Balancing Materials, researching the circularity of ZOAB

Bachelor Thesis report

Version 3.0

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Preface

This report has been written for Rijkswaterstaat to give insights into the current potential of circularity and recycling of porous asphalt mixtures in the Netherlands. The incentive for this report came from contractors claiming the emergence of a shortage of high-quality porous asphalt milling. Rijkswaterstaat wants to get more insights into this claim by increasing its knowledge about the state of porous asphalt recycling in the shifting economy where circularity will play a crucial role. This report aims to provide an overview, status and investigation into the circularity of porous asphalt mixtures in practice. This will include a case study in which the closed-loop recycling (also known as horizontal recycling) of two representative construction projects will be thoroughly examined. This report can help the discussion around circularity by informing about the current practices. It also intends to demonstrate considerations to be made as well as noticing problems surrounding the transition towards a circular economy. The target audience is knowledgeable within the asphalt industry as well as familiar with circularity and sustainability aspects.

During the project, I have been under the supervision of Dr. R. Hofman and Dr. S.R. Miller. I would like to personally thank them for the help, support and interesting insights into the subject. I would also like to thank Rijkswaterstaat and ASPARi for making it able to conduct an internship at Rijkswaterstaat. Lastly, I would like to thank all interviewees for participating and sharing their knowledge with me.

Colophon

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Terminology

Term	Dutch translation	Definition
Bruising	Kneuzen	Recycling technique: Utilizing a rotating drum, chunks of milled asphalt will fall apart. Less breaking of asphalt milling has to be done resulting in a higher yield of high-quality coarse fractions of RA.
Closed-loop recycling	Horizontaal hergebruik	The process of recycling a product back into its original form without loss of quality
EPD-value	Millieukostenindicator (MKI)	Environmental Product Declaration (Rijkswaterstaat, 2019)
IenW	-	Ministry of Infrastructure and Water Management
IGO	Integraal groot onderhoud	Integral Major Maintenance projects
NL-PCR-Asfalt	-	Product Category Rules for bituminous materials in traffic carriers and waterworks in the Netherlands. (Keijzer, et al., 2020)
PA	ZOAB	Porous asphalt
Porous asphalt milling	ZOAB-frees	Porous asphalt Milling, Product gained from milling end-of-life porous asphalt layers.
RA	PR	Reclaimed Asphalt, also known as Partial Recycled (PR), recycled granulate to be used as a resource for new layers of asphalt.
RWS	-	Rijkswaterstaat, the Dutch department of Public Works
VBW	-	Vakgroep Bitumineuze Werken, association of construction and infrastructure companies in the Netherlands

Summary

Balancing materials, researching the circularity of ZOAB is a bachelor thesis carried out for Rijkswaterstaat to gain insights into the circularity of porous asphalt in the current Dutch asphalt industry. The purpose is to Investigate current circularity potential by looking at the closed-loop recycling of porous asphalt in the Netherlands. As well as Indicating the current issues concerning the circularity of porous asphalt and the collecting of the required secondary resources.

The questions above have been researched through a combination of literature review and interviews with experts in asphalt recycling and circularity. Furthermore, a case study has been carried out in which a secondary material balance has been used to indicate the circularity of two construction projects. Since one of the projects is a maintenance project and the other a widening project, differences in the circularity strategy have been noticed. These projects can be regarded as representable for Rijkswaterstaat projects.

To determine the circularity of a project, it is crucial to map the material flows. The project focuses on porous asphalt and determines circularity based on the percentage of porous asphalt milling that does not leave the system and is not down cycled. This approach is adapted from the guideline "Measuring circularity" (Platform CB'23, 2020),[1] and aims to reduce the quality of the material as little as possible.

The data used in the case is provided by the contractors, this data includes quantities of milled asphalt and the asphalt mixture planning. With this information, a percentage of circularity for porous asphalt has been calculated. For the first project, this was 33%. The second project realised a closed-loop circularity of porous asphalt of 56%. The differences can be explained by looking at the strategies.

In the first project, porous asphalt mixtures with a maximum of 40% reclaimed asphalt were chosen to use the porous asphalt milling as effectively as possible. This does not necessarily imply closed-loop recycling, but rather the most effective use of material.

The second project used porous asphalt mixtures with up to 70% reclaimed materials. This percentage could be achieved through the use of mixtures, including both reclaimed asphalt and PA-stone. A problem is that there is not enough porous asphalt milling in this project to achieve this 56%. Therefore, extra porous asphalt milling has to be imported from other projects. This demonstrates the scarcity existing on the porous asphalt market. It has been noticed that the shortage only occurs for coarse fractions of the asphalt milling. This is due to the breaking of coarse fractions into smaller fractions during recycling. Leading to a shortage of coarse aggregates and a surplus in fine aggregates. The contractor indicated that not the technology, but the availability of material was a limiting factor in the process.

Literature determines the current maximum percentage of closed-loop recycling of porous asphalt around 60% (Jacobs, Frunt, & Rering, 2016)[2]. The case study showed that 56% circular could be possible, but it will lead to a shortage of porous asphalt milling. This shows that the sector can improve its circularity further, but some challenges have to be overcome.

The main conclusion from this report is that to increase the circularity of the asphalt market in the Netherlands, the focus has to be put on the logistical challenges. The level of circularity for a project is difficult to express because it is influenced by many project-specific factors. It, therefore, is key to

[1] (Leidraad ''Meten van circulariteit'', 2020)
[2] (PA-stone: Op weg naar asfalt met 100% recycling, 2016)

see circularity as a broader and logistical problem. Balancing the supply and demand for reclaimed asphalt is vital to ensure a more circular economy. It is recommended to integrate circularity on a larger scale than project-wise. Since focussing on circularity in one project leads to compensating on other projects. Lastly, many of the interviewees indicated the need for information. To achieve high circularity in a project, it has to be known what materials will become available to use. As well as more overview of the supply and demand for specific types of secondary materials in projects. Increasing the availability and quality of data can ensure a better logistical process and therefore a more circular industry.

Samenvatting

Dit verslag onder de naam: Balancing materials, researching the circularity of ZOAB. Is een bachelor thesis verslag uitgevoerd voor Rijkswaterstaat. Het onderzoek is Engelstalig maar bevat een samenvatting in het Nederlands. Het onderzoek is uitgevoerd om inzicht te verwerven in de circulariteit van poreus asfalt in de Nederlandse asfaltmarkt. Het doel is om de potentie van circulariteit te onderzoeken door te kijken naar het horizontale hergebruik van ZOAB in Nederland. Evenals als inzicht vergaren in de huidige problemen met betrekking tot het gebruik van circulaire ZOAB en het vergaren van de benodigde secundaire grondstoffen.

Bovenstaande vragen zijn onderzocht door een combinatie van literatuuronderzoek en interviews met experts op het gebied van asfaltrecycling en circulariteit. Daarbij is er een casestudie uitgevoerd waarin een secundaire materialen balans is opgesteld om de circulariteit van twee bouwprojecten weer te geven. Deze projecten kunnen worden gezien als representatief voor werken van Rijkswaterstaat omdat er zowel een verbredings- als onderhoudsproject is onderzocht. Deze verschillende projecten hebben een verschillende circulariteitsvisie.

Om het begrip circulariteit uit te leggen is er gekeken naar de leidraad ''Meten van circulariteit'' (Platform CB'23, 2020)[3]. Zij stellen dat het in kaart brengen van materiaalstromen cruciaal is om de circulariteit van een project te beoordelen. De circulariteit van een project wordt in dit onderzoek beschreven als het percentage ZOAB-frees dat het systeem niet verlaat en niet wordt gebruikt in een lagere toepassing. Hierdoor kan het een goede indicator zijn van de hoeveelheid oude ZOAB die hoogwaardig wordt hergebruikt binnen het project.

