin films of 33mu for PA courses.

PA heating experiment

In the PA heating experiment, the main research question was how the temperature over depth develops during steam and infrared heating. Since steam transfers heat throughout the PA course, because of its internal voids, it was expected that the difference between temperatures over depth would be lower for steam heating than for infrared heating. However, comparing the data from the thermocouples for both the first steam heating experiment and the infrared experiment showed that this might not be fully true. Figure 35 shows the temperature difference between the thermocouples at 2.0 cm and 4.5 cm for the steam experiment and both infrared heating experiments. It was chosen to take 2.0cm as the upper temperature, since the surface temperatures of IR would make the different heating methods incomparable. For both methods in all experiments, the temperature difference is between 30 and 40 °C, where there is no great difference between steam and IR except the wavy IR plot due to the intermitting.

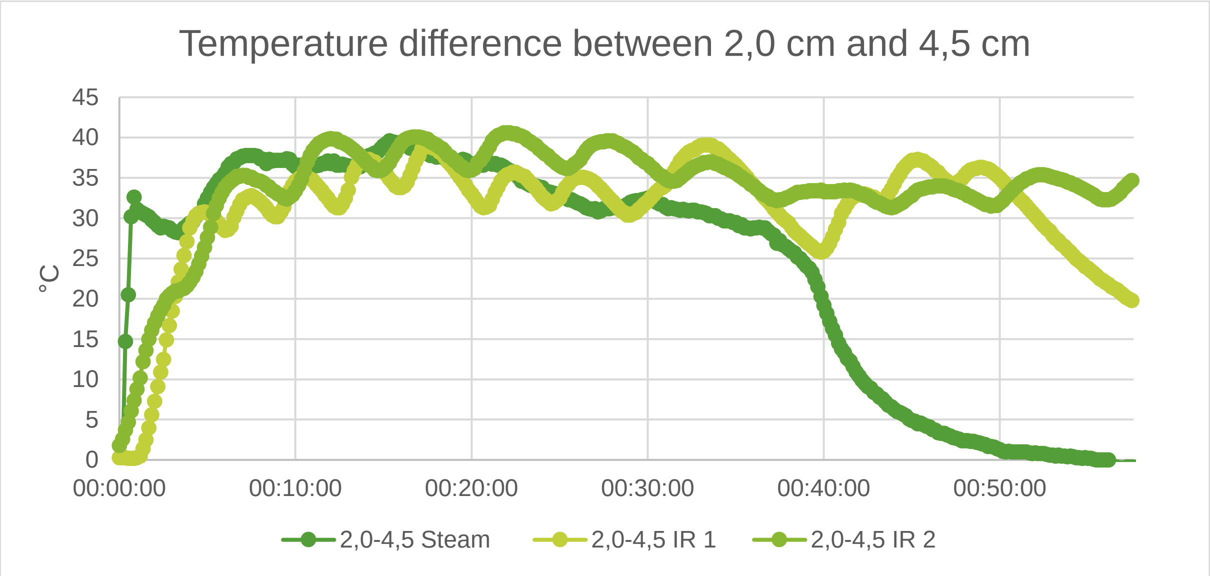

Figure 35: Temperature difference over depth between steam and IR

Therefore, from this data it can be seen that there little to no difference on the temperature development over a depth of 4.5 cm between steam heating and IR heating.

In all experiments, the thermocouples where placed into slots which were cut into the PA course. The slots were filled with coarse sand to prevent the thermocouples from being heated directly. The sand could have influenced the readings of the thermocouples.

After the steam heating experiment, the heated PA section was used to test if it could be loosened using a scarifier and a shovel. It was experienced that it was easy to loosen the PA, where there was no notable difference found between the top and bottom of the PA. Over time, it became more difficult to loosen the PA, where the observation was made that at least a bottom temperature of 70 °C is mandatory to loosen the PA.

4. Evaluate and discuss

Here, the research questions of the last phase will be treated with the knowledge of both the theoretical and experimental analysis in the conclusion. These concern the minimal temperature needed in an ART and which heating method requires the least time to heat the PA to a degree that it can be recycled only exposing it to the lowest temperature needed. In the discussion, a reflection on the main question of this research will be given. Finally, recommendations will be stated for Dura Vermeer for the further development of an ART to recycle 100% PA.

