Tracing roads

Developing a porous asphalt material passport

Bachelor thesis

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Preface

Before you lies the bachelor thesis Tracing Roads. The research has been conducted at the request of Heijmans in cooperation with the ASPARI research group. I worked on this research assignment from April until June 2022.

I want to thank my supervisors, Wouter Heijser, João Santos, and Seirgei Miller, for their support and guidance throughout this process and even more for providing a steep learning curve and challenging me to get the most out of myself. I would also like to thank all of the interviewees who took the time and effort to answer my questions in one or more sessions; this bachelor thesis would not have been possible without their cooperation. To the other colleagues at Heijmans: I would like to thank you for your kindness and friendliness and for providing a source of knowledge and a place to express my thoughts and dilemmas whenever I was stuck.

Lastly, I would like to thank my family, who provided a place for discussion and listened to my ideas and difficulties, and for their support from start to end, as they have always done.

I hope you enjoy your reading.

Yours Sincerely,

Bas van der Zande

Hengelo, July 1, 2022

Executive summary

This research aims to identify data requirements for a porous asphalt (PA) material passport (MP) to increase the potential circularity of this pavement type, focusing on existing PA layers.

As interest in circularity increased in all domains, including the road pavement construction domain, the need for tools facilitating the transition to circularity is rising too. Key elements of this transition are reducing the amount of virgin material used and preventing the production of unrecoverable waste by using materials that can be reused efficiently and resuing those materials at the highest possible value. Data on materials and their qualities are essential for reusing materials as not all materials are suitable for every application, and some materials can be reused more efficiently than others. To enable circularity in PA pavement, data on the materials that are used, data that enables calculating circularity indicators, and data that allows for analyzing if materials support or block reuse is required.

MPs are considered an important tool, providing a framework in which the required information types are listed. In this research, a MP for PA is proposed, indicating data requirements in terms of information types, unit, purpose, and the moment of capturing. Four steps have been taken to come to the final PA MP.

In the first step of this research, a literature review was conducted to identify the current state-of-the-art MP in the road construction sector. Indicating recent development on MP in general and MP focused on asphalt. The literature review showed that MP as a concept is novel and little research has been done on the application in the road construction section. Furthermore, insight was provided into how MPs are structured regarding the different layers that hold different types of information, and existing MPs for asphalt are presented.

Secondly, interviews have been conducted with experts in the field of asphalt construction to identify an initial set of data requirements and get insight into how a MP is expected to work. Additionally, themes such as the meaning of circularity, difficulties of circularity for asphalt, and data management have been discussed to investigate implicit PA MP applications that can increase the potential circularity of PA.

In the third step, a conceptual PA MP is designed, indicating which information types should be included, how the data should be managed, what section a single MP represents, and how MP can hold data from multiple reuse cycles. This PA MP is not limited by feasibility and represents a MP for which all data is assumed to be obtainable. However, this research focuses on a MP for existing PA, and not all data is obtainable.

Therefore, a case study was performed in the final step to check whether the proposed PA MP can be applied to existing PA layers. This resulted in a list of information types obtainable with retroactivity and information types for which data is considered unobtainable. Additionally, the data currently provided on existing PA layers are compared with the PA MP, illustrating the present lack of valuable data.

Considering the results, it was concluded that the current state-of-the-art MP in the road construction industry is nothing more than combining already available information. Additionally, essential agreements, for instance, normalizing road decompositions in terms of data, are just starting to be made. Therefore it can be said that the development of MP in the road construction industry is in an early stage of development and unsuitable for application. Moreover, it was concluded that a data gap exists between data supplied in the tender phase of road construction projects with existing PA and the required data to enable the full circular potential of the existing PA. The PA MP, as conceptualized in this research, closes this gap.

Samenvatting

Dit onderzoek heeft tot doel de gegevensvereisten voor een materiaalpaspoort (MP) voor zeer open asfalt beton (ZOAB) te identificeren om de potentiële circulariteit van dit type verharding te vergroten, met de nadruk op bestaande ZOAB-lagen.

Naarmate de belangstelling voor circulariteit in alle domeinen toeneemt, inclusief het domein van de wegenbouw, groeit ook de behoefte aan tools die de transitie naar circulariteit faciliteren. Sleutelelementen van deze transitie zijn het verminderen van de hoeveelheid nieuw materiaal dat wordt gebruikt en het voorkomen van de productie van niet-herbruikbaar afval door materialen in te zetten die goed kunnen worden hergebruik en dat ook op een zo hoog mogelijke waarde te doen. Om circulariteit in ZOAB-verharding mogelijk te maken zijn gegevens over de gebruikte materialen nodig voor de volgende doelen: het inzicht krijgen van de beschikbare materialen, het berekenen van circulariteitsindicatoren en het anlyseren of materialen hergebruik ondersteunen of blokkeren.

MPen worden als een belangrijk hulpmiddel beschouwd, omdat ze een kader bieden waarin de verschillende soorten informatie die nodig is voor hergebruik wordt opgesomd. In dit onderzoek is een MP voor PA voorgesteld, die de data eisen aangeeft in termen van informatietypes, eenheid, doel en het moment van vastleggen. Er zijn vier fases doorlopen om tot het definitieve ZOAB MP te komen.

In de eerste stap van dit onderzoek is een literatuuronderzoek uitgevoerd om de huidige staat van het MP in de wegenbouwsector te identificeren. Vermelding van recente ontwikkelingen over het MP in het algemeen en het MP gericht op asfalt. Uit het literatuuronderzoek blijkt dat het MP als concept nieuw is en dat er nog weinig onderzoek is gedaan naar de toepassing in de wegenbouw. Verder is inzicht gegeven in hoe data is gestructureerd met betrekking tot de verschillende niveaus en worden in eerder onderzoek gevonden data-eisen voor asfalt gepresenteerd.

Ten tweede zijn interviews gehouden met experts op het gebied van asfaltbouw om een eerste set aan data-eisen in kaart te brengen en inzicht te krijgen in hoe een MP zou kunnen werken. Daarnaast zijn thema's zoals de betekenis van circulariteit, moeilijkheden van circulariteit voor asfalt en datamanagement besproken om impliciete ZOAB MP-toepassingen te onderzoeken die de potentiële circulariteit van PA kunnen vergroten.

In de derde stap is een conceptueel MP voor ZOAB ontworpen, waarin de verschillende elementen van het MP zijn uitgelegd. Dit ZOAB MP is niet beperkt door haalbaarheid en vertegenwoordigt een MP waarvan wordt aangenomen dat alle gegevens verkrijgbaar zijn.

Dit onderzoek richt zich echter op een MP voor bestaande ZOAB. Daarom is in de laatste stap een case study uitgevoerd om te controleren of het voorgestelde ZOAB MP kan worden toegepast op bestaande ZOAB-lagen. Dit resulteerde in een lijst van informatietypes die met terugwerkende kracht verkrijgbaar zijn. Daarnaast ook een indicatie van informatietypes waarvoor gegevens als onbereikbaar worden beschouwd. Bovendien zijn de momenteel verstrekte gegevens over bestaande ZOAB -lagen vergeleken met het ZOAB MP, wat het huidige gebrek aan waardevolle gegevens illustreert.

Kijkend naar de resultaten, kan er geconcludeerd worden dat de huidige staat van het MP in de wegenbou niet meer inhoud dan een combinatie van de al beschikbare data. Daarbij zijn afspraken over de decompositie van wegen op het gebied van data nog maar net gemaakt en nog niet voledig. Er kan daarom ook gesteld worden dat de ontwikkeling van MPen in de wegenbouw in een vroege fase van ontwikkeling zit en nog niet bruikbaar is in de praktijk. Ook kan er geconcludeerd worden dat er een gat zit tussen beschikbare en benodigde data van bestaande ZOAB lagen in de tender fase. Het ontworpen ZOAB MP dicht dit gat.

Terms and definitions

Environmental cost indicator
The **Environmental Cost Indicator** is a monetary unit used to express the environmental impacts that products and materials during their life cycle.
In dutch: Milieu Kosten Indicator (MKI)

Porous Asphalt
Asphalt with a high voids content, allowing for the passage of water and air.
In dutch: Zeer Open Asfalt Beton (ZOAB)

Crushed stone
In dutch: Steenslag klasse (Crushed stone class 3 = Steenslag classe 3)

Skid resistance
In dutch: Stroefheid

Reclaimed porous asphalt
Porous asphalt pavement that has been removed and or reprocessed.
In dutch: Asfalt granulaat

Milling
Milling is removing existing asphalt by separating it from other layers. The size of asphalt chunks depends on the type of milling machinery.

Abbreviations

MP	Material passport
PA	Porous asphalt
PMB	Polymer Modified Bitumen
RPA	Reclaimed porous asphalt
RAP	Reclaimed asphalt pavement
CE	Circular economy
DPP	Digital product passport

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1. Introduction

This bachelor thesis assignment is commissioned by Heijmans, one of the major infrastructure contractors in the Netherlands. The project will provide the foundation for the material passport (MP) data requirements for porous asphalt (PA) used in the surface layer of road pavement, with the ultimate goal of increasing the circularity of this type of pavement layer.

The problem context is introduced in this section, after which the problem statement is provided. Finally, the research objective and questions are stated.