De data die is gebruikt in de casestudie is afkomstig van de aannemers. De gegevens omvatten de hoeveelheden gewonnen freesasfalt en de asfaltmengelplanning. Met deze informatie gecombineerd met de effectiviteit van het verwerken van ZOAB-frees naar secundaire grondstoffen is het percentage circulair gebruik bepaald. Het eerste project haalde een percentage van 33%, dit betekent dat 33% van de vergaarde ZOAB-frees hoogwaardig hergebruikt is in de nieuwe ZOAB. Het tweede project bereikte 56% hoogwaardige hergebruik van ZOAB. Het verschil kan deels worden verklaard door de recycle strategie van beide projecten te analyseren.

Het eerste project heeft gekozen voor ZOAB-mengsels met maximaal 40% hergebruikte materialen. Dit is gedaan om de hoeveelheid beschikbare ZOAB-frees zo efficiënt mogelijk te benutten. Dit betekent niet noodzakelijkerwijs recycling in een gesloten kringloop, maar eerder het meest effectieve gebruik van materiaal. Het tweede project gebruikt ZOAB-mengsels met maximaal 70% hergebruikte materialen. Dit is mogelijk door een combinatie van PR en PA-stone te gebruiken. Een probleem is dat er in dit project te weinig poreus asfalt wordt gefreesd om de 56% circulariteit te behalen. Daarom is besloten om extra ZOAB-frees te importeren uit andere projecten. Dit leidt tot schaarste.

Door middel van onderzoek naar dit tekort is gebleken dat er enkel een tekort optreedt voor de grove fractie asfaltgranulaat. Een verklaring hiervoor is dat gedurende het recycleproces, de grove fracties granulaat breken. Er komt dus minder grove fractie vrij dan dat er benodigd is. Het knelpunt ligt dus in de beschikbaarheid van materiaal en niet in het ontbreken van technieken.

Het huidige maximale horizontaal hergebruik percentage voor ZOAB ligt volgens de literatuur rond de 60% (Jacobs, Frunt, & Rering, 2016)[4]. Uit de casestudie blijkt dat 56% hoogwaardig hergebruik

[3] (Leidraad ''Meten van circulariteit'', 2020)
[4] (PA-stone: Op weg naar asfalt met 100% recycling, 2016)

mogelijk is, maar dat zal leiden tot een tekort aan ZOAB-frees. Een verbetering is mogelijk, maar er zullen voornamelijk logistieke uitdagingen worden overwonnen. De belangrijkste conclusie uit dit rapport is daarom dat de focus moet komen te liggen op de logistieke aspecten van circulariteit. Deze focus kan de circulariteit van de Nederlandse asfaltmarkt verbeteren. De mate van circulariteit van een project is moeilijk uit te drukken en nog moeilijker om onderling te vergelijken doordat deze wordt beïnvloed door veel project specifieke factoren. Het balanceren van vraag en aanbod voor ZOAB-frees is essentieel. Het is aan te raden om dit op een grotere schaal te doen dan projectgewijs. Doordat focus op circulariteit binnen een project veelal leidt tot schaarste op de ZOAB-frees markt, met als gevolg dat andere projecten moeten compenseren op hun circulaire ambities.

Tenslotte is er geconcludeerd op basis van de interviews dat er een behoefte aan data is. Om circulair te plannen en te werken is er informatie nodig over de hoeveelheid, en kwaliteit van de beschikbare grondstoffen. Dit kan leiden tot een beter logistiek proces en efficiënter gebruik van de beschikbare secundaire grondstoffen.

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1. Introduction

1.1. Organisation

Rijkswaterstaat is an agency of the Ministry of Infrastructure and Water Management focussed amongst others on the construction and maintenance of the major infrastructure networks in the Netherlands. The agency has multiple subbranches with specialities, tasks and goals. This thesis has been conducted within the road construction group of the organizational unit of Major Projects and Maintenance.

1.2. Background

Depletion of resources proposes a significant problem in the near future. Humanity is depleting the natural resources of the earth. Subsequently, it has become apparent that these natural resources might no longer be available for mining in the future. The Dutch national government is attempting to change the way the Netherlands consumes and produces goods and services. The government has implemented a circular economy implementation program. (Uitvoeringsprogramma circulaire economie) (Rijksoverheid, 2019)[5]
Based on the above-mentioned program, Rijkswaterstaat wants to adapt and encourage a paradigm shift in the way of constructing infrastructure. A circular economy must become the routine in infrastructural projects. The ambition of Rijkswaterstaat to work climate neutral and circular in 2030 (AanbestedingNieuws, 2020).[6]

This research will focus on visualizing and grasping the current status of circularity in the asphalt industry. The report will demarcate itself by focussing on the circularity of PA (ZOAB) surface layers. PA is the preferred pavement for high-intensity roads in the Netherlands. A substantial part (>80%) of the road network of Rijkswaterstaat comprises of ZOAB surface layers. Currently, the task is to improve its circularity rapidly.

It is technologically possible to create porous asphalt with up to 90% reclaimed material. Though, it is currently not possible to realise 100% circularity. This is because of the high demand for asphalt and the occurring of material loss in the process of recycling asphalt. This report describes the current situation. It describes the circularity which can currently be achieved in practice.

1.3. Goal

Rijkswaterstaat is looking for insights and oversight regarding this topic. The opportunity for this project came to light because of claims of contractors worrying about the potential shortage of porous asphalt milling. This claim has to be researched. Lastly, Rijkswaterstaat would like to get informed about what opportunities and threats face them regarding the circularity of porous asphalt so they can act on these.

This will be done by investigating the techniques and methods regarding the recycling process of porous asphalt. There will be a case study, trying to set up and test a structure to overview the incoming secondary materials and facing them against the to be created asphalt mixtures. The idea behind this is that this will give insight into the recyclability potential of porous asphalt. A case study will be set up to review two real-world examples and gain an understanding of the current circularity and its potential. Rijkswaterstaat can use this data to improve its decision making and to improve the effectivity of contract requirements.

[5] (Nieuwsbericht Uitvoeringsprogramma circulaire economie, 2019)
[6] (Marktdialoog: Koplopermarkt voor duurzaam asfalt, 2020)

The NL-PCR Asfalt (Keijzer, et al., 2020)[7] and the Platform CB'23 (Platform CB'23, 2020)[8] serve as a basis for this research since these are generally accepted documents regarding the environmental and circularity aspects of the asphalt construction market.

1.4. Framework

1.4.1. Research questions

The primary research question is:

What are the current limits for closed-loop recycling in the rapidly transitioning porous asphalt market?

To provide an adequate answer to this question, the research has been split up into multiple sub-questions:

1. **What are the characteristics of porous asphalt?**

   This question is being asked to get a starting point and a general understanding of the term porous asphalt in the Dutch market.

2. **How can porous asphalt be recycled?**
   Gaining an understanding of the major and promising techniques involved in the processing of old porous asphalt debris, which has been milled off the roads, towards secondary material to be used as an ingredient for new layers of porous asphalt.

3. **What is the definition of circularity in the asphalt construction market?**
   To find a solution to this question, documentation dealing with this question has to be examined. Getting an overview of the aims, goals and strategies will be the focus and used to determine the definition of circularity within the porous asphalt market.

4. **Why could a secondary material balance help gain insight into circularity?**

   The case study aims to gain insight into the current standing and potential of circularity of porous asphalt. It also tries to provide issues and opportunities on the path towards increased circularity. Though it is essential to ask why the proposed secondary material balance would help? What can a secondary material balance add to the awareness surrounding circularity?

5. **What difficulties arise with closed-loop recycling of porous asphalt?**
   The transition towards the circular economy is happening, though it never is expected to be a smooth one. Gaining information about the challenges surrounding this transition is useful to steer it in the right direction. The incentive for this research is based on a concern surrounding the implementation of a circular economy, more specifically, closed-loop recycling. Therefore, it is important to research it.