4.1 Conclusion

In this conclusion, the research questions of the last phase will be treated, together with the main research question.

Minimal temperature of PA course

In this study, the minimal temperature of the PA throughout the whole ART has been research using a literature study, where all individual process steps needed were reviewed. These process steps, including the minimum and maximum temperatures found from both the theoretical and experimental analysis, are displayed in Table 9.

Process step	Theoretical analysis	Experimental analysis	Conclusion
Pre-heating	<230 °C <135 °C (aging)	-	<230 °C <135 °C (aging)
Loosening	106 °C	70 °C[1]	70 °C
Reconditioning	-	-	-
Post-heating	<230 °C <135 °C (aging)	-	<230 °C <135 °C (aging)
Homogenizing	>100 °C	-	>100 °C
Paving	113 °C	-	113 °C
Compacting	125 °C	-	125 °C

Table 9: Temperatures for heating PA in ART

From the field tests done during the experimental analysis, it was determined that a temperature of 70 °C within the PA course is sufficient to loosen the PA from the test section without fracturing the aggregates. This also defines the minimal temperature the PA course needs to gain during the heating step. For the heating steps, there is a hard maximum of 230 °C above which the PA is irreparably damaged. Since the aging of the PA binder increases greatly above temperatures above 135 °C, it is favourable to use this as limit if possible. After the loosening, a minimal temperature of 100 °C is required, where the following steps of paving and compacting require temperatures of 113 °C and 125 °C respectively.
Depending on the techniques in the ART used, it is favourable to only heat the PA to the minimal required temperature for the loosening step at the heating step, because of the heat loss to the base course when heating a PA course. Post-heating the loosened PA after loosening and before or while mixing using a drum mixer/heater for instance results in more effective heating due to no loss of heat to the base course. Having a higher temperature during the mixing phase results in less need of additive aggressivity, mechanical input and time needed.
Therefore, the minimal temperature needed for the PA course to be recycled in an ART is the temperature needed for the compaction, which was determined at 125 °C, but depends on the type of asphalt mixture. However, due to the lower temperature requirements in the preceding steps of the recycling process, the ART should be designed such that it is able to heat the collected PA after loosening and not only during the heating of the PA course where heat is lost to the base course.

[1] Using new HM 20/30 bitumen, see section 3.3

Best heating method for heating a PA course

In this research, 3 heating methods to heat a PA course have been reviewed. In the theoretical analysis, the use of hot air versus superheated steam has been reviewed. In the experimental analysis, field tests using both steam and infrared heating have been done on PA. Since there was no field test using hot air heating nor an extensive review on infrared heating, this comparison is not complete. However, using the findings from both the theoretical and experimental analysis, these three methods can be compared.

The thermodynamic properties of hot air and superheated steam have both been reviewed in the theoretical analysis. It was found out that steam holds much more heat than air for the same temperatures, due to the higher heat capacity of steam. Moreover, steam has the advantage of its phase change at 100 °C, where it condenses to water. Due to the latent heat of vaporization, which is released during the condensation, the temperature does not change where a great amount of heat is released. Since the temperature of the steam does not decrease during the release of this latent heat, the temperature difference between the condensing steam and the PA only decreases due to the temperature increase of the PA. Since the rate of heat transfer is proportional to the temperature difference, this rate does almost not decrease. However, due to its latent heat and higher heat capacities, generating superheated steam requires a lot more energy than generating hot air of the same temperature. Also, the exact difference in heat transfer is determined by the heat transfer coefficient, which were not determined in this research. However, the experience gained in researching heat transfer coefficients learned that this coefficient for steam is always higher than for air. Thus, steam will always be able to transfer its heat faster to the PA than air, which will be an important factor in the design of an ART.

Radiative heat transfer is dependent on the area it is subjected to, as is convective heat transfer for both hot air and superheated steam. Using hot gas, the area around the internal air voids of PA is also used, where infrared is only subjected to the top surface area of the PA course. Therefore, according to the theoretical analysis, steam heating should take the least time.

In the experimental analysis, field tests were done for both steam and infrared heating. Using the thermocouple temperature measurements, the increase of temperature over time at the same depth can be plotted, as displayed in Figure 36.