1.1. Problem context

In the past decades, increasingly more attention has focused on climate change and the depletion of raw materials. With that, the topic of sustainability has risen on all agendas. Multiple climate summits have taken place, hosting many of the world's leaders. Last year, the most recent one aimed at transitioning toward a climate-resilient future in 2030 (Climate Adaptation Summit, 2021). With the worldwide pressure on the leadership to decrease pollution and increase circularity, the European Union has presented the European green deal (Eurpean Commision, 2019). One of the building blocks of this plan is economic growth without exhausting raw materials by the year 2050, also known as the circular economy plan. With this plan, the European commission targets sectors with high potential circularity, among which the construction and buildings sector is prominently highlighted. This sector alone is responsible for 50% of the material extraction and 35% of EU waste production (European Commission, 2020).

The new EU green deal agreements on circularity have directly affected national policymaking. The Dutch government published a nationwide program on circularity, in line with the green deal called "Nederland circular in 2050" (Rijksoverheid, 2016). In this report, the construction sector is again identified as one of the largest sources of material depletion and waste production and is, therefore, an essential element in the new policymaking (Rijksoverheid, 2016). Rijkswaterstaat (RWS), the executing agency of the ministry of infrastructure and water management and the commissioning party of all major public roads in the Netherlands, follow the national policies. They have set the goal of 100% circularity in 2050. Furthermore, they include a sub-goal in 2030, aiming to use 50% less raw building materials compared to the start of the program 'Nederland Circular' (2015), accompanied by 100% circular working. RWS describes circular working as reusing raw materials while maintaining value and producing as little waste as possible (Rijkswaterstaat, 2018).

The strategy of RWS directly affects the construction and maintenance process of the Dutch highway network. RWS commissions roads and therefore has the power to enforce its circularity goals in the tendering process. For contractors to remain relevant in road construction tendering processes, their working methods should include circular aspects. Rijkswaterstaat (2020) claims to award contractors that work more circularly than others in new projects by using the environmental cost indicator (ECI) (In Dutch MKI-indicator). The ECI calculates a monetary value by combining all environmental effects a project has. Scoring lower on the ECI value with a project compared to other contractors can result in beneficial awarding from RWS. For instance, CO_2 reduction within a project can lower the ECI value. Also, a higher level of circularity can, in some cases, have this effect. However, the ECI value is not a measuring instrument for circularity, and an increased level of circularity does not, per definition, result in a lower ECI value.

According to Platform CB'23 (n.d.), an initiative to increase circularity in the construction sector, the transition towards circularity requires the construction process to be completely transformed. The MP concept has a crucial role in this transition to circularity. Its primary goals are to enable high-value reuse of materials and decrease the use of raw materials and waste production (Platform CB'23, 2020c). According to Platform CB'23 (2020c), MPs are digital representations of objects in construction that enable the data exchange necessary for circular construction. Depending on their purpose, there are different MPs for different construction levels.

Since road pavement construction is a part of the construction domain, MPs are also introduced in the road construction sector. However, due to the relative novelty of its concept, they are often not available for existing pavements (Bouwend Nederland, 2020). This poses a problem since data on existing pavements is vital for the transition to circularity. The general concept of a MP is currently in the development phase, made ready for application in real projects by initiatives such as Platform CB'23 (n.d.) and BAMB2020 (2019). Further research connecting the MP to the road construction industry has been conducted by Bouwend Nederland (2020), which provides a basis for the data requirements. However, it misses out on explicit details required for operationalizing MPs.

1.2. Problem statement

According to a study conducted by Huurman & Demmink (2016), asphalt production for new roads is expected to decrease by 75% in 2050 compared to 2016, covering only 5% of the total asphalt production (Figure 1). This illustrates that asphalt production is predicted to be primarily for maintaining the existing pavement constructions in the coming years. In most cases of pavement maintenance, old pavement is milled, providing reclaimed porous asphalt (RPA), which can be used to create new asphalt.

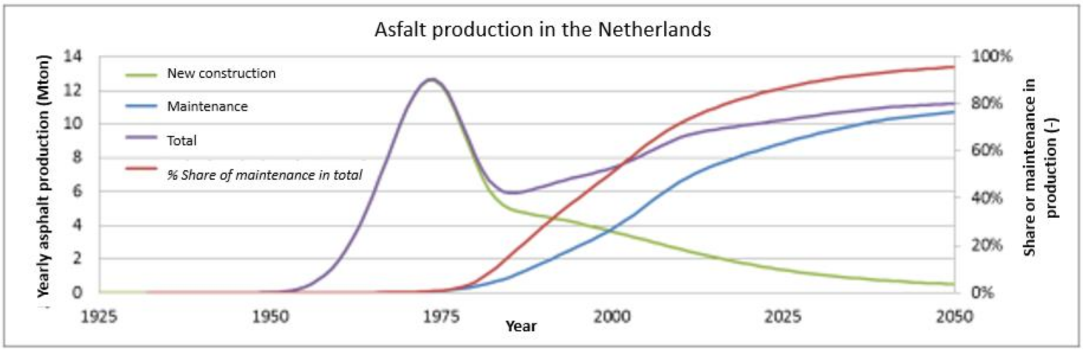

Figure 1: Production of asphalt in the Netherlands (Huurman & Demmink, 2016)

Heijmans has raised concerns about the information provided by RWS on existing PA layers that are replaced. They question whether the use of RPA can be optimized to increase circularity, given that they are provided with more data on the existing PA layers. Additionally, they note that for some materials in the RPA it is unknown whether it prevents reuse and obstructs circularity. Furthermore, they are raising concerns about estimating the potential circularity of projects in which PA is milled and reused. Estimations that do not represent the situation properly put the contractor at risk of being penalized for not being able to reuse the quantity of old PA as promised to the client.

As stated by CB'23 (n.d.), it is evident that the road pavement construction sector should become more circular, but the exact steps to be taken toward that goal are unclear. MPs can provide real-time information on a material and/or product in all stages of its life cycle, supporting the transition to circularity (Walden, Steinbrecher, & Marinkovic, 2021). However, MPs are often not available either for existing road pavements nor for new roads (Bouwend Nederland, 2020). Furthermore, knowledge of the data items MPs should include would help understand the information that contractors need to collect and store in the post-construction and maintenance phase. It would also define the data that road owners should make available in projects where old pavement layers are milled into RPA.

1.3. Research objective

Considering the increasing importance of circularity in road paving and the lack of research on MP for PA, the present thesis aims to increase the circularity potential of existing PA, by defining the outline and data requirements of a MP for PA pavement layers. Thus, the main research question in this paper reads as follows:

RQ: What characteristics should a MP for existing PA pavement layers have to increase the circularity potential of this type of asphalt?

For the sake of clarity, the state-of-the-art MP in road pavement construction has to be identified, to provide a basic understanding of what a MP is, what different purposes it suits, and how it is structured. Subsequently, the data requirements for a PA MP must be found. These requirements are not constrained by feasibility as they indicate what is necessary, not what is possible to obtain. Finally, the data requirements must be applied to a case study to identify what should be included in a MP for existing PA. Thus, the following sub-questions need to be addressed.

SRQ 1: *What is the state-of-the-art of the MP concept used in road pavement construction?*

SRQ 2: *Which data requirements and properties should a MP for PA have to increase the potential circularity for this type of asphalt?*

SRQ 3: *To what extent can the proposed PA MP be applied to a case study of an existing porous asphalt pavement layer?*

2. Theoretical background

2.1. The meaning of circularity

The Circular Economy (CE) has increased in popularity among politicians and researchers and gained momentum through promotions by the EU, governments, and businesses. However, the specific definition of CE remains unclear. Many recent studies have focused on the problem of defining the concept of circularity. However, its particular meaning is diverse among different people. Kircherr, Reike & Hekkert (2017) provided evidence to this claim by analyzing 114 definitions of the circular economy with empirical evidence and even stated: "some of the authors [….] seem to have no idea what they are talking about". Besides the many different concepts, they did find a common conceptualization that circularity is often understood as a combination of reduction, reuse, and recycling.

CE definitions have also been changing rapidly in the last couple of years. A study performed by Murray et al. (2015) defined CE as a model in which planning, resourcing, procurement, production, and reprocessing are designed to maximize the outputs ecosystem and human wellbeing. Nonetheless, in light of circularity, maximizing output does not avoid but postpones resource depletion. The Ellen McArthur Foundation (2013) provided a more focused definition of CE, claiming that a CE is restorative or regenerative by intention and design. However, this definition remains open to different interpretations and does not provide any indicators of what a restorative or regenerative intention and design is. However, a revision of this definition by the Ellen MacArthur Foundation in 2015 added a more tangible approach by indicating that products, components, and materials should be kept at their highest usage and value. More specific and measurable definitions are provided in more recent studies. CE aims to reduce the consumption of raw materials and energy while preventing waste and emissions (Korhonen, Honkasalo, & Seppälä, 2018). Moreover, it should have a notion of input reduction reuse and waste recycling (Homrich, Galvão, & Abadia, 2018). Because of the wide range of domains in which the term circular economy is used, a single, strict definition may be too idealistic.