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[7] (Product Category Rules voor bitumineuze materialen in verkeersdragers en waterwerken in Nederland (''PCR Asfalt''), 2020)
[8] (Leidraad ''Meten van circulariteit'', 2020)

6. **What could Rijkswaterstaat do to contribute to the transition towards circular porous asphalt?**
   At the end of the research, a substantial amount of insight into the transition has been collected, challenges will be noticed, and opportunities will have become apparent. The final part of the report will be informing Rijkswaterstaat about the findings and proposing points of attention.

Answering this set of sub-questions will provide enough basis to answer the primary question and recommend steps of action for Rijkswaterstaat to pursue.

1.4.2. Hypothesis

The hypothesis is that a shortage of porous asphalt mining exists. Multiple contractors have raised awareness of this shortage. It is expected that the techniques used are fairly optimised since porous asphalt including 90% reclaimed asphalt is possible already.

1.4.3. Research methodology

A research model aims to visualise an overview and the interconnectedness of the project. This research model has been split up into five phases. These phases are depicted in the figure below and will be described accordingly.

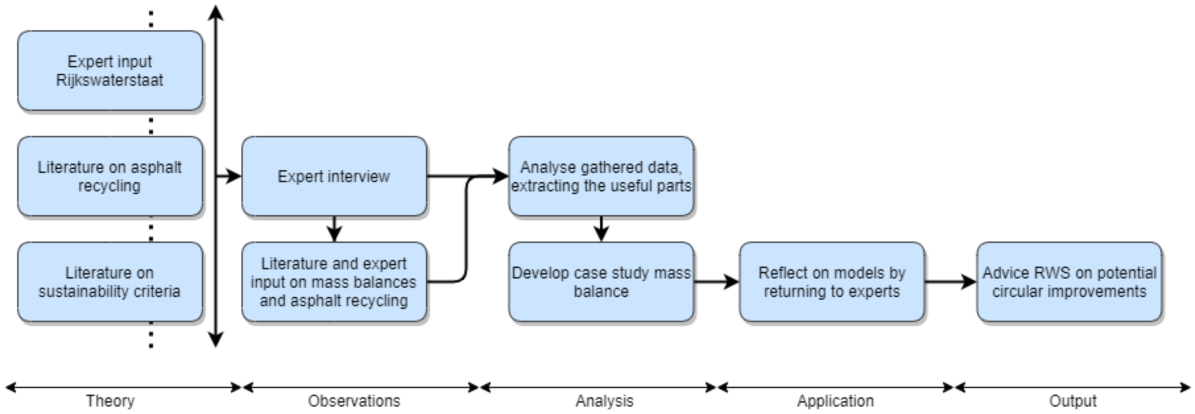

Figure 1 - Research model

During the theory phase of the research model, the theory will be collected and analysed. The theoretical analysis will focus upon Rijkswaterstaat's intention of researching circularity and its knowledge on the subject. The aim is to gather data and reports connected to the topic and let them serve as a baseline for the research. It will also create a clearer picture of what the external supervisor aims to get out of the project. This will then help lead towards a sensible and usable answer to the primary research question. The primal input to this theoretical analysis will come from experts at Rijkswaterstaat. This has been decided since it will point the definition towards the clients' expectation and serves as an introduction with the experts in the field too. A preliminary investigation into the literature has shown a substantial list of reports dealing with aspects such as the development of circular asphalt as well as the difficulties related to that. A full list of material used to prepare this report is included at the end of the report. The up-down arrow (↕) indicates that these inputs are confronting each other and will be combined to analyse.

Once a general understanding of circularity has been achieved, the focus will shift towards observation. In this phase, the field research will take up a more prominent role. It is key to conduct interviews with experts in the field. These experts have turned up in reports and investigations related to the subject or have been recommended through the expert input from Rijkswaterstaat.

The experts will be asked about their knowledge concerning the efficiency of the procedures in asphalt recycling. To develop an accurate and rigid secondary material balance, information needs to be gathered concerning the processes in the asphalt chain as well as losses and residues in these processes. Observing strategies and documents related to creating a secondary material balance and the recycling of porous asphalt is vital in producing a useful balance in the end. Therefore, during the observation phase, much detail is being put in gaining insights into the recycling process and experts will be questioned regarding that.

After collecting the theory and observations, the analysis starts. Extracting and combining useful information and data in order to develop a case study. The idea is to use the interviews to gain data about two projects and combining this with the literature to develop a secondary material balance where the differences between the amount of reclaimed material and secondary material used as ingredients for the new pavement will be balanced. The projects being studied are representative of the arsenal covered by Rijkswaterstaat since they are a big maintenance project and a road widening project. These types of projects are very common projects for Rijkswaterstaat. The aim is to gain a better understanding of the possibilities and achievability of this. The model will then be discussed with the experts to verify the model and discuss the results. This will be done during the application phase. After possible alterations to the models have been made, the focus will shift towards developing a piece of advice for the client. Since the tool will be used by Rijkswaterstaat in order to explore possibilities to improve circularity, the final part of the project will be to generate a piece of advice for further research.

2. Porous Asphalt

In the research's context, asphalt can be described as a commonly used type of road surface in the Netherlands. A road generally consists of a foundation layer, bin/base layers and a surface layer. This report will demarcate itself by only focussing on the surface layers of asphalt. More specifically, this research will focus on the circularity of surface layers of the so-called "ZOAB (Zeer Open Asfalt Beton)" Porous asphalt is the most used asphalt type on the main national road network of the Netherlands.

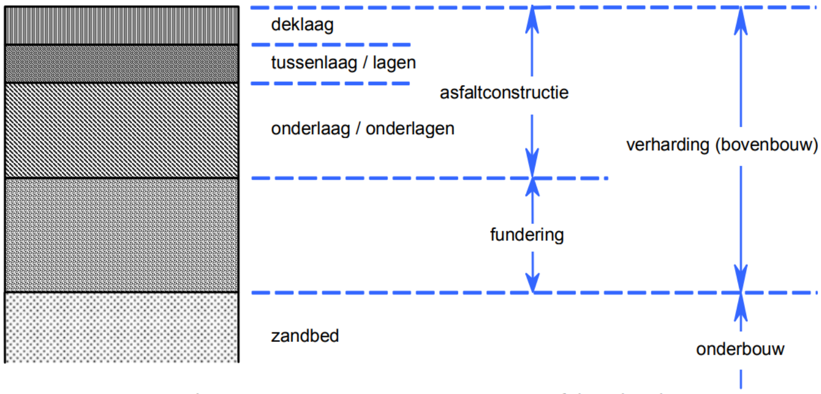

Figure 2 - Structure of an asphalt surface road consisting of surface, bin/base and a foundation layer (Rijkswaterstaat; Dienst Grote Projecten en Onderhoud, 2016)[9]

A regular layer of ZOAB consists of four main ingredients: Crushed stone, bitumen, crusher sand and filler material. (Keijzer, et al., 2020)[10] There are many types and gradations of these crushed stones and the specific mixture of these fractions ensures the permeability that porous asphalt is known for.

In order to increase the circularity, reclaimed asphalt (RA) can be used as a construction material. RA is a secondary ingredient and using it decreases the number of raw materials used. Henceforth increasing its circularity.

Porous asphalt production is done by heating the components and mixing them in specific proportions. At the end of its lifetime, a porous asphalt layer will be removed and recycled. An asphalt layer is, in theory, 100% recyclable, though in practice this is not possible. Material losses are occurring at different times in the process. The EAPA established that almost 70% of asphalt is being recycled. This means that 30% will be used differently. (European Asphalt Pavement Association, 2019)[11] The NL-PCR asfalt (Keijzer, et al., 2020)[12], describes these losses in its module D. The project focusses on the loss of material during the lifespan of a porous asphalt layer including the recycling phase. It is, therefore, useful to observe these losses.