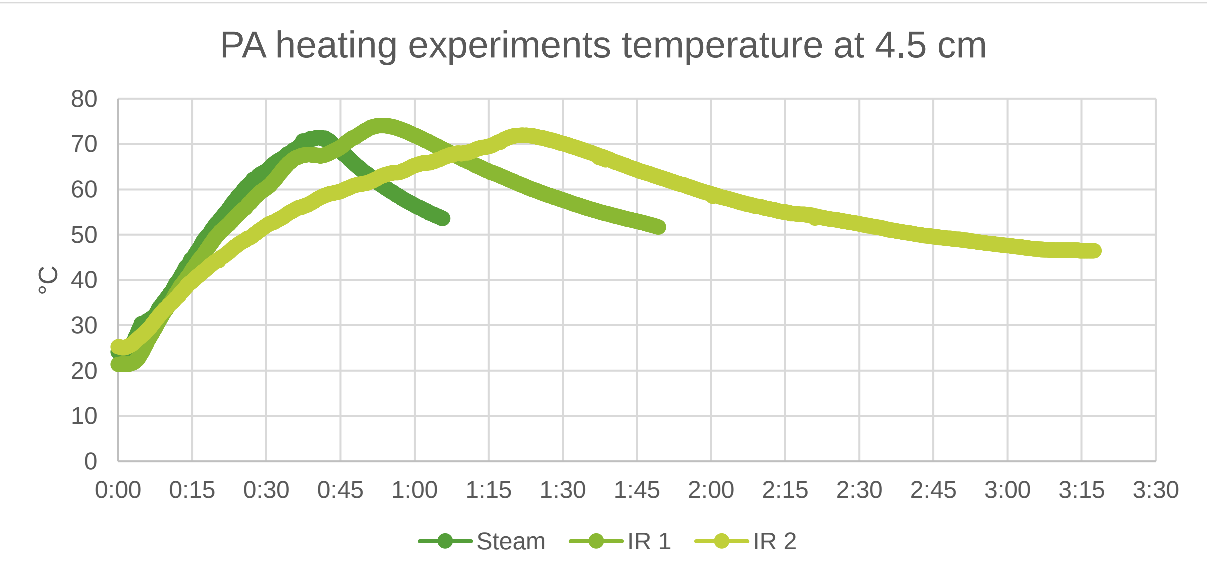

Figure 36: Heating methods temperature increase over time

From the field tests, it can be seen that the steam heating method took less time to heat the PA to the target temperature of 70 °C. However, the first infrared experiment took almost as much time as the steam experiment, where an empty gas cylinder during the experiment caused the extended duration to reach the target temperature. The second infrared experiment took place at a section which was not used for testing before, where the first infrared experiment took place at the same section used by the

steam experiment, where sand was infiltrated in the PA. During the second infrared experiment, it took considerably longer to reach the target temperature of 70 °C.
Though the duration of the first infrared experiment is almost equal to the steam heating experiment, the infiltrated sand may have increased the conductivity of the section around the thermocouples. Also, it is not possible to decrease the time needed for heating using an infrared heater with a greater heat output, since this will only cause the surface to heat up faster, where it must be turned off before the surface temperature reaches 230 °C.
Since IR heating leads to extreme temperatures, there are far more emissions due to burning the bitumen. Hot air heating also uses high temperatures over 600 °C which can also lead to burning the bitumen. Superheated steam heating leads to far less emissions since the bitumen is guaranteed not to burn since temperatures will in most cases not exceed 100 °C since the bitumen is covered by a small film of water resulting from the condensation of the steam.
With the steam experiment, steam from a firebox steam boiler was used with a temperature of 100 °C. Using slightly superheated steam, almost all water will be vaporized such that the superheated steam can transfer its full latent heat of vaporization to the PA, which can cause faster heat transfer and thus less time needed to heat the PA.
Therefore, the results of both the theoretical analysis and experimental analysis showed that heating using superheated steam takes the least time to heat PA to a temperature of 70 °C. All results combined on the three alternatives are summarized in Table 10, where green indicates the most favourable alternative for the indicator and red the least favourable.