Not only is there a lack of a clear CE definition, but there are also many different limitations to CE in the current time and age. Perhaps, this is rooted in some of the preliminary CE concepts, such as "ecoeffectiveness" (Braungart, McDonough, & Bollinger, 2007), which are idealistic and rely on unlimited renewable energy usage and complete recycling of materials (Korhonen, Honkasalo, & Seppälä, 2018). Since the topic of circularity is becoming more regularly used in practice, an idealistic definition may propose difficulties. Simplifying the concept can therefore help in increasing the applicability. However, this poses the risk of deviating from the ultimate goal of circularity.

2.2. Circularity in the context of road pavement construction

Reusing material is not new in the road pavement construction sector. RAP material has been used for years, often motivated by economic reasons. Nonetheless, the increasing importance of sustainability moves the road pavement construction sector toward a more circular-driven way of working, incorporating but not limited to reuse. In road pavement construction, the terms high-value reuse and upcycling/downcycling are often used when spoken of circularity. Still, these terms are subject to different interpretations. Downcycling is a reduction in the quality of a reprocessed material with respect to the original quality (Helbig, et al., 2022). Hence, high-value reuse is reusing a product without downcycling. Upcycling is seen as an antonym for downcycling (Helbig, et al., 2022). This implies that upcycling improves the quality of a reprocessed material relative to the original quality. It is noteworthy to stress that downcycling and upcycling refer to the original quality of a material and not to the quality before down or upcycling. A material that can be reprocessed to its original quality is considered regenerative material.

The concept of circularity has not yet been widely and adequately implemented in road pavement construction projects (Mantalovas & Di Mino, 2020). This can be partly attributed to bitumen, the binding ingredient used in asphalt. Bitumen poses a problem in terms of circularity. Xu. et al. (2020) indicate that no solutions have been found to regenerate bitumen to its original quality after aging. Some original quality is permanently lost. However, upcycling is often mentioned in combination with the process of rejuvenating bitumen as the quality of the aged bitumen increases. Nonetheless, rejuvenating bitumen does not result in bitumen that has the same quality as the original bitumen that left the refractory. Therefore, rejuvenating bitumen can enhance the quality of old bitumen. However, a certain degree of downcycling will always occur.

Downcycling can also be found in coarse aggregates, another ingredient of asphalt. Currently, coarse aggregates are separated from existing road construction to create RAP, with a technique called milling. However, milling is a destructive method in which massive forces are used that causes some portion of the coarse aggregates to be broken into finer aggregates. The reduction in the size of the coarse aggregates is irreversible. Hence this process is non-regenerative.

Significant research is focused on identifying alternative products to solve the regeneration problems of asphalt ingredients. For bitumen, research is conducted to identify regenerative alternatives. Bio-based binders are found to be a promising alternative. For coarse aggregates, however, no research was found on regenerative alternatives. Most of the research on coarse aggregates focused on finding waste materials from different applications, suitable for use in road pavement construction. For instance, Martinho et al. (2018) claim that some waste aggregates, waste products from a different production process, can substitute natural aggregates and contribute significantly to circularity by reducing material consumption. Lederer et al. (2020) support this statement with their case study, indicating that using waste material streams enhances circularity. This way of managing the material streams provides a way to minimize waste, but waste is still produced in the long run.

2.3. Measuring circularity

For the concept of circularity to be operationalized for usage, the indicators that allow measuring circularity should be defined. There has been an increase in studies defining indicators that allow circularity to be measured, caused by the need for monitoring CE transitions (Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019).

Because of the many attempts to define indicators for CE, it is essential to choose the right ones that provide a credible "image" of the degree of circularity in the specific use cases. As the focus of this research lies on PA indicators relevant to measuring circularity in the construction industry should be included.

The EU provides indicators used to measure circularity on a macro level, indicating how well a country performs in terms of Material footprint and Resource productivity (European Commission, sd). Naturally, these indicators are too broad to be used at project level (i.e., micro-level). The guideline designed by CB'23 (2020b) "measuring circularity" is aimed at providing unambiguous agreements on how to measure circularity in the construction sector at all levels (Macro, Micro). CB’23 (2020b) created a material balance, indicating all material flows (Figure 2).

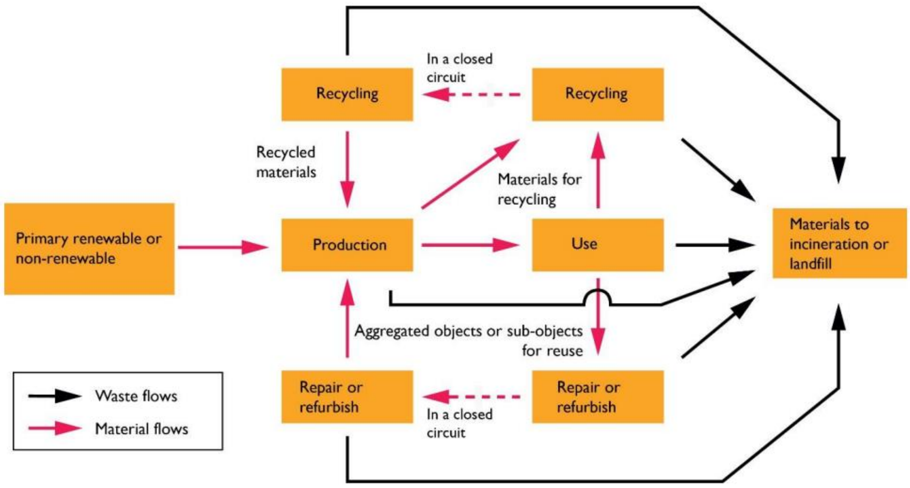

Figure 2:Material balance (CB'23,2020b)

CB'23 (2022b) proposes six leading indicators in their new 3.0 guide on measuring circularity. These indicators cover three main goals: protecting material stock, protecting the environment, and retaining material value. These three goals are represented by six leading circularity indicators (Table 1).

Table 1: Circularity indicators for construction, adapted from CB'23 (2022)

	Indicator
1	Amount of input material used to produce or repair an object
2	Amount of output material available for next cycle
3	Amount of output material lost for next cycle
4	Indicators equal to the environment-impact categories as defined by the NMD foundation
5	Amount of functional-technical value at the end of life cycle
6	Amount of economic value at the end of life cycle

Mantalovas & Di Mino (2019) provided a model to measure the circularity of reclaimed asphalt (RA). This model took multiple parameters into account, such as the amount of necessary virgin material and the unrecoverable waste produced. Comparing the CB’23 (2020b) indicators with those of Mantalovas & Di Mino (2019) shows that the general concept of measuring circularity is concerned about the material flows, especially the inflow of virgin material and the outflow of unrecoverable waste. The indicators show that circularity can be increased if the inflow of virgin material and the outflow of unrecoverable waste is limited. In an ideal situation where no inflow or outflow of material occurs, absolute circularity has been achieved. The advantage of looking at the inflow and outflow of materials is that it can be used on either single cycles or an infinite number of cycles. Recent development in terms of circularity in the construction industry has resulted in innovations that minimize the production of unrecoverable waste. Considering these innovations on single cycles shows significant improvement. However, when the scope is extended to a higher number of cycles, even the most negligible generation of unrecoverable waste results can still result in a large amount of unrecoverable waste in the long term. This indicates that minimizing unrecoverable waste only delays the problem, whereas eradicating unrecoverable waste would solve the problem.

In this research, potential circularity is the possible circularity that can be achieved, measured according to a set of indicators. For example, if increasing the knowledge of what materials are included in an existing road by providing a PA MP can prevent downcycling to a certain degree, the potential circularity has been increased. Therefore, it is of paramount importance that the PA MP designed in this research enables circularity calculations.

The circularity indicator proposed by CB'23 (Platform CB'23, 2022) enables calculating circularity. The PA MP should therefore provide the input data for those calculations. Two main types of information are fundamental in calculating circularity: material identification, mass, and quality. The circularity indicators are calculated based on material-specific parameters such as whether the material is primary or secondary, whether the material is renewable, and at what environmental cost recycling or reusing can be achieved. Hence, to allow for circularity calculations, a MP should indicate which materials are used in an object. Secondly, the amount of material used, expressed in mass, is required to calculate the circularity indicators, as found in the complete list of input values for the CB'23 (2022) indicators (Appendix A, Table A1). Lastly, material qualities can differ, for instance, due to degradation. It is, therefore, crucial that the quality of a material is included in the MP.

3. Methods

This section presents the methodology used for conducting the research. The methodology can be divided into four parts (Figure 3).