Module D describes the environmental costs and benefits at the end of the life cycle. The material which can be used for recycling is regarded as a benefit and the losses are regarded as costs. There are four types of costs included: Degradation, material leaving the system, loss of function and loss of quality. Degradation can be explained as the erosion of bitumen in the surface layer while the road is being used. Reclaimed asphalt which is used for a lower-quality purpose can be regarded as material

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[9] (Specificaties Ontwerp Asfaltverhardingen, 2016)
[10] (Product Category Rules voor bitumineuze materialen in verkeersdragers en waterwerken in Nederland (''PCR Asfalt''), 2020)
[11] (Asphalt in figures 2017, 2019)
[12] (Product Category Rules voor bitumineuze materialen in verkeersdragers en waterwerken in Nederland (''PCR Asfalt''), 2020)

leaving the system. Loss of function happens due to the ageing of material; bitumen becomes stiffer over times and therefore loses its function. Lastly, loss of quality happens due to usage and milling practice. The aggregates used in asphalt can lose its sharpness or break while milling. These decrease the quality of the aggregates.

Decreasing these abovementioned losses increases the amount of available secondary resources and thereby increasing the circular potential. The focus of the report however is to increase the knowledge and display the current operations and capabilities of the recycling of porous asphalt in regard to circularity. The next chapter will focus on explaining the way circularity is measured.

3. Circularity of asphalt

A circular economy, as described by the Dutch national government. (Het ministerie van Infrastructuur en Milieu, 2016)[13] Is an economy in which raw materials usage is optimised. (Rood & Hanemaaijer, 2017)[14] A transition towards a circular economy requires a paradigm shift in the general understanding of an economy. A linear economy focusses on the take-make-waste method, whereas a circular economy highlights the reusing of materials and minimizing waste. When thinking about circularity, the 7R-Principles as described in the Platform CB'23 (2020)[15] are widely accepted. It describes seven steps of thinking about high-quality usage of materials. The asphalt industry in the Netherlands already incorporates many of these steps. They rethink and reduce the amount of asphalt used by trying to construct roads based on expected demand. As well as repairing roads to extend their lifetime and asphalt has to be recycled. It is not allowed to dump asphalt anymore.

The guideline ''Measuring circularity'' (Platform CB'23, 2020)[16], intends to create a general method of measuring the circularity of a system. It aims to create a general understanding and structure to measure circularity in the building industry. Indicating the material flows is key in measuring circularity. It, therefore, is the starting point of the Platform CB'23. Figure 3 shows a material balance created to indicate the material flows between stages. The intend of this project is to gain insights into the material flows connecting the use phase, recycling phase and production phase. How much of the materials can be recycled and how much will become waste or will be used in another system?

Minimizing the waste flows contributes toward increasing the circularity of the asphalt chain. It, therefore, is important to minimize the output flows indicated by the black arrows. These arrows show the flow of material from a certain stage of the product out of the system. This means that the product can be recycled in another system or the material can be dumped and has no further use.

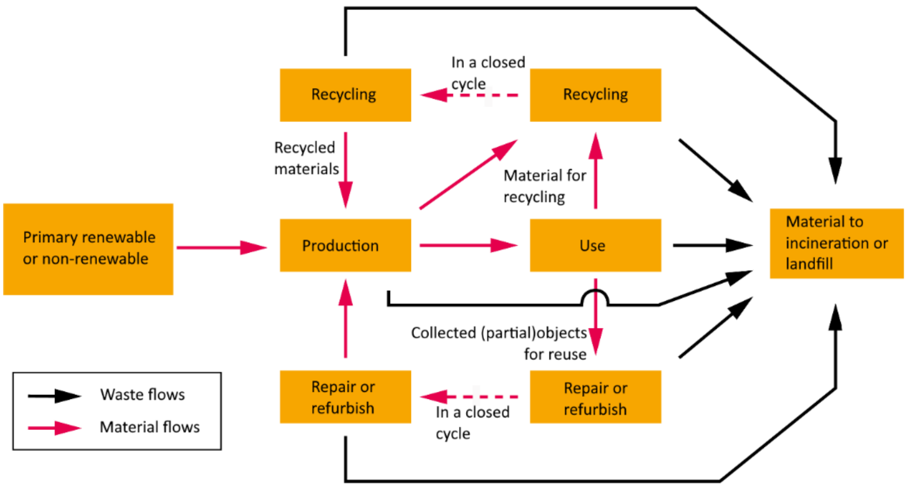

Figure 3 - Material balance displaying material and waste flows adapted from (Platform CB'23, 2020)[17]

Current practice is to use the reclaimed asphalt for foundation and bin/base layers as current regulation limit the amount of RA in surface mixtures. This is down cycling since a high-quality material is being used in a lower-quality purpose. The new surface layer has to be created with more

[13] (Nederland circulair in 2050, 2016)
[14] (Waarom een circulaire economie?, 2017)
[15] (Leidraad ''Meten van circulariteit'', 2020)
[16] (Leidraad ''Meten van circulariteit'', 2020)
[17] (Leidraad ''Meten van circulariteit'', 2020)

natural resources as a result. As described in the chapter before, circa 60% of the harvested porous asphalt milling can be recycled into new porous asphalt layers. This also tells that at least 40% is being down cycled or used in another way. The interviewees expressed that it is not possible to achieve 100% closed-loop recycling and that there will always be down cycling. Nonetheless, investing in techniques which improve the percentage which can be recycled without loss of quality is vital. Because it further decreases the need for primary resources.

The environmental impact of bituminous works is measured using the DuboCalc instrument. DuboCalc uses a life cycle assessment using the shadow cost method to transform the environmental impact costs into one value, the Environmental Product Declaration (EPD), Known as the Millieukostenindicator (MKI) in Dutch. These calculations involve the entire life cycle starting from extracting the raw materials until the disposal. (Rijkswaterstaat, 2019)[18]

This EPD-value gives a good insight into the environmental impact of a plan and can be used to compare plans based on their impact. Though this is only applicable if those EPD-values are derived similarly. Therefore, Vakgroep Bitumineuze Werken (VBW) developed a guideline for this. The guideline is called NL-PCR-Asfalt and at the time of writing is in its first version. VBW describes the NL-PCR-Asfalt as a tightening up of the Assessment Method (SBK) and also is based on the NEN-EN15804. (Smal, 2020)[19]

The EPD-value is a widely accepted way of determining the environmental impact of a project though, in its current state, it has some shortcomings in the circularity aspect. A case study by Keijzer, Bizarro, Oranje & De Wijs (2020)[20], investigating the practical applicability of the NL-PCR showed that increasing the amount of recycled material in new asphalt mixtures decreased the environmental impact. One of the results from the case study however indicated the absence of an indication of the level of recycling. Meaning that there is no difference between the closed-loop recycling and down cycling of asphalt. One of the interviewees explained that in the LCA-model, there are no different qualities of the reclaimed asphalt (RA). Using a higher quality RA does not affect the EPD-value.

Through the interviews with experts and the case study from TNO (Keijzer, Bizarro, Oranje, & De Wijs, 2020)[21], it became clear that there is no clear distinction between closed-loop recycling and down cycling of asphalt in the NL-PCR v1 calculations. This means that there is no clear sign of circularity. Making a secondary material balance of a project could be used to display the amount of closed-loop recycled asphalt in a project and could, therefore, serve to establish the circularity of a project.

Generating a project scale secondary material balance could be a way to quantify the aspect of circularity. The next chapter will give insights into current techniques related to the recycling of porous asphalt in the Netherlands. It will investigate the possibilities and techniques used to increase the amount of recyclable material and therefore decrease the amount of waste in the material balance.

[18] (DuboCalc, 2019)
[19] (NL-PCR Asfalt: Rekenregels voor de bepaling van de milieueffecten van asfalt, 2020)
[20] (Rekenregels voor de MKI van Circulair Asfalt, 2020)
[21] (Rekenregels voor de MKI van Circulair Asfalt, 2020)

4. Porous asphalt recycling

Porous asphalt has to be recycled. Recycling techniques are used to turn an end-of-lifetime road into secondary materials. There are different strategies for this, and through literature and interviews, these have been gathered. The techniques discussed below are representative and commonly used approaches, but do not provide a full overview of the market. Each technique will be plainly explained, and the advantages and disadvantages will be discussed. Porous asphalt is a high-quality material and therefore quite valuable. The porous asphalt milling harvested from old porous asphalt layers therefore is of a higher quality compared to asphalt milling from bin/base layers.