	Hot air	**Superheated steam**	**Infrared heating**
Rate of heat transfer			
Bitumen emissions			

Table 10: Heating methods conclusions

Optimal Asphalt Recycling Train layout

In this research, the process steps in an ART have been defined where they where all researched on how they are implemented in existing ART's together with the use and effects of heat are in these steps. For the pre-heating stage, different alternatives have been theoretically and experimentally analysed on their effectiveness. This knowledge combined, an optimal layout of an Asphalt Recycling Train to 100% recycle PA surface courses can be described.
First, the ART needs to be able to perform all process steps, namely: (1) pre-heating, (2) loosening, (3) reconditioning, (4) post-heating, (5) homogenizing, (6) paving and finally (7) compacting. For the pre-heating stage, theoretical and experimental research resulted in the use of superheated steam being the most effective method in taking the least time to heat the PA to a temperature at which it can be loosened. Loosening should be performed gently, but also needs to ensure an even base course to provide good adhesion with the recycled surface course. From literature study on existing ART's, rotating scarifiers should result in a minimal risk on fracturing and an even base course.
Reconditioning should be performed such that the recycled mixture's quality is as good as a new asphalt mixture. Therefore, it is important to determine the reclaimed asphalt characteristics, on which the addition of new materials can be based. When reactive liquids are added, these should immediately be homogenized with the reclaimed asphalt to ensure good dispersion and thus even diffusion. These liquids should always be added with a temperature at which they are liquid enough to ensure good dispersion. When only a small amount of aggregates is added to the reclaimed asphalt, it can be considered to not heat the aggregates on beforehand, to simplify the logistics and design of the ART. On the other hand, heated aggregates reduce the need for more extensive post-heating of the recycled mix. An optimal ART needs to be able to perform post heating, both on the recycled mixture as on the base-course. To post-heat the asphalt mixture, a drum mixer heater ensures effective and fast heating, while also having a positive effect on the homogenization of the recycled asphalt mixture. The base course should be heated using hot air or intermittent IR, such that there is good adhesion between the recycled surface course and the base course, removing all moisture from the base course

surface. Homogenization should be performed using a closed twin-shaft pugmill to ensure good final homogenization of the asphalt mixture, where there is an even gradation and even bitumen characteristics throughout the whole recycled asphalt mixture.
The final steps, 6 and 7 should be done in one pass using for instance an oscillating screed to minimize uncertain factors but can also be performed using conventional paving and compacting equipment.
Note that the design as described above does only implement the requirements of the ART within the scope of this research. An optimal ART should also be able to implement more processes within the processes described above, such as the cleaning of the PA before loosening.

4.2 Discussion

The aim of this research was to contribute to the development of an implementation of the Asphalt Recycling Train in the Netherlands to achieve 100% recycling of PA courses in-situ. This research consists of a theoretical analysis which focusses on the Dutch guidelines on what PA is, and how an ART would fit in these guidelines. The processes of an ART to recycle PA are defined, and existing ART's are reviewed to investigate the technologies used. Finally, thermodynamic relations and properties are reviewed for both superheated steam and hot air.
Using the thermodynamic relations and important properties, it was the idea to develop a model which can accurately describe the heat transfer to the PA using hot gas such as superheated steam and hot air. However, the number of parameters which was needed for the model was underestimated. Since these parameters are not all known for PA, it was chosen to only create a conceptual model, which can be used in the creation of an actual model in a separate research.
The field tests provided practical experience with the heating of PA. It was observed that it was practically possible to heat PA using steam, and loosening could easily be performed at the target temperature. Also, a lot of data has been generated from these field tests, which can also be used in future research on the ART.
Now, the aim of this research was very broad, which resulted in broad research questions which do all relate with each other, but do not go in depth. Therefore, it was difficult to determine the scope of this research. Some aspects needed a more in-depth review than anticipated, such as the model, and was therefore left out. This resulted in some complications, since the research design had to be altered very often. Also, some results which were found where interesting to mention and thus deserved a research question. In doing this however, the scope of this research was widened again.
The most important question is if this research is able to answer its main question, namely:

What use and effect does heat have on the processes within an Asphalt Recycling Train for recycling 100% PA in-situ, and which method for heating a PA course performs best on efficiency?

In the theoretical analysis, the use and effects of heat in an ART have thoroughly been described. Minimum and maximum temperatures have been determined using literature, where the minimal temperature for the loosening of PA has been determined using field experiments. Also, a good overview of the three reviewed heating methods was made, where efficiency is determined by the time each method needs. The efficiency on energy required for each method was not determined however, due to the complications in creating the model which would have resulted this.
In the end, this research provides a stand-alone overview of the Asphalt Recycling Train concept, and what use it could have in the Netherlands, and how this should be done.