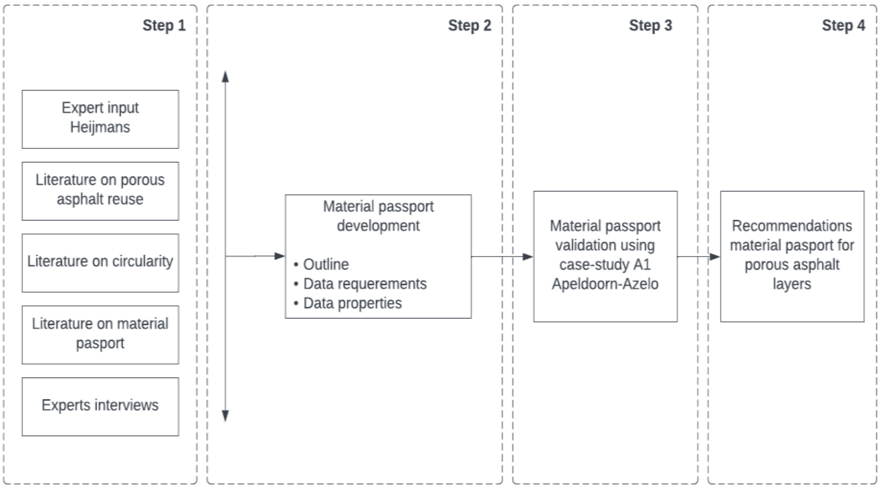

Figure 3: Research model

In the first phase, the theory on MPs is collected and analyzed. This desk research aims to identify the concept of MP in both the broader context and the context of road pavement construction. The information obtained serves as a baseline for this research and could answer the first research question, "*What is the state-of-the-art of the MP concept used in road construction?*"

Next, multiple semi-structured interviews are conducted with representatives of various contractors (including Heijmans), provinces, and RWS. These interviews provide insight into the participants' experience concerning the PA MP. The interview process is described, and the validation of the results is explained. This part could answer the second sub-question, "*Which data requirements and properties should a material passport for porous asphalt have to increase the potential circularity for this type of asphalt?*". The desk research and interview results are used to design a material passport for PA.

In the final part of this research, the MP's applicability is explored using a case study "A1 Apeldoorn-Azelo". This case study will provide insights into what elements of the proposed material passport can be applied to a project in which Porous RAP is reused. Additionally, information is obtained about the current data gap between the data provided in the tender phase and the data necessary to complete a project.

3.1. Boundaries

This research is constrained to PA pavement. This decision has been made where most of the Dutch top-asphalt layers on the highway network consist of PA. Additionally, according to the RAW (CROW, 2015) standards, PA has the strictest requirements for material quality.

4. Literature review on material passports

The literature review was conducted to identify the state-of-the-art MP in the broadest context and, more specifically, in relation to the road pavement construction industry. The time span for this literature review was three months, between May 2022 and June 2022. In order to find suitable peer-reviewed references, Scopus was used (a citation index type database for researching scientific research). Grey literature (reports) was found by identifying organizations and companies working on MPs in the construction industry. Scopus listed only 32 results for the search query: "material passport" (Figure 4). The absence of a broad set of literature justifies the choice of including gray literature to increase the sources of information and prevent a bias towards published research.

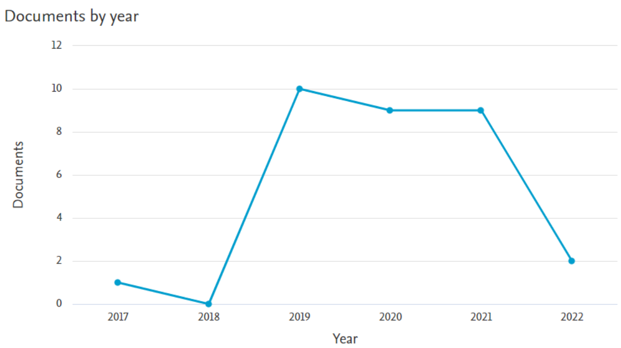

Figure 4: Published documents per year on the Scopus database

The complete set of keywords used to identify academic literature (peer-reviewed) can be found in Appendix B (Table B1). Multiple criteria have been applied to identify the initial set of literature. Only English or Dutch publications were considered, and the time span was limited to 2017 and 2022. The literature selected was also checked for its relation to circularity. Limiting to English publications is justified where it covers a broad pool of references and English is primarily used in the scientific community. Allowing for Dutch publications is acceptable, where the Netherlands has already put much effort into circularity and MPs in consortia such as CB'23. Therefore, many reports on MPs are available in Dutch. The period is justified by the fact that in 2017 the first publication concerning the construction sector and MP was published.

After initial searching and removing duplicates, 46 peer-reviewed articles were identified, of which 29 match the criteria. Additionally, seven grey literature (reports, norms, frameworks, guidelines, and user manuals) have been identified. They were sourced from consortiums BAMB2020, CB'23, Bouwend Nederland, NIBE. Moreover, they were sourced from MP software companies Madaster (Buildings), pavement information model (PIM), and standards as provided by the Dutch normalization institute (NEN).

4.1. Defining a material passport

The concept of the MP is relatively novel. Nevertheless, this concept is critical in transferring the construction sector towards a more circularity-driven way of working (Platform CB'23, 2020c). Different views on the definition of MPs can be found in the literature. A MP is defined by Honic et al. (2019) as a place documenting the material composition of buildings in both quantitative and qualitative terms, including the potential material reusability. Platform CB'23 (2020c) provides a broader definition for the MP, defining it as a digital document that secures information about an object in both the building and utility sector, as well as the ground-, road- and hydrological engineering sector. It holds data on where an object is located and what it is made of in qualitative and quantitative terms.

Besides MPs, digital product passports (DPP) have also been mentioned in the literature. Therefore, it is essential to identify the relationship between these two types of passports. DPPs include product information concerning the origin, composition, and dismantling options and allow tracking of this information consistently (Adisorn, Tholen, & Götz). Walden et al. (2021) identified the link between MP and DPP, indicating that both passports are digital representations of physical objects. The building industry adopts the term “material passport.” for this. Implying that there is no real difference between MPs and DPPs. Research indicating the difference between DPP and MP is currently missing.

In literature, MPs are often referred to as ingredient labels, similar to labels on food items. However, the purpose of a MP is broader than indicating a list of materials. As Luscuere (2017) points out, the products and composition in construction are complicated. Furthermore, the context of how materials are applied is crucial. Additionally, in contrast to food labels, MPs cannot be considered static, as the data changes throughout the life cycle of a construction object (Luscuere, 2017). Suppliers and manufacturers are generally considered the main actors who provide specific product information. In road pavement construction, the contractor is often a supplier and manufacturer.

Significant differences can be found regarding which data should be included in a MP, as different purposes require different data types. For the sake of clarity, data requirements will be seen as the types of data in a MP. These data requirements are expressed as information types, which in turn include a dimension of information such as height, volume, brand, and strength. Information types have a fixed unit in which they are expressed.

4.2. Purpose of a material passport in road pavement construction

MPs are relevant to different user groups and require different levels of detail (Adisorn, Tholen, & Götz). Therefore, the different purposes of a MP need to be identified. MPs can be used to identify circularity scores based on the materials or indicate reusability and recyclability (Atta, Bakhoum, & Marzouk, 2021). Some researchers describe the purpose of MPs broadly, applicable construction domain-wide. Luscuere (2017), for instance, describes the MP as a tool for maximizing circularity by maintaining the value of materials. CB'23 (2020c) describes the purposes as: A MP to measure circularity, a MP to manage and maintain an object, and a MP to facilitate reuse and value retention in the future. A MP can therefore be seen as a combination of information types that all suit one or more purposes.

4.3. Material passport levels in road pavement construction

A material passport consists of multiple layers as different levels of detail for the included data are present (Bouwend Nederland, 2020). Platform CB'23 (2020c) indicates seven levels: Area, Complex, Structure, Element, Construction products, Material, and Raw material (Figure 5). However, research conducted by NIBE (2022) only considers five levels: Object, Element, Product, Building material, and Raw / semi-finished materials. Despite the difference in the number of levels, the general framework remains the same in both cases. The material passport becomes more detailed from left to right and is based on one-to-many relationships (e.g., an area can consist of multiple complexes, and a complex can consist of multiple structures). The different levels can be grouped into two types found in the NEN 2660-2: functional entities (aimed at executing a function) and materialized entities (indicating amounts of materials).

Figure 5: MP levels as defined by CB'23 (2020c)

In the NEN-2660-2, a decomposition of road pavements is provided (Figure 6). This decomposition provides a clear basis for the levels a MP should cover for road pavements. Additionally, the one-to-many relationships can be found as a single top layer containing multiple types of asphalt. Furthermore, a type of asphalt can contain different mixtures identified by different codes.

Figure 6: Decomposition of a road. Adapted from NEN-2660-2 (2022)

4.4. Material passport information types for road pavement construction

As noted in chapter 2.2, MPs contain different information types, each suiting a purpose. CB'23 provides a long list of items used in a material passport, including the properties, purpose, and owner of these items, in combination with a guideline (2020c). Bouwend Nederland (2020) has reported in their "material expedition" on multiple case studies of using the MP in road pavement construction, following the CB'23 guideline. This has resulted in a selection of the items on the MP long list that is at least necessary to enable high-value reuse on a material level (Table 2). Any other literature or documents that described a MP for road pavement as specific as Bouwend Nederland did have not been found. This shortlist, however, does not indicate what is considered an element in road pavement construction. It does not elucidate material qualities and does not provide any purpose for each information type. No literature has been found indicating MP information types related explicitly to PA.

Table 2: Material passport shortlist, translated from Bouwend Nederland 2020

Object level		**Element Level**	
Information	**Unit**	**Information**	**Unit**
Geographic location	Coordinates	Material	Material type
Date of commissioning	Date	Strength class	EU determined
Dimensions	mm	Supplier	Name / Address
Design lifetime	Years	Thickness	mm
Owner	Name / Address	Specific weight	kg/m^3
Object type	Text	Volume	m^3
Decomposition	Text (NEN1660)	Mixture	Ingredient names Ingredient amounts
		Binder	Type
		Crush stone type and aggregate size	Type, origin, size in mm
		Type of filler	Material type
		Type of additive	Material type

5. Expert interviews

Semi-structured interviews were conducted to have a deeper understanding of the material passport role in PA circularity and how information types can increase the potential circularity of PA. Additionally, views were gathered on why certain information types are relevant and who should carry responsibility for data creation and management.