Recycling starts with the removal of the old asphalt from the roadside. This is done by milling the layer off and transporting the debris to be turned into secondary resources. An upcoming technique in the milling is selective milling. Whilst common milling scrapes off multiple layers of asphalt at once, selective millers try to mill one layer at a time. This creates different piles of debris consisting of different quality material. Decreasing the chance of mixing high-quality aggregates with lower-quality material. A consideration is that selective milling is more expensive, time-consuming and a logistic challenge as interviewees explained that separate storage piles will have to be made and by accidentally dumping the wrong fraction, the quality (and therefore value) of the pile will decrease.

In the asphalt plant, a typical and widely used method of recycling asphalt debris is to break it into smaller fractions and sieve the gradations. These gradations are clumps of reclaimed asphalt (RA) and are heated and added to the new asphalt mixture through a parallel drum. Adding RA to porous asphalt mixtures is a relatively inexpensive measure, though there are issues connected to it. The addition of RA is only allowed when the product has been validated by Rijkswaterstaat (Jansen, 2020)[22]. Furthermore, emission legislation limits the temperature of reclaimed asphalt in the parallel drum. To produce large quantities of porous asphalt with high percentages of RA, big investments into the asphalt plants have to be carried out. As a result of these complications, the experts which have been interviewed estimate the current maximum percentage of RA in ZOAB layers to be around 60. This percentage is also found in the literature. (Jacobs, Frunt, & Rering, 2016)[23] Increasing this percentage could be possible but require massive investments into the asphalt plants. Therefore, technically, the asphalt plants are a bottleneck.

An interviewee claimed that after the processing from debris into secondary material, about 60% could be reused into ZOAB layers. The other 40% will be of lower quality and therefore has to be applied in a lower quality layer, e.g., AC bin/base. This is called down cycling. A big part of this is due to the stones getting smoother and stones breaking or chipping off. Because of this, the number of finer aggregates increase, whereas the coarse aggregates decrease. This decreases the quality of the overall material since larger fractions have to be added to compensate for the breaking and to ensure the qualities and specifications ZOAB has to meet.

A technique which aims to decrease the breaking of aggregates during recycling is by bruising the aggregates instead of breaking it into smaller chunks. This is done by deposing the asphalt chunks into rotating drums. By means of this rotating drum, the chunks fall apart, and fewer parts of the stones break off. This increases the percentage of larger fractions in the reclaimed asphalt. Consequently, increasing the amount of material useable in new ZOAB layers to circa 70%. This increases the circularity of ZOAB though there is still a surplus of the finer fractions.

[22] (RAW ondersteunt asfalt met certificaat van Asfaltkwaliteitsloket, 2020)
[23] (PA-stone: Op weg naar asfalt met 100% recycling, 2016)

The latter technique which will be discussed is the process which turns ZOAB debris into PA-stone. This technique uses a fast-moving rotation separator to separate the mastic from the stones. As a result of this, the composition of the new mixtures can be more controlled resulting in a higher percentage of secondary materials with no loss of quality. Additionally, these stones can be heated inside the main drum of the asphalt plant along with the raw materials. As a result of this, less environmental and odour pollution will be released in the process. This ensures that higher percentages of circularity can be achieved. The downside to this is that creating PA-stone is more time consuming, expensive and relatively more losses to get the material of this quality. Common practice, therefore, is to first use RA and add PA-stone if necessary.

The abovementioned techniques all contribute toward an increase in circularity of ZOAB. To get a clear overview of the recycling of porous asphalt in practice, a case study has been set up. The case study discussed in the next chapter, will explain and express the idea, procedure and results from trying to develop a project scale secondary material balance. It will also serve as a representative example of two typical Rijkswaterstaat projects.

5. Case study

5.1. Idea

In order to gain insights into the current state of closed-loop recycling and trying out the practicability of project scale secondary material balances, a case study has been set up. The idea behind this case study is to observe the common practice around circularity within a project today. What techniques are being used? What difficulties arise? And what is the impact of the paradigm shift towards a circular economy on the market? These questions are raised by Rijkswaterstaat to gain a better understanding of the implementations of circularity measures as well as to reflect on their contribution towards this paradigm shift so far.

5.2. Case projects

Finding representative cases is challenging. Projects can vary extensively. For example, the opportunities and possibilities with circularity in a new construction project can be different from a maintenance project. Furthermore, major road-specific factors as; types of asphalt surface- and bin/base layers, construction, and traffic load have a substantial impact on its recyclability and circularity.

It has been decided to investigate two substantial maintenance projects since Huurman & Demmink (2016)[24], estimate that the percentage of new construction projects will keep dropping. This can be seen in Figure 4. Whereas maintenance will increase. Additionally, projects with increased activity in the field of circularity will be preferred since these are believed to present a better overview of the status of the circularity aspect. Since two case projects have been researched, some conclusions can be reached based on the quality of data provided and useability of the data provided.

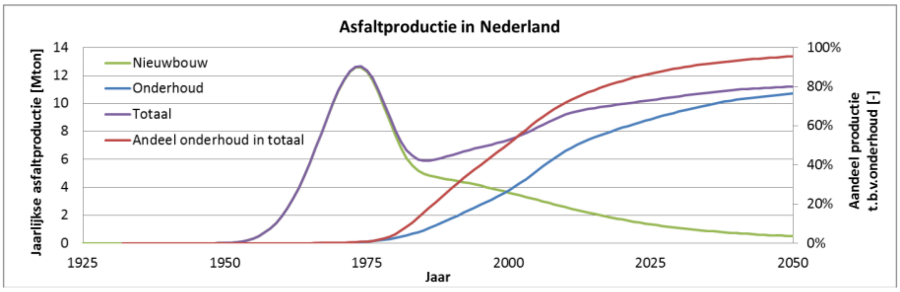

Figure 4 - Asphalt production in the Netherlands (Huurman & Demmink, 2016)[25]

One of the projects in the case study is a maintenance project on the A50 between Heerde and Waterberg interchange. This project is carried out by BAM infra as part of the big maintenance project east Netherlands. (IGO Oost) (Rijkswaterstaat, 2020)[26] This project covers a stretch of road of almost 50 kilometres and uses about 185.000 tonnes of asphalt, including 145.000 tonnes of ZOAB-like mixtures.

The other project is the widening and maintenance of the A1 between Apeldoorn and Azelo. This project is carried out by Heijmans. (Rijkswaterstaat, 2019)[27] This project stretches about 40kilometres of distance and includes 410.000 tonnes of asphalt, including 145.000 tonnes of ZOAB-like mixtures.

[24] (De landing van de Nederlandse Asfaltmarkt?, 2016)
[25] (De landing van de Nederlandse Asfaltmarkt?, 2016)
[26] (Rijkswaterstaat gunt groot onderhoud wegen Oost-Nederland aan BAM infra, 2020)
[27] (Uitbreiding A1 Apeldoorn - Azelo, 2019)

These two projects have been selected since they both focus on circularity and decreasing the environmental impact. Their strategies, however, differ. They also are, roughly similar in size and substantially big to be representative works. The A50 Project is a maintenance project whereas the A1 is a widening and maintenance project. It is, therefore, interesting to observe the differences this brings to both material balances.

5.3. Data collection

The data used in this case study is provided by the contractors. The data consists of the types and quantities of milled asphalt and types and quantities of asphalt to be mixed for the projects. These sources have been used to determine the amount of porous asphalt milling harvested on one side of the balance, and the number of secondary materials on the other side. By doing this, a balance can be created which displays closed-loop circularity of the ZOAB-like materials in these projects. An important factor missing in this overview are the losses in the recycling process. As mentioned in the chapter concerning circularity, not all porous asphalt milling can be reused in new ZOAB layers. A portion of this is down cycled. Through the use of literature and interviews with the contractors, percentages corresponding to this have been determined. The values concerning the project have been anonymised due to confidentiality. However, these values have been checked by external experts and are considered plausible and representative.