4.3 Recommendations

The recommendations of this research are addressed to Dura Vermeer for their further research on the Asphalt Recycling Train.
As stated in the project framework, Dura Vermeer will continue researching the impact of construction and use on the gradation of the PA course, and also how the PA binder can be rejuvenated to a level such that the recycled PA course is as good as a new PA course. To perform this research, aged PA will be collected from a Dutch national road in September this year. Here, the same way of working as

with the steam heating experiment will be applied. As a result of this research and the observations done during the steam heating experiment, the following recommendations are done on the collecting of PA from a national highway.

- Due to its age and use, the PA will be contaminated with dirt. When drill cores are drilled, weighing the contamination in the PA by soaking and washing the drill cores before other tests are done would provide a good validation to the contamination percentages found in the theoretical analysis. This also prevents tests on the PA core after extraction to be inaccurate.
- When a section is chosen to collect by heating the PA, it should be thoroughly cleaned using a PA-cleaner before the PA is heated and collected, to ensure that there is as little contamination in the PA as possible, such that mastic tests do not show a great weight percentage of fine particles.
- As also stated in the conclusion, the latent heat of vaporization of steam provides a huge amount of heat, which should all be transferred into the PA to create maximum efficiency. Therefore, during the steam heating, the supply of steam should be just enough that there is no steam escaping through the PA around the covering steam foil. Then all steam condenses within the PA, thus using the steam effectively.
- The field tests were performed on a non-contaminated young PA course, which had a void percentage of 28%. Since the void percentage is usually 20% at a well-constructed national road, a longer heating time should be anticipated. This because more heat is required because of the higher density, and because there is less surface area on the internal voids. To prevent the steam boiler used from being at low pressure during the experiment, the recommendation stated above should be applied.
- The thermocouple data collection during the experiments was easy to setup and to dismantle. Therefore, it is recommended to perform the same data collecting during the heating of the PA sections at the highway, to generate more data which can be used for future research on heat transfer in PA.
- In the reconditioning phase of the ART, the addition of materials should be based on the characteristics of the reclaimed asphalt. However, the question is how this can be measured, and to what extent these characteristics vary in a surface course which has been paved in one pass, and how to cope with repair patches. Therefore, quality control in an ART is an important subject for future research.
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In this research, it was tried to develop a model which could accurately predict the temperature of PA course when subjected to heating using a hot gas. The main parameter which was not able to be determined was the heat transfer coefficient. Since calculating the heat transfer coefficient for PA would take a lot of assumptions, it is recommended to measure this coefficient using PA cores in a test device, where steam, superheated steam or hot air can be applied on a core, where multiple thermocouples measure the temperature increase over the height of the core to determine the heat transfer coefficient empirically. This could be done in a study to develop a PA heating model, where more research should be done on the thermodynamics of convective heat transfer. This research can serve as a research gap, since this research shows the need of such a model and provide data from the field tests and a template for the conceptual model. Using this model, it can also be determined what the optimal temperature for superheated steam would be to have maximum heat transfer within the PA.

According to the theoretical analysis, the aging of the PA binder increases greatly at temperatures above 135 °C. Therefore, it is assumed that the PA ages more when heated with infrared heating in contrast to heating with superheated steam. However, extreme temperatures caused by infrared heating are only present on the surface. To see if the difference of aging between infrared heating and steam heating is negligible, the samples taken for both heating methods from the field test can be tested on the binder its rheological properties and compare these. This then can also be used to quantify the aging effect of infrared and steam heating which is needed to account for by adding more additives.