Many different types of interviews can be conducted in qualitative research, such as focus groups or structured interviews. The objective of a research project determines the interview strategies that can be applied. For example, testing a hypothesis requires a structured interview using standardized questions and analytical methods (DiCicco-Bloom & Crabtree, 2006). However, the qualitative element of this research is aimed at exploring what information types could be relevant for a material passport. Therefore, this research requires a qualitative interviewing method, which is more flexible. Encourages the interviewee to share descriptions of events and opinions while leaving interpretations and synthesizing to the researcher.

DiCicco-Bloom and Crabtree (2006) stated that semi-structured in-depth interviews are the most used interview format in qualitative research. This interviewing method provides a structure regarding the topics discussed and the initial questions posed. However, it leaves room for the interviewee to determine the contents and flow (Boeije, 2009).

5.1. Procedure

Eighteen people were interviewed during interviews lasting on average 1 hour and up to 1,5 hours (Table 3). The interviews were either on an individual basis or per group (up to three participants per interview). Participants have only been combined when working at the same company, which allowed for a reduction in the necessary time. Almost all contacted people responded to the invitation and were willing to contribute to this research by taking the interview. However, two companies did not respond for unknown reasons to the invitation. The invitation made it clear that the final report would be publicly accessible.

Table 3: List of participants in the interviews

ID	Company	Name	Interviewed on (2022)	Type	Interview
1	AfaltNu	Michiel-Martijn Willemsen	24 May	Online	14
2	Ballast Nedam / Dibec	Radjan Khedoe	3 May	On location	9
3	Ballast Nedam / Dibec	Stefan Geneugelijk	3 May	On location	9
4	Ballast Nedam / Dibec	Thomas vermeer	3 May	On location	9
5	Bam	Marco Oosterveld	6 May	Online	11
6	Boskalis	Berwich Sluer	2 May	Online	8
	Dura Vermeer	*Known by author*	*No response*		
7	Gelderland (province)	Mathieu van den Hurk	3 May	On location	10
8	Heijmans	Adrie van der Burgt	2 May	Online	7
9	Heijmans	Jeroen Braak	26 April	Online	2
10	Heijmans	Rijk Pellikaan	2 May	On location	6
11	KWS	Jasper Keizer	28 April	Online	1
12	P.I.M	Sietse Robroch	9 May	Online	12
13	Rijkswaterstaat	Marc Peerdeman	28 April	Online	3
14	Rijkswaterstaat	Paul Kuipers	29 April	Online	4
15	Rijkswaterstaat	Peter van der Hem	29 April	Online	5
16	Rijkswaterstaat	Sylvia Drok	29 April	Online	4
17	Rijkswaterstaat	Wilma Middel	29 April	Online	5
	Strukton	*Known by author*	*No response*		
18	Reinten Infra	Ronald Diele	12 May	On location	13

Some interviews were held on locations, whereas others were conducted using the online video conference tool “teams.” Before every interview, the purpose of the interview was explained, and the interviewee was asked two standard questions:

1. Can this interview be recorded for analysis?
2. Do you allow your name to be mentioned in the report solely to construct a list of participants?

The interviewees were allowed to ask any questions during or after the interview. After each interview, the further research steps were explained, and the interviewee was informed about the possibility of a second deepening interview. Additionally, participants were informed about the validation step, for which they were contacted after completing all interviews. Thirteen out of the fourteen interviews have been recorded.

5.2. Qualitative analysis

A thematic analysis was conducted on the recorded interview data as a qualitative method. As described by Braun & Clarke (2006), a thematic analysis consists of six phases: (1) getting familiar with the data, (2) generating initial coding, (3) identifying themes, (4) reviewing themes, (5) define and name themes, (6) producing the report. It is important to note that a theme only counts when it captures something related to the research question (Braun & Clarke, 2006).

Due to the time constraint of this research project, only some interviews have been transcribed superficial using software to identify the initial codes and themes. The further steps of the thematic analysis have been performed based on the recordings.

5.3. Validation

Validation is an essential step in qualitative research as it influences the trustworthiness of the results. As Miles & Huberman (1994) mention, the researcher is often also the data analyst in qualitative research, posing the risk of researcher bias. In some cases, the researcher might also impose personal beliefs in the interview, influencing the interviewee (Mason, 2002). As one person conducts this research, the same researcher performs both the data collection and analysis, creating a risk for both influences on the interviewees and researcher bias. Therefore, validation is crucial.

Member checks show to be a crucial technique to create credibility for the interpretations and conclusions drawn from the data (Lincoln & Guba, 1985). Member checks of synthesized data validate the results by creating the opportunity to add data (constructivism) and explore contradicting voices (objectivism) (Birt et al., 2016). This research project has applied member checks after the first round of interviews. The information types synthesized from the interview data have been combined in a list and sent back to all interviewees. With all information types, two questions were accompanied.

1. Is this information type relevant to the MP, in your opinion?
2. Why is this information type relevant, or why is it not relevant?

7 out of the 11 interviewees working at contractors reviewed the list of information types.

5.4. Results

Thematic analysis of the interviews has resulted in five themes related to the research objective: Role of the material passport for PA in circularity, Passport boundaries, Information types, Data management, and difficulties with identifying information types. The results from the interviews have been summarized and can be found in the following sections.

The interviews resulted in various interpretations and views, not only concerning the MP in particular but also regarding what circularity means and what difficulties are recognized in incorporating circularity in the road pavement industry. The different answers of the interviewees to how they would describe circularity in the context of asphalt and what difficulties they identify in this context can be found in Appendix C: Additional insights from the interviews (Table C1 and C2, respectively).

5.4.1. Role of material passport for PA in circularity

During the interviews, multiple remarks were made on the role of the material passport and the potential circularity of PA. Four participants mentioned that not all materials are suitable for reuse, where MPs would indicate which materials are present, identifying what can be reused and what not. Additionally, three participants mentioned that a higher percentage of reclaimed asphalt in new layers increases the percentage considered unknown. They described it with the analogy of a black box, where the use of RAP material is a black box that is difficult to control. According to them, a higher percentage of RAP in new mixtures would result in less control over the quality.

All of the participants working at contractors mentioned that the information provided in the tender phase of a project is insufficient to provide a correct estimation of the level of reuse that can be reached. These same participants indicated that their company would always do more research before milling the asphalt to identify the current state and composition of the existing PA layer to estimate the reuse possibilities. Sometimes this research was done at their cost during the tender phase. Data, structured in a material passport, would make this research for individual contractors unnecessary.

Interesting was the reporting of two of the participants concerning the knowledge gaps that are currently existing. These participants mentioned that not all materials are reusable indefinitely, whereas one of the participants mentioned that the effects of materials that have been reused for more than one generation are unknown. An example of this is the reuse of reclaimed asphalt with PMB. The participant mentioned that until now, no problems had been reported with the reuse of PMB asphalt. However, the effect in the future after multiple reuse cycles is not yet researched.

5.4.2. Material passport boundaries

The second theme in the data analysis can be described as follows: what can be seen as a materialized unit to which a material passport can be assigned, both in physical space and time. All of the participants working at a contractor mentioned throughout the interview that in an ideal situation, the material passport belongs to a homogeneous PA layer of the same thickness. However, this poses a problem, where layer thickness can vary significantly over the length and width of a layer. Therefore, one participant mentioned using a so-called execution unit, a section of PA constructed during a single operation. Such an operation could sometimes be a few kilometers long but consist of a single homogeneous mixture.

Additionally, some participants mentioned that due to maintenance throughout the life-cycle of a homogeneous PA section (now referred to as PA section), parts within this section could be subject to replacement or treatment with specific substances. This would change the composition of parts within the PA MP section compared to the original sections. Some participants indicated that this could result in a new MP for the section affected by the maintenance. However, a division could be found between the participants' answers regarding when a PA section has a significant size to have its own MP. A straightforward answer in terms of dimensions was not provided. Moreover, some participants mentioned that this would depend on the degree to which unsuitable material could be used in new mixtures. In-depth questioning indicated that the current rules on using unsuitable material in new mixtures are ambiguous.

5.4.3. Information types

During the interviews, only the participants working at contractors mentioned information types that could be included in a material passport for PA. It is noteworthy that each participant mentioned different information types, for which the cause could be rooted in the participants' different definitions of circularity.

The coarse stone type was often mentioned as the bare minimum necessary for reusing PA layers without downcycling. Furthermore, the type of bitumen (penetration or polymer-modified) was also deemed necessary. In Table 4, a list of all the mentioned information types can be found. These represent the data from the interviews, not the researcher's view. The arguments provided in the validation step of the interviews on why an information type is relevant are also provided. Noteworthy is the absence of “presence of tar” in the list. Participants have mentioned this as necessary. However, as indicated by CROW publication 210, PA may be considered tar free. Therefore, for the scope of this research, the presence of tar does not add value to the PA MP.