5.4. Secondary material balances

5.4.1 A50

The balance can be visualised with pie charts, these charts below show the material gained from milling before fabrication into secondary raw materials and the secondary materials required for the project. First, the A50 will be examined.

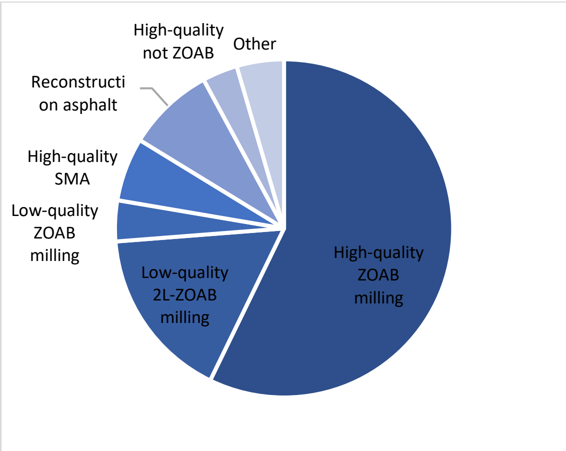

Figure 5 - Types of asphalt milling harvested in A50

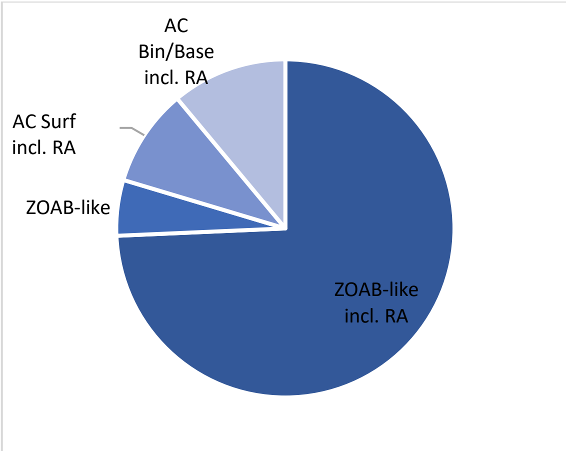

Figure 6 - Shares of mixtures to be used in the A50 project

In Figure 5 and Figure 6, it can be seen that ZOAB-like materials are most prominent. The majority of the harvested material is high-quality ZOAB milling. The data also shows that the amount of material harvested is almost equal to the amount of material required for construction. This indicates that this project is a maintenance project since there is minimal need for additional material.

Focussing on the mixture planning, the amount of ZOAB-like mixtures can be calculated. Since each mixture has its distinct ingredients ratio, the percentage of secondary materials within these mixtures are known. The average percentage of secondary materials used in the ZOAB-mixtures has been calculated to be 56%. Remembering that the total amount of ZOAB-like asphalt is 145.000 tonnes, this indicates that 81.200 tonnes of this is secondary material. The division between primary and secondary materials can be seen in Figure 7. This means that, in this context, the circularity percentage of the ZOAB-mixtures is 56%, since 56% of the ZOAB-mixtures consists of reclaimed material which has been used closed-loop. This fairly high percentage has been achieved through the use of mixtures including both RA and PA-stone. This combination of secondary ingredients makes it possible to use mixtures with up to 70% secondary materials. The downside of this is that the milling from this project does not provide enough specific secondary material in order to achieve this. Therefore, porous asphalt milling has to be imported from other projects. Further analysis of this shortage will be done during chapter 5.5 Examine shortage.

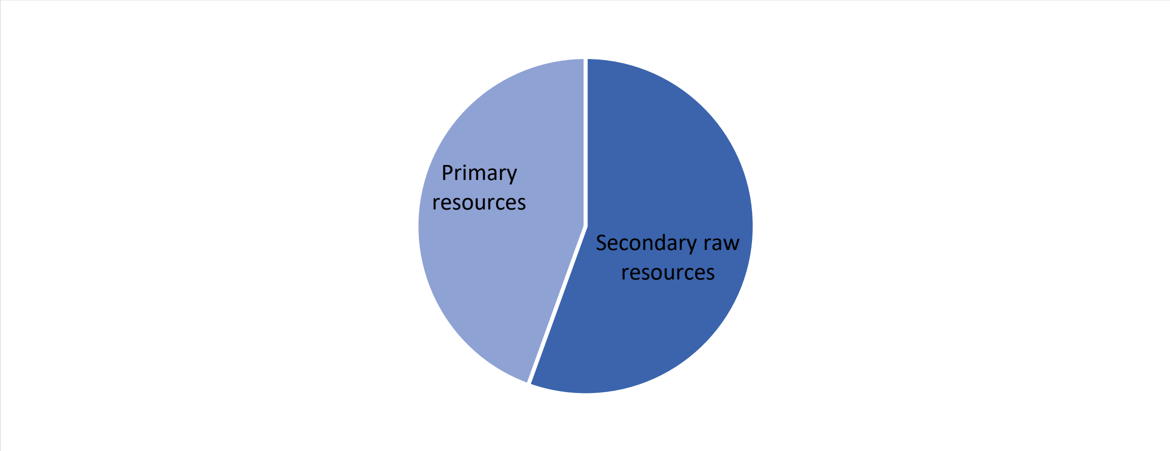

Figure 7 - Average division primary and secondary materials in ZOAB-mixtures

In planning projects like this one, there is a consideration to be made, increasing the circularity and lowering the EPD-value can be achieved by using asphalt mixtures with higher percentages of secondary material. These mixtures exist and could be used but would require even more high-quality secondary material. Thereby increasing the shortage further.

5.4.2. A1

In contrary to the A50, in Figure 8 and Figure 9, it can be noted that the Bin/Base milling is the most harvested and Bin/Base mixtures make up most of the asphalt used in the project. This creates a secondary resource balance vastly different from the other project. Because this is a widening project, it is expected that the absolute amount of material required exceeds the number of resources gained from harvesting. This is true, the data provided showed that the amount of material needed exceeds the amount harvested by 65%.

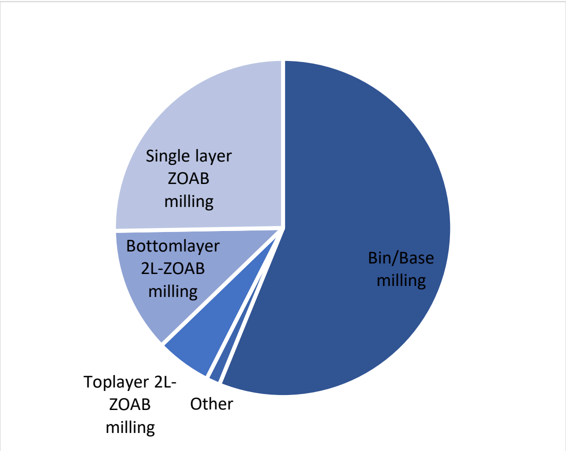

Figure 8 - Types of asphalt milling harvested in A1

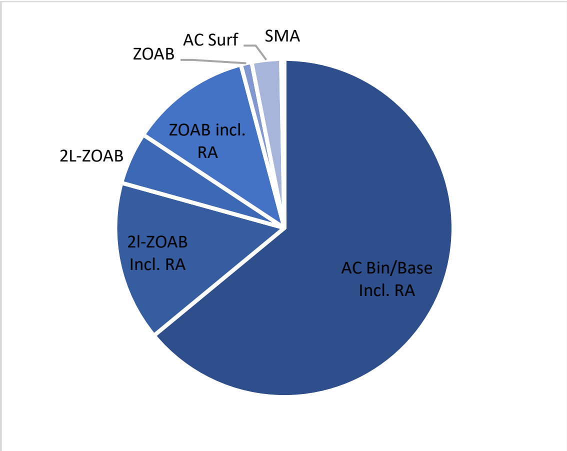

Figure 9 – Shares of mixtures to be used in the A1 project

When the closed-loop recycling of ZOAB-like mixtures is examined. It can be noticed that, based on the asphalt milling planning, the amount of closed-loop recycling is around 33%. This indicates that of the 135.000 tonnes of ZOAB-like mixtures used in the project, 44.550 tonnes is secondary material. For this project, it has been decided not to use ZOAB-mixtures including high RA percentages. This does not imply that this project does not use the available RA effectively. Calculations show that the total amount of secondary material used in this project is close to the amount of milling harvested from the project. The focus in this widening project has been put on using the secondary resources as effectively as possible. This does not necessarily imply using porous asphalt milling in ZOAB-like mixtures.