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6. Appendices

A. ZOAB specifications

Name [45]	**Bitumen** [45]	**Min. voids(%)** [45]	**Binder content (%)** [45]	**Min/Recommended/Max thickness (mm)** [43], [46]
ZOAB 16	70/100	20	4.5	50/50/60
ZOAB 16 +	70/100 or polymer modified	20	5.2	50/50/60
ZOAB 11	70/100	20	4.5	25/30/40
2L- ZOAB 8	Polymer modified	20	5.4	-/25/-
2L- ZOAB 5	Polymer modified	20	5.4	-/20/-
2L- ZOAB 16	70/100 or polymer modified	25	4.2	45/-/50

	(% mass/mass)					
	ZOAB 11	ZOAB 16	ZOAB 16 +	2L- ZOAB 16	2L- ZOAB 5	2L- ZOAB 8
Aggregate type (1-3) NEN-EN 13043	2	2	3	2	3	3
Sieve size (mm)						
22,4		100	100	100		
16	100	93-100	93-100	90-100		
11,2	91-100	70-85	70-85	DV		100
8	15-40				100	90-100
5,6					90-100	NR
4					NR	
2	15-25	15-25	13-25	5-25	5-25	5-25
0,5	NR	NR	NR	NR	NR	NR
0,063	2,0-10,0	2,0-10,0	2,0-10,0	2,0-10,0	2,0-10,0	2,0-10,0

DV: Declared value, given by producer
NR: No requirement

B. Highway road marking pollution

In this appendix, the amount of pollution of road markings in kilogram per square meter will be calculated. For these calculations, the Dutch guidelines for the beaconing and marking of roads is used [78]. Here, a simple stretch of straight 2-lane highway is considered with a lane-width of 3.5m is considered, where continuous road marking is applied at the edges and discontinuous marking between the lanes, as visualised in Figure 37.

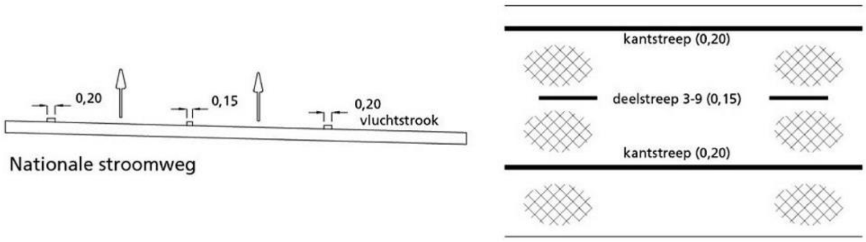

Figure 37: Division and edge markings for Dutch highways [78]

According to the guidelines, thermoplastic road marking is applied with a minimal thickness of 3mm. The division marking naming, 3-9 for highways, indicates 3m of road marking after which 9m of does not have to be marked. The amount of road marking for a standard Dutch highway can then be calculated as such:

$$V_{road\ marking} = \frac{0.003 \times (2 \times 0.2 \times 12 + 0.15 \times 3)}{12 \times 2 \times 3.5} = 187.5 \times 10^{-6} \frac{m^3}{m^2}$$

Where thermoplastic road marking has a density of 2000 kg/m^3 [79], the amount of pollution by thermoplastic road marking on standard road sections is 0.375 kg/m^2.

C. Asphalt loosening

Nilsgart and Grybb [31] determined the relation between temperature and viscosity of aged bitumen using an altered version of the WLF formula, given by Equation 9.

$$\log\left(\frac{\eta}{\eta_{ref}}\right) = -\frac{C1(T-T_{ref})}{C2+T-T_{ref}} \text{ [31] [32] [33] (9)}$$

Where,
η is the calculated viscosity,
η_{ref} is the reference viscosity, which is normal at 1.3 kPa s,
T_{ref} is the reference temperature and
T is the temperature for which the viscosity is calculated

C1 and C2 are constants determined by fitting on a set of data. Nilsgart and Grybb [31] performed this fitting for RFTOT (Rolling Thin Foil Oven Test) and PAV (Pressure Aging Vessel) aged 70/100 bitumen, which represents the final stage of bitumen in aged pavements. In Table 11, the constants for the WLF formula are given.

Bitumen	**C1**	**C2**	**T_{ref}**
70/100 RTFOT + PAV	8.23	119.0	63.6

Table 11: Constants in the WLF formula for aged 70/100 bitumen [31]

Using the altered WLF formula, the temperature can be determined for a certain viscosity. The maximum viscosity allowed before aggregate fracturing occurs in PA loosening can be calculated using Equation 10.

$$F = \mu A \frac{u}{y} \text{ (10)}$$

Where:
F = Magnitude of force acting on the aggregate (N)
μ = Viscosity of the fluid (pa s)
A = Area of binder contact between aggregates
u = The shear speed
y = The thickness of the binder between the aggregate

Here, the maximum force F is determined by the shear strength and dimensions of the aggregate. A shear strength of 60 N/mm^2 is taken for granite aggregate with a mean diameter of 8mm for PA 16 [80]. The area of contact was determined by assuming an 8mm sphere with 20% contact area with the binder. The shear speed was determined at 2.5 m/min, being the speed of the ART if scarifiers are used. With these parameters, a maximum viscosity of 9838.25 Pa s was determined. Using Equation 9, a minimum mastic temperature of 106 °C was determined.
It must be noted that this value is purely theoretical and is only valid when the binder only consists of bitumen, while mastic is considered to be stiffer than bitumen. Also, the mean diameter of 8mm is an assumption, where the stone orientation and shape will matter most.