Table 4: Proposed information types (As answered by interview participants)

Theme	Information type	Description	Relevance
MP boundaries	Area	The area to which a single MP applies.	It is relevant to know the area to which the MP belongs, both for indicating which material will be milled (milling plan) and determining which quantities of material become available
MP boundaries	Layer thickness	The thickness of a single PA layer.	The layer thickness is required for similar reasons as the area. To indicate the amount of available material and the depth of the milling machine to prevent mixing materials from different layers.
Information types	Binder content	The amount of binder per unit of PA.	In new mixtures, the binder content is set to a specific value. Therefore, it is necessary to know the binder content in the RPA. Knowing the binder content of the RPA is required for calculating the amount of new binder to be added.
Information types	Mixture density	The density of the complete asphalt mixture.	Together with the area, layer thickness (combined provide the volume), and the density, the total amount in mass can be calculated. This indicates the amount of RPA that will be available for reuse.
Information types	Production/ processing temperature	The temperature log of the asphalt during production at the asphalt plant or processing at the project location	Knowing the temperatures an asphalt mixture has endured was deemed valuable by one of the participants. Mixtures that have been heated to excessive temperatures can have degraded qualities compared to mixtures that have not reached those temperatures. However, all participants mentioned that it is impossible to determine for existing roads. Additionally, some participants mentioned that the current quality is of greater value and that the production or processing temperature is unnecessary.
Information types	Friction after polishing value (FAP)	The friction value obtained by performing a FAP test. This is an indicator of the friction of the exiting PA layer.	The FAP value is only considered relevant for new sections, providing proof of skid resistance. One of the participants mentioned that if the FAP of existing pavements is sufficient, this could be used as proof that the RPA is suitable for reuse in new PA layers. However, most participants indicate that if the crushed stone class and PSV value are known, the FAP value is irrelevant. One of the participants mentioned that the FAP has a high chance of being low as the road pavement is already up for replacement.
Information types	Origin crushed stone	The exact location of the crushed stone quarry.	Participants mention that if the crushed stone class is known, the origin is not relevant anymore, as material characteristics and categories are essential and origin is not. However, if the crushed stone class is unknown, the origin can provide valuable information to estimate the stone class.
Information types	Crushed stone class	The crushed stone class is indicated as one, two, or three, where three is the highest class.	New PA mixtures require crushed stone class 3. Therefore, to use RPA in new mixtures, it is essential to know the crushed stone class of the RPA.
Information types	Grading	The percentage share of certain fraction aggregates. (e.g., 10% 0-2mm, 50% 2-4mm and 40% 4-8mm)	The grading determines which mixtures RPA can be used (e.g., SMA 8 can only be used in SMA 8, the same counts for SMA 11). Additionally, the grading is relevant as asphalt mixtures have a fixed grading according to their design. Therefore, virgin material is adapted to use RPA in new mixtures to reach the design mixture grading.

Information types	Polished stone value (PSV)	A value contributed to individual aggregates indicating the skid resistance.	This value is relevant as it is necessary to identify the PSV of the mixture in which the RPA is used. Most participants, however, mentioned that it could be assumed that the PSV value is known if the crushed stone class is known
Information types	% broken surface of stones	The percentage of the broken surface is an indicator of the roughness of the stone surface	Participants mentioned that the percentage of the broken surface is related to the crushed stone class. Therefore, if the crushed stone class is known, the percentage of the broken surface is also known. However, the percentage of broken surfaces should be investigated if the crushed stone class is unknown.
Information types	Stone shape	The stone shape indicates if any flat surfaces are present on the aggregates	Knowing this would indicate the reusability of the coarse aggregates. Most participants mentioned that the stone shape would be correct as it is already used in an asphalt mixture and follows from the crushed stone class. However, this is based on the assumption that the material used in existing asphalt mixtures is correct.
Information types	Resistance to the fracturing of stone	The resistance to fracturing indicates the strength of the aggregates to withstand specific loads	Some participants find it valuable to know the resistance to fracturing of the stone, as it determines if a stone can be reused in a new PA layer. However, one of the participants mentioned that the resistance to fracturing occurs most often during the milling of old asphalt layers. Therefore, this value should be determined after milling.
Information types	Bitumen type	The bitumen type is the product name and brand.	Knowing the original identification name of the bitumen would provide valuable information as original qualities are related to this identification. However, most participants mentioned that it is impossible to identify the name or brand of existing asphalt layers.
Information types	Modification type bitumen	Bitumen is, in some cases, modified to add necessary characteristics.	It is essential to know if bitumen is modified or not as it affects the reusability. Knowing whether the bitumen is modified or not allows for assessing measures to upcycle the mixture's quality and identify environmental and health effects.
Information types	Bitumen additives	The type of additives added to the asphalt mixture	One of the participants mentioned that knowing the type of additive is essential as it helps in knowing all the ingredients in the asphalt. Another participant mentioned that it is relevant as knowing the additive helps identify effects on the new mixture. However, most participants mentioned that it is not relevant as the hardness and softening point of the bitumen are the only relevant information types for bitumen.
Information types	Bitumen hardness	Characteristic of bitumen indicating stiffness at a specific temperature	The hardness of the bitumen (penetration) is necessary for calculating the amount of necessary new bitumen and/or rejuvenation substances.
Information types	Bitumen softening point	Characteristic of bitumen indicating at which temperature a certain viscosity is reached	Same as for hardness bitumen
Information types	Filling material	The type of filler used in the asphalt mixture	As one of the participants mentioned, the amount of filling material is essential and will follow from the grading. However, the exact type of filling material can not be determined and is not considered relevant.
Information types	Fibers	The type of fiber used in the asphalt mixture	One participant mentioned that what happens with fibers in the recycling process is unknown. Therefore it is relevant to know if fibers have been used
Information types	Sealing	Type of sealant. Sealing is often done during the life cycle of asphalt to extend the lifespan.	Same as fibers
Difficulties in identifying information types	Reclaimed porous asphalt (RPA) (characteristi cs	The characteristics of any RPA used in the mixture. This could be an original MP of the RPA or multiple MPs when multiple types of RPA are used	Most participants mentioned that this is irrelevant, as it is essential to know about the material qualities now, not what they were. However, some participants did find this relevant. Three of the participants mentioned the relevance of knowing if the existing pavement already included RPA. In such a case, they indicated that it would be valuable to know the original characteristics of the reclaimed asphalt, such as the hardness of the bitumen and crushed stone class. Also, the number of cycles the materials within the RPA have endured was found relevant.

5.4.4. Data management

16 of the 18 participants suggested the road owner (for PA, most often RWS) as suitable for managing the material passport and ensuring completeness. One participant described this as follows: "The client should arrange, and the contractor should supply the data." Multiple arguments were given concerning this statement. One of the participants suggested that to create fair competition, clients should always provide a complete material passport in advance. Providing the same data to all contractors was mentioned as the only way to have the same starting point. Additionally, this participant described that RWS already supplies data on structural qualities and that they should similarly provide data to indicate the circular potential. Specific comments were also made on the possibility for clients to use the contracts to demand data supply.

Two participants did not agree that RWS should be the only one responsible for managing the data. One indicated that RWS is the largest client in PA construction and is therefore expected to manage all the data. However, the participant stated that if the scope is widened, considering, for instance, the B&U sector, there will be many more individual clients and owners. Therefore, we should find a type of data management that does not only work in asphalt construction but for every construction object.

5.4.5. Difficulties in identifying information types

All participants indicated at least one difficulty in designing and maintaining the material passport. One participant mentioned that the concept of the material passport is novel, resulting in discussions about what should be included, which should have never been discussed in the first place. The participant also added that the information needed differs per client and or contractor. Some information necessary for the contractor is unnecessary for the client.

Some participants mentioned that the current regulation on using RPA is outdated. Therefore, the amount of RPA used can differ on a project basis. One of the participants mentioned that if the existing standards are followed, not a single stone of a lower than required crushed stone class can be used in new PA pavement. This would imply that a MPs should be extremely detailed regarding each stone within the pavement. In practice, a certain percentage of lower-quality stones is allowed. This percentage does fluctuate per use case. Therefore, it is difficult to identify if an information type is relevant as it depends on the rules that apply to the new mixture.

A significant problem directly affecting the way the material passport was pointed out by one participant: "There is not yet a standardized approach to decompose a road."

Two participants mentioned pavement degradation over time as a difficulty, especially when data is collected during the tender phase. Often, there is a time gap between the tender phase and the actual construction work, making data in the PA MP inaccurate compared to the actual situation. However, this was toned down by one of the participants. If a binder is already quite stiff, it does not matter if it gets somewhat stiffer.

One of the participants pointed out that it is challenging to follow material harvested in a project. The milled asphalt often ends up on a large pile of material. In some cases, it can be mixed for homogenization, after which the material to which a passport belonged is combined with other materials with different passports. The more cycles of recycling that occur, the more difficult it gets to follow where the material is located.

6. Conceptualization of a porous asphalt material passport

This section presents the MP for PA based on the interview results, the literature review, and input from experts within Heijmans. It is essential to design a MP for PA that can facilitate the current data demand and, subsequently, the information needs that might occur in the future. For designing the proposed PA MP, an ideal situation is assumed in which there are no limitations on which data can be obtained. In the next phase, the extent to which the different information types in the MP can be applied to existing PA pavement will be explored in the next phase of this research (Case study A1 Apeldoorn-Azelo).