5.5. Examine shortage

During the calculations in the case study, it became apparent that a shortage of porous asphalt milling exists in the A50 project. Through further examination of this shortage, it was noted that the only shortage existed in a small fraction from the porous asphalt milling. There is a shortage of coarse aggregates especially 5/8mm and 11/16mm. This could be explained by the fact that due to the recycling process, parts of the aggregates can break or chip off. Thus, larger aggregates break into smaller aggregates. This creates a problem on both sides since there is not only a shortage of coarse material but also a surplus of fine aggregates.

5.6. Difficulties

There are practical difficulties with carrying out project-wide secondary material balances. It is challenging to discover the path material takes while being recycled. The logistical task of milling the material, processing it into usable secondary ingredients and delivering them to where they can be used as effective as possible, is complicated. Porous asphalt milling does not have to be reused immediately and in the same project. Therefore, a project-wide scale does seem too small. Implementing a circularity strategy heavily depends on the type of project. The ratio of available material compared to the required secondary material strongly depends on the type of project. A new construction project, for example, has almost no harvesting of secondary material but a massive need for ingredients, whereas, in a maintenance project, this ratio is more balanced. Furthermore, there are many considerations when planning the mixtures for a project. Availability of material, time pressure, quality of the material, costs and asphalt plant limitations are just some of the factors involved in this decision-making process. A higher percentage of closed-loop recycling does not imply a more successful project.

5.7. Results

Through a thorough investigation into the expected milling yields and the materials required for paving the new roads, a secondary resource balance has been created to compare the projects. This showed that the two projects examined have made different choices regarding the circularity focus. The strategy used heavily depends on the type and characteristics of the project. To gain a relatively high closed-loop recycling of ZOAB-like materials, in the A50 case around 56%, a shortage of coarse aggregates arises. This is partially due to coarser fractions breaking into smaller fractions during recycling. The shortage of this coarse material has to be imported from other projects with the risk of decreasing that projects circularity and environmental goals. The achieved 56% is not a technological maximum, more reclaimed material could have been used. A higher circularity percentage could have been achieved, but then the shortage of porous asphalt milling for this project would have been even greater. This would put even more stress on the porous asphalt milling market. The circularity of other projects would have to be even further compensated.

The case study also made clear that a project-wide secondary material balance has issues. The scale is too small and secondary material in practice is being transported to other projects based on demand and supply, it could therefore be more effective to look into the arsenal wide, or yearly logistics of secondary material flows.

The differences between types of projects are big, the balance between harvested products and secondary material of the widening project is completely different from the maintenance project. This resulted in other choices regarding circularity and therefore different results for the closed-loop recycling. Secondary material harvested from old porous asphalt layers does not necessarily have to be used in new porous asphalt layers to be efficient. The efficiency is heavily dependent on the supply and demand at that moment and therefore circularity is not really a technical challenge but much more of a logistical challenge. In this rapidly shifting paradigm towards circular and environmentally friendly economies, it is vital to work as efficient as possible with the material available, there are many considerations to be made but with the threat of primary resources becoming scarce, it is crucial to use the secondary materials as efficiently as possible and because of that, thinking about the circularity of projects and making substantiated decisions is needed.

6. Recommendations

This report and the carried-out case study highlight the current effectiveness of horizontal recycling. Throughout this research, it became obvious that the market is rapidly and enthusiastically transitioning towards a circular economy. Porous asphalt in itself is a suitable product for horizontal recycling. However, no transition comes without its complications. In all individual cases, a trade-off must be made regarding the circularity, environmentally and economic aspects. In this chapter, recommendations will be made to extend the knowledge surrounding this issue even further.

Rijkswaterstaat's approach towards a sustainable economy is to decrease the maximum EPD-value (see chapter circularity) for a project in steps. (Uijting, 2018)[28] This seems like a reasonable, measurable and fair goal. The NL-PCR asfalt has been developed to be able to compare project tenders more fairly. But the current version falls short on certain aspects. As described in the case study by Keijzer, Bizarro, Oranje and De Wijs (2020)[29], the current version does not distinguish between different types of reclaimed material. As a result, RA from porous asphalt has the same value as RA from Bin/base layers. This is not true and impacts decision making negatively. There is no distinction between closed-loop recycling and down cycling and there is no space for individual innovations. These points of attention appeared in the case study as well since the interviewees explained that to decrease the EPD-value, more high-quality reclaimed asphalt has to be down cycled instead of being used closed-loop. This does not comply with the definition of circularity discussed in this report.

Currently, about 30% of all asphalt leaves the system. It's being used in foundations or used elsewhere. (European Asphalt Pavement Association, 2019)[30] Combining that with the facts that only 60% of porous asphalt milling can actually be reused closed-loop, (Jacobs, Frunt, & Rering, 2016)[31] and it can be noted that 100% circularity in the asphalt chain is a utopia. Huurman and Demmink (2016)[32] expect a decrease in the share of new construction and an increase in the share of maintenance projects in the near future. It, therefore, is even more important to be able to use secondary material as efficiently as possible without unnecessarily losing its value through down cycling.

An issue arising with this focus on increasing the circularity is an expected shortage of high-quality secondary coarse aggregates. The existence of this shortage has been proven through the case study where in order to achieve a circularity percentage of 56%, external porous asphalt milling had to be imported. This is partially due to the breaking of coarse fractions into smaller fractions during recycling. Leading to a shortage of coarse aggregates and a surplus in fine aggregates. The negative implications can already be noticed because multiple contractors acknowledge this problem and it has been acknowledged that to meet circularity goals in certain projects, the environmental goals of other projects had to be compensated since they are being deprived of their harvested milling. It is, therefore, crucial to widely acknowledge the shortage. A possibility to decrease the shortage is to further invest in techniques which minimize the losses occurring during recycling. These techniques have not been the focus of this report but should be investigated further.

Many of the interviewees indicated that the biggest complications with circularity are not regarding technology but are based on lack of information and logistics. In order to achieve high circularity in a

[28] (Versnelling in verduurzamen asfalt, 2018)
[29] (Rekenregels voor de MKI van Circulair Asfalt, 2020)
[30] (Asphalt in figures 2017, 2019)
[31] (PA-stone: Op weg naar asfalt met 100% recycling, 2016)
[32] (De landing van de Nederlandse Asfaltmarkt?, 2016)

project, it has to be known what materials will become available to use. As well as more overview of the supply and demand for specific types of secondary materials in projects. This has to be evaluated on a bigger scale then project-wise. It is recommended to constructively work together and develop a database for this. An increase in the quality and availability of material-specific data can contribute towards a more effective and efficient method of using secondary materials. Incentives such as a material passport, as described in: “Leidraad; paspoorten voor de bouw” (Platform CB'23, 2020)[33] can help to improve the logistics.

At last, porous asphalt milling, harvested from old porous asphalt layers do not have to be used in new porous asphalt mixtures. The case study showed two different methods of dealing with secondary material balances. One project tried to incorporate a lot of secondary material in the porous asphalt layers whereas the other project tried to use its reclaimed materials as efficiently as possible. This does not necessarily imply using it closed-loop. Due to the case study only focussing on the closed-loop recycling of porous asphalt, a clear comparison could not be made. It, however, is advised to further investigate both methods.