D. Mixture composition ZOAB 16

Asfaltproductie Eemnes
Eemweg 82
3755 LD Eemnes

Telefoon 035 54 33 520
Fax 035 54 30 421
EMail productie@asfaltproductiedeeem.nl

AIS
MR09

Mengselrecept Samenstelling
Datum laatste wijziging: 20-03-2017

blad 1

Recept : **757000** **ZOAB 16 70/100**

Bouwstoffen :

Bouwstof		Ontwerp hoeveelheid	Her-berekening
4610	Bestone 4/8	%	14.94 %
4620	Bestone 8/11	%	39.77 %
4630	Bestone 11/16	%	26.58 %
5030	Schotsgraniet Brekerzand 0/2	%	9.86 %
6190	Eigenstof	%	1.00 %
6300	Wigro 60K	%	3.45 %
7030	Bitumen 70/100	%	4.40 %

Samenstelling :

Zeef	Doel-samenstelling (% m/m)	Her-berekening (% m/m)	FPC Soort	FPC Min. (% m/m)	FPC Max. (% m/m)	Samenstelling na extractie (% m/m)
C 22,4	100.0	100.0	14D	98.0	100.0	
C 16	96.7	96.7	DZF	87.7	100.0	97.5
C 11,2	72.5	72.5	CCS	63.5	81.5	70.2
C 8	37.2	37.1				
C 5,6	22.4	22.4				
2 mm	15.0	15.0	2MM	8.0	22.0	14.3
500 µm	8.5	8.4				
125 µm	5.3	5.2	CFS	0.3	10.3	
63 µm	4.5	4.5	63U	1.5	7.5	5.1
Bindmiddel-gehalte (% in m/m)	4.4			3.8	5.0	

100% LIJST METACOM

E. Mastic film thickness and void surface area calculations

To calculate the mastic film thickness and void surface area of PA, the analytical formulas from Radovskiy were taken [72].

To determine the mastic film thickness, the following formula can be used.

$$a_1 t + a_2 t^2 + a_3 t^3 = \ln\left[(1-\varphi]/V_{air}\right]$$

Where:

$$a_1 = \frac{6qm_2}{m_3}$$

$$a_2 = \frac{12qm_1}{m_3} + \frac{18q^2(m_2)^2}{(m_3)^2}$$

$$a_3 = \frac{8q}{m_3} + \frac{24q^2 m_1 m_2}{(m_3)^2} + \frac{16q^3(m_2)^3}{(m_3)^3}$$

$$q = \frac{\varphi}{(1-\varphi)}$$

$$\varphi = (1 - VMA)(1 - P_d)$$

$$VMA = V_{Air} + \frac{m_d}{d_b} * d_m \text{ [81]}$$

$$d_m = \frac{100}{\frac{m_s}{d_s} + \frac{m_z}{d_z} + \frac{m_f}{d_f} + \frac{m_b}{d_b}}$$

To determine the average surface area on the boundary of the air voids per unit volume of pavement, the following formula is used.

$$S(t) = (1-\varphi)(a_1 + 2a_2 t + 3a_3 t^2)\exp[-(a_1 t + a_2 t^2 + a_3 t^3)]$$

Variable	**Description**
m_1	Mean of diameter of aggregate particles over particles' number distribution
m_2	Mean of diameter squared
m_3	Mean of diameter cubed
P_d	Volume fraction of aggregate passing sieve of diameter d, where d = t
V_{Air}	Volume fraction of air voids in compacted mixture
m_s, m_z, m_f, m_b	Mass fractions of stone, sand, filler and bitumen in mixture
d_s, d_z, d_f, d_b	Density of stone, sand, filler and bitumen