6.1. Purpose of the porous asphalt material passport

The objective of the designed MP is to increase the potential level of circularity of PA, so each information type included should fulfill that goal. This implies that information types included in the MP for PA should support one of the following criteria: document the type of material used, document the amount of material available, document the quality of the material available, and document external factors which can influence the quality of the material. These purposes align with the inputs for the circularity indicators proposed by CB'23 (2022). Suppose an information type matches one of these criteria. In that case, it fulfills one or more of the following purposes: inform about the materials in the PA, allow for calculating circularity indicators as proposed by CB'23 (2022), and enable analysis of the effect of specific materials on the potential circularity of the PA. That last purpose is something not yet mentioned and requires some more explanation.

Analyzing the effect of specific materials on the potential circularity of PA entails research to identify which materials can be considered more circular than other materials. For instance, the PA MP should include data that can be used to identify the rate at which downcycling occurs for different materials. Based on that information, materials with a lower rate of downcycling can be chosen, increasing the potential circularity of PA.

6.2. Dynamic material passport for porous asphalt

Asphalt top layers such as PA are subject to traffic load and weather conditions, thereby degrading the PA. However, the degradation process is not identical in all parts of the PA. For instance, some areas are more subject to wear due to traffic than other parts. Throughout the life cycle of a PA layer, multiple events can change the composition, quality, amount, or type of material. This indicates that a MP should be considered a dynamic document, not only created after the construction of a road but maintained throughout the entire life cycle. This implies that updates on the PA MP do not occur at a fixed rate or predefined intervals, but updates should occur whenever a change occurs. However, this poses a challenge in terms of managing the information. For instance, bitumen degrades daily, admittedly an unmeasurable amount, but still degradation. This would mean that the PA MP requires updating every day. As degradation information is only valuable for analyzing the effects of materials on the potential circularity, the benefits are unlikely to outweigh the costs. Therefore, updating the PA MP when maintenance has been performed seems sufficient.

Part of a PA MP section can be subject to maintenance (replacement, rejuvenation, or any other type of action that would change something about the composition). This would result in two new PA MP sections, each with its own MP. If all changes occurring on a PA layer are updated in the MP, and repairs of cracks and potholes are accompanied by new MPs, keeping all MP up to date becomes undoable, and the number of MPs will grow beyond control.

The current problem with providing a guideline on managing the MPs is that little data is available on reusing PA materials for multiple cycles, and rules and regulations are not yet adapted to the implications of circularity. In other words, it is currently unknown what maximum percentage of impurity in RPA due to repair areas can be allowed without affecting the potential circularity. Additionally, the regulations on PA, such as the CROW 81.2 (2015), do not allow any impurities in new asphalt mixtures from lower-quality materials. Hence every impurity in the RPA must be known.

Considering the problems of providing a guideline for managing MPs, the following is proposed. Current regulation demands knowing each material used in a PA layer. Therefore, despite the size, each change in composition should be updated in the MPs, possibly resulting in thousands of MPs holding data on every repair or maintenance action. However, as soon as complete road maintenance is performed, the amount of MPs is reduced as a new homogeneous layer is applied over the entire stretch of road.

As the PA MP is a dynamic document, digitalization is required. Different actors such as clients and contractors use the data held in the PA MP, and these actors access and update the data in different stages of the PA life cycle. Additionally, as different contractors work on a single road, data provided by one contractor should be accessible by a different contractor. Such a data exchange can best be achieved by digitalizing the PA MP in which the different actors have different rights and responsibilities. The contractor is responsible for ensuring all necessary data is updated, whereas the client can manage this process by checking if contractors oblige to their responsibilities.

6.3. Material passport levels

A MP can have different levels of detail. The MP for PA includes four levels of detail relevant to this type of pavement (Figure 7). Accompanied by each level is a table listing all the information types per level. The broadest level is the element level (Table 5), indicating where the layer is located, including geometric details such as area and layer thickness. The PA MP section (homogeneous PA layer) only includes one more detailed level (asphalt mixture) because it has only the asphalt mixture as an ingredient (Table 6). Mixture-related details, such as mixture density, additives, and temperature ranges, are displayed at this level. The PA mixture consists of two types of ingredients: aggregate materials and binder materials. Therefore the PA mixture consists of two more detailed layers (material layer). The aggregate layer includes crushed stone, sand, and filling material (Table 7). The binder level only includes the bitumen, as this is the only binding material in PA (

Table 8). The crushed stone used in PA mixtures requires a more detailed MP level, as some of its raw-material characteristics are valuable, such as class and resistance to fracturing (Table 9). For the other items at the material level, it is not necessary to have more detailed data. For instance, the hardness and softening point are relevant for bitumen, which can be found on the material level. However, information on the raw material (oil) from which the bitumen was made does not add any value.

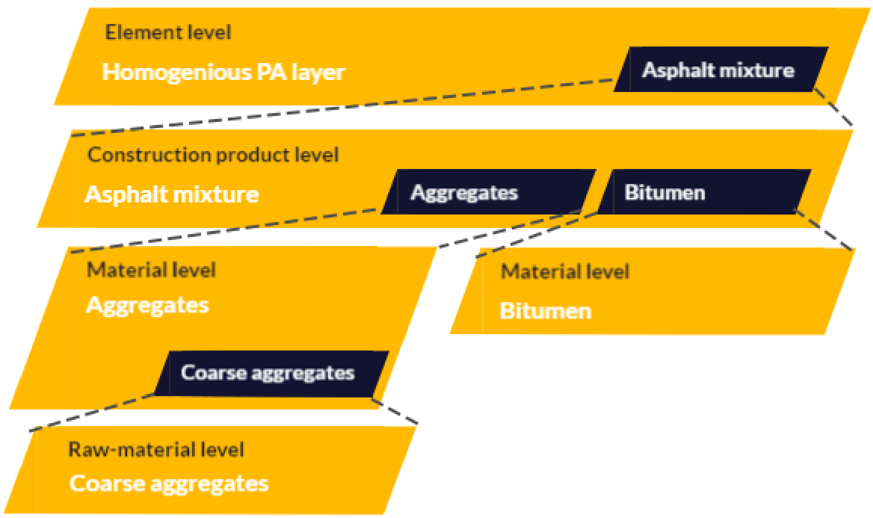

Figure 7: Porous asphalt material passport layers

6.4. Role of porous asphalt material passports in the end-of-life phase

One of the major problems in using MP over multiple cycles of PA is rooted in how recycling currently happens. Old PA layers are milled, resulting in RPA. Milling machines do not mill each section, corresponding to a single MP separately, so materials with different MPs get mixed. Additionally, in conventional PA production, where PA is produced at an asphalt plant, RPA is stored in large piles containing different types of PA with different MPs. Therefore, mixing of the material can again take place. Using a different type of PA production, such as in-place recycling, would solve this problem.

To illustrate the problem of mixing materials with different MPs, take the following example (Figure 8). Three batches of RPA, each with their own MP, are deposited on a single pile. A new mixture created from the material in this pile would result in a new mixture with its own MP. The result is a new PA mixture containing information from two recycling cycles: the current and previous cycles. The current cycle is a MP containing the current information of the PA layer, whereas the previous cycle is the collection of the three MP from the RPA used for the new mixture. The MP from previous cycles does not provide any information that cannot be found in the current MP regarding which materials are included and what the quality is. However, the data in the MP from previous cycles can provide insight into what happens with materials that are used for multiple cycles. For instance, if PA produced from RPA with modified bitumen degrades faster after a certain amount of cycles than PA produced with RPA without modified bitumen, insight is provided into the effect of using RPA with modified bitumen in multiple cycles.

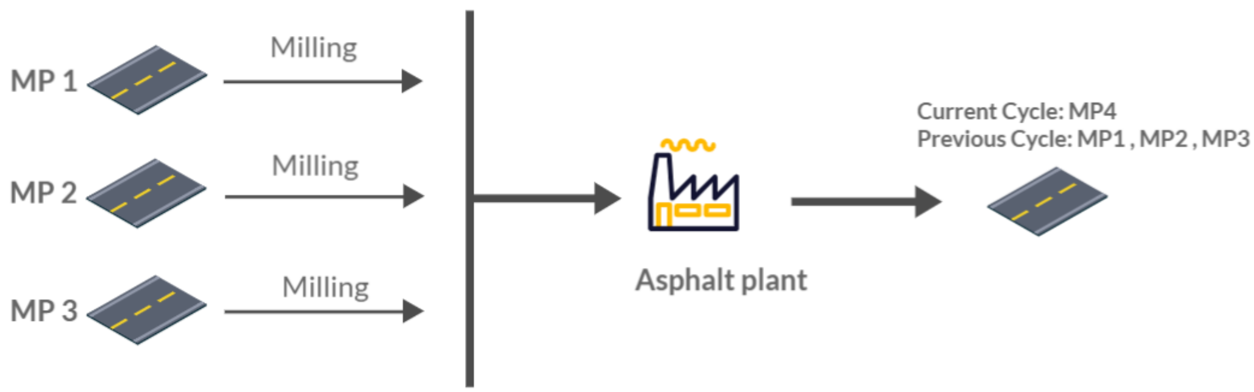

Figure 8: Illustration of mixtures including multiple material passports

Table 5: Homogeneous PA layer: Element level

Level: Element (Homogeneous PA layer of the same thickness)				
Information type	**Unit**	**Purpose**	**Timing of data collection**	**Comment**
Date of construction	Date	- To identify the age	After construction	
Location (edges)	Coordinates	- Indicate boundaries to which this passport is applicable	After construction	
Area	Area (m^2)	- Required for determining the volume	After construction	Based on the location (edges)
Thickness	mm	- Inform about milling depth	After construction	Actual thickness, not design thickness
Volume	Volume (m^3)	- Indicate the amount of material	After construction	Based on Area and Thickness
Asphalt Mixture	Mixture Id	- Provide information about 'design' characteristics of the mixture applied mixture	Before construction	MP (Asphalt mixture)

Table 6: MP asphalt mixture: level construction product

Level: Construction product (Asphalt mixture)				
Information type	**Unit**	**Purpose**	**Timing of data collection**	**Comment**
Aggregates	--	--	--	MP (Aggregates)
Bitumen	--	--	--	MP (Bitumen)
Density mixture	Kg/m^3	- The density of the mixture is necessary to determine the amount of product that gets available	After construction	
Binder content	Mg/m^3	- The binder content in the reclaimed asphalt is necessary to determine the amount of binder that should be added	After construction At a predefined time interval (e.g., yearly) Before milling	Binder content decreases over time
Additives	Type of additive	- To analyze the effect of specific additives on the potential circularity (e.g., do certain additives have adverse effects when reused in multiple cycles).		For each additive, a separate passport can be included
Fiber type	Type of fiber	- To analyze the effect of specific fibers on the potential circularity (e.g., do certain fibers have adverse effects when reused in multiple cycles).		For each fiber type, a separate passport can be included
Sealing type		- To analyze the effect of specific sealants on the potential circularity (e.g., do certain fibers have adverse effects when reused in multiple cycles).	After application	Sealing is often done to extend the lifetime of an asphalt top layer.
Temperature bandwidth during production/application	Degrees Celsius	- High temperatures during production can have a negative effect on the quality of the bitumen. - To analyze the effect of temperatures on the potential circularity (e.g., whether adverse effects occur on the quality of PA constructed with RPA that has had a too high or low temperature in production during previous cycles).	During construction	
Skid resistance	Skid resistance unit	- To analyze the effect of using RPA for multiple recycling cycles on the skid resistance (e.g., does RPA used for multiple cycles lose its resistance to skidding faster than RPA reused only ones)	After construction t a predefined time interval (e.g., yearly) Before milling	

Table 7: MP Aggregates: level material

Level: Material (Aggregates)				
Information type	**Unit**	**Purpose**	**Timing of data collection**	**Comment**
Coarse granulate	--	--	Before construction Before milling	MP (Course granulate)
Grain distribution	Percentage of stone per fraction	- PA mixtures have a predefined percentage of the aggregates with a specific size (e.g., 10 percent 11-16mm, 75% 2-8mm, and 15% < 2mm). Therefore, it is necessary when using RPA to know the grain distribution.	After construction	
Filling material	Type of filler material	- To analyze the effect of specific filling materials on the potential circularity (e.g., do certain fillers have adverse effects when reused in multiple cycles).	After construction	

Table 8:MP Bitumen: level material

Level: Material (Bitumen)				
Information type	**Unit**	**Purpose**	**Timing of data collection**	**Comment**
Bitumen type	Name	- The bitumen type indicates which bitumen is used - To analyze how well specific bitumen types can be reused for one or more reuse cycles.	Before construction	A material passport going one level down can be included, indicating the chemical decomposition of bitumen
Bitumen Brand	Brand name	- The bitumen brand can tell something about the quality - To analyze how well specific bitumen brands can be reused for one or more reuse cycles.	Before construction	
Modification type	PB or PMB SBS or EVA	- A maximum of 10% with PMB RA can be used in a new PMB mixture according to NEN 13180-7 - To analyze the effect of different bitumen modification types on reuse in multiple cycles	Before construction	
Hardness	Penetration value	Used for calculating the penetration of new mixture following NEN 13108-7	Before construction At set interval Before milling	
Softening point	Degrees Celsius	Used for calculating the softening point of new mixture following NEN 13108-7	Before construction At set interval Before milling	

Table 9: MP course stone: Level Raw-material

Level: Raw material (Course stone)				
Information type	**Unit**	**Purpose**	**Timing of data collection**	**Comment**
Origin	Quarry name Corridor name	- To analyze the effect of stones from different quarries in the long term. Corridor names can also be relevant as stone quality can differ per corridor within the same quarry	Before construction	
Crushed stone class	1,2 or 3	- The class of crushed stones determines if they can be used in PA or not. Only class 3 is allowed in the new PA.	Before construction	
Polished stone value	PSV	- The course granulate must have a specific PSV value to be suitable for reuse.	Before construction At set interval Before milling	
% broken surface	% of the surface, which is rounded	- The course granulate must have a specific % of broken surface to be suitable for reuse.	Before construction At set interval Before milling	
Stone shape	% of the surface which is not flat	- The course granulate must have a specific shape to be suitable for reuse.	Before construction At set interval Before milling	
Resistance to fracturing of the stone	Amount of force that can be applied without cracking the stone	- The course granulate must have a specific resistance to fracturing to be suitable for reuse.	Before construction	
Density stone	Kg/m^3	- The density of the stone is needed to calculate the mass of the new mixture	Before construction	

7. Case study

In this section, the results of a case study are presented. During this case study, the data available during the tender phase is analyzed to provide insights into the current data provisioning. The second part determines the extent to which the data requirements set in the PA MP design can be fulfilled.

7.1. Background case study

The case study is the widening of the A1 Apeldoorn Azelo, a two-phased project costing around 400 million euros (Figure 9). RWS is simultaneously the owner of this road and the commissioning party and thus has the client role. Heijmans has provided the best offer and represents the contractor in both phases of the project. Currently, they have completed the work of phase one and will be completing the work of phase two in around 2025. The project's location is between A1-A35 intersection Azelo and A1-A50 intersection Beekbergen.

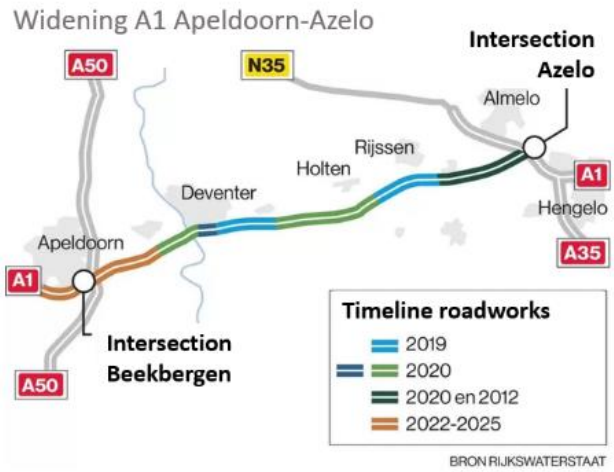

Figure 9: Widening of the A1 Apeldoorn Azelo (Rijkswaterstaat, n.d.) (translated)

7.1.1. Project description

On the A1 Apeldoorn Azelo (now referred to as A1 AA), the project included increasing the number of lanes and performing maintenance on the existing lanes. In terms of PA, new PA layers were added, and old PA layers were replaced by new PA. The reason for this project was the rising traffic demand on highway A1 between Apeldoorn Azelo and to enhance the quality of the construction.

The project description provided by the client (RWS) identified three primary goals based on which the proposed plan was weighted.

1. Minimizing traffic hindrance on the A1 connecting roads and surroundings during the construction.
2. Maximizing sustainability, being 1) climate and energy, 2) circular economy, and 3) vital natural resources
3. Maximizing spatial inclusion in the environment.

7.2. Data provided by the client in the tender phase

7.2.1. Information types provided in the tender phase

In the tender phase, RWS has supplied the contractors with data on the state of the existing pavement. However, only one type of research conducted provided relevant information for PA, which is the drill core research. The drilling cores that have been provided to identify:

1. The composition of the road construction in terms of layers
2. Identify the presence of tar

Specific information types presented in the reports are: location of the drilling sample (coordinates), image of the drilling sample, type of pavement (e.g., PA, DAC), layer thickness (mm), flourishing area indicating the presence of tar (range in mm).

7.2.2. Data intensity provided in the tender phase

The number of drilling cores provided fluctuates highly throughout the project (Figure 9, Figure 10). Orange dots represent construction drillings, blue dots asphalt drillings, and green dots drillings on infrastructural objects such as bridges. However, all dots consist of the same type of drilling core, whose purpose only reflects why a particular drilling core has been provided at a specific location. Some areas have been drilled extensively at a fixed interval of 250m (Figure 10). Other areas have been drilled at very low intensities leaving stretches of multiple kilometers untouched (Figure 11). In most cases, the right driving lane has been drilled more extensively than the left driving lane.

Figure 10: Drilling cores 100-meter marker 188.3 – 188.9 (Google earth, imaging 2017)

Figure 11: Drilling cores A1 100-meter marker 110.1 - 110.8 (Google earth, imaging