[33] (Leidraad ''Paspoorten voor de bouw'', 2020)

7. Conclusion

Rijkswaterstaat is very committed to contribute towards the transition from a linear towards a circular economy. It enables and cooperates with contractors to test and verify new ZOAB mixtures including more reclaimed asphalt and other secondary materials. ZOAB is an excellent material for pioneering in the paradigm shift since it has been used in a substantial part of Rijkswaterstaat's road network. Porous asphalt consists of high-quality material which is very suitable for recycling. The CB'23 guideline circular building provides a generous overview of circularity aspects, as well as illustrating the change of thinking involved in this paradigm shift.

Developing the NL-PCR asfalt has created a level playing field for contractors and an objective way to compare tenders. The document is heavily detailed and based on much professional expertise. It covers a wide range of environmental aspects. This document is improving from version to version, and certain aspects have to be improved upon. Currently, no difference between closed-loop recycling and down cycling can be noticed is the EPD-value. This does not comply with the thought of circularity since down cycling decreases the quality of the material and requires more high-quality material to be newly delved. Secondly, there is no space for individual innovations. This could decrease the willingness of contractors to invest in out-of-the-box or revolutionary ideas.

The current maximum percentage of closed-loop recycling of porous asphalt sits around 60%. (Jacobs, Frunt, & Rering, 2016)[34] There are techniques in development which open up possibilities for more closed-loop recycling. In the report, Bruising and PA-stone have been examined but there are many more techniques which can contribute to the circular economy. The technology, however, is not the main challenge in this transition.

Circularity is more of a logistical challenge than a technical one. Balancing the materials is a big problem, this starts with the wrong evaluation of porous asphalt milling. It is often regarded as debris or waste, but it actually is a valuable resource made from high-quality materials.

The case study has shown that balancing materials on a project scale is not recommended. To be able to use the secondary material as effectively as possible, the focus should not only be on the project, but also on projects happening around it. Different types of projects have different need for secondary material and therefore, interaction between the projects is advisable. Transitioning towards a circular economy demands efficient usage of secondary materials, this could be the pursuit towards a high percentage of closed-loop porous asphalt recycling, but that does not have to be the case. The A50 project has shown that trying to achieve 56% closed-loop recycling of porous asphalt results in an expected shortage of porous asphalt milling. The interviewees also claimed that in order to meet environmental demands in certain projects, other projects had to be compensated in their environmental goals simply because of the shortage of porous asphalt milling occurring. This shortage mainly exists for coarse gradations of porous asphalt milling since these fractions tend to break down into smaller gradations during the recycling process. Further investigation into recycling techniques is needed to investigate whether it is possible to reduce the breakdown of the coarse fraction into finer fractions.

The availability of data could improve the effectivity of circularity measures. By having a better expectation of what materials will become available from projects, a more efficient secondary material balance can be developed. With improved data availability, secondary material availability could even play a role in the planning of projects. Balancing supply and demand over a country scale.

[34] (PA-stone: Op weg naar asfalt met 100% recycling, 2016)

This report concludes that circularity is more of a logistical than a technical problem. It is important to develop an overview of the availability and quality of the available material. Especially the high-quality porous asphalt milling. Research regarding the processing of the old asphalt into secondary materials has to be done since there could be room for improvement and more efficient use of the material. As well as research into the availability and quality of data regarding the asphalt recycling process. This will contribute towards higher quality material and a better logistical process of handling porous asphalt milling.

8. Discussion

The focus of this discussion will be on the case study. Although the results seem to comply with the hypothesis, it is difficult to say the hypothesis is true. Specific project-related factors strongly impact the circularity and therefore the strategy. The projects analysed in the case study had many different characteristics and different circularity methods have been used by the contractors. It is therefore difficult to compare the projects. This case study was limited to only considering the closed-loop circularity of porous asphalt mixtures. In further research, a broader scope could be examined including other types of asphalt as well as bin/base layers.

The argument can be made that the validation of the case study results can be difficult to prove. This is common in the asphalt industry since information is little and confidential. The results have, however, been validate by checks of external experts. These external experts think that the results are plausible, and the cases are of a big enough arsenal to be regarded as representative. Because of the case study including both a widening and a maintenance project, it can be said that these projects give a good overview of a typical and representative Rijkswaterstaat project. Most of the projects handed out by Rijkswaterstaat are either widening or maintenance.

The case study could be further improved by gaining more information regarding the recycling step. In this study, claims of the contractors have been used. But it would add much credibility to the study. This data, however, proved hard to come by since methods of recycling and their respective efficiency and proceeds are often confidential.

9. Reflection

The focal point of the reflection section of the report is to reflect on the gathered results, do they match up with the literature and the expert's input? What were noticeable things during the research and what were surprises?

The gathered results were expected, based on the incentive of the research, the result confirmed it. Noticeably different from the expectations was the discovery that circularity is mostly a logistical challenge. The possibilities and knowledge exist but the logistics combined with rules and regulations around organising it proposed to be a substantial challenge. The literature reviewed was in line with the view of the experts. The literature is concise, precise and clear. This consistency can be explained by the fact that the literature applied is fairly case-specific and therefore the interviewees were most of the times involved in the creation of the literature. The most surprising thing is the enthusiasm and motivation of the experts in this field. All experts were open, approachable and interested in the research. Although these experts all have different stakes in the process, they understand the need for cooperation in this shifting paradigm.

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Appendix A: Interviews

The field research has primarily been executed through interviews. Eight interviews have been held during the process. The interviewees have been invited to discuss their involvement in the paradigm shift towards circular porous asphalt. The interviewees were selected based on their expertise regarding porous asphalt recycling or circularity. The interviewees have been asked to share their knowledge and insights into this topic, as well as explaining about their occupation and company. The structure of the interviews is semi-structured. Questions were prepared in advance, though elaboration on the questions was encouraged. Questions asked have been adjusted for several interviewees based on their expertise. A general overview of the interviewees, length and topic of the interviews can be found in Table 1. The interviews took between 60 minutes and 90 minutes. A general overview of the questions asked can be found below.

General interview questions

Could you tell me something about yourself?

- What is your expertise?
- What is your function in your company?
- Could you explain something about the ambition of the company regarding circularity?
- Could you share some things regarding your involvement in the process of increasing the circularity of porous asphalt?

Concerning the recycling of porous asphalt:

- Can you tell me about the process?
- Can you elaborate on specific techniques?
- Could you indicate and explain which losses occur during this process?
- What developments are happening in the process?
- Which challenges arise in the process?
- Could you elaborate on these challenges?
- Do you experience/foresee a shortage in porous asphalt milling?
- What could Rijkswaterstaat do to improve the process?

Interviews conducted

Table 1 - Interviews conducted

Date	Time	Interviewee	company	remarks	Contact details
11-11-2020	10:00 - 12:00	Laurens Smal	Dura Vermeer	Nl-PCR asfalt, recycling practices and material losses	l.smal@duravermeer.nl
20-11-2020	11:00 - 12:00	Laurens Smal	Dura Vermeer	Elaboration on the previous interview	l.smal@duravermeer.nl
24-11-2020	9:30 - 11:00	Gerbert van Bochove	Heijmans	Recycling practices and case study	gbochove@heijmans.nl
25-11-2020	12:30 - 13:30	Elisabeth Keijzer	TNO	Nl-PCR asfalt, recycling practices and material losses	elisabeth.keijzer@TNO.nl
3-12-2020	9:00 - 10:00	Kevin Oranje	Bam	Nl-PCR asfalt, recycling practices and material losses	kevin.oranje@bam.com
11-12-2020	13:00 - 14:00	Marco Oosterveld	Bam	Recycling practices and case study	Marco.Oosterveld@bam.com
Follow up interviews					
25-1-2021	10:00 - 11:00	Gerbert van Bochove	Heijmans	Reflection on case study	gbochove@heijmans.nl
15-1-2021	11:00 - 12:00	Marco Oosterveld	Bam	Reflection on case study	Marco.Oosterveld@bam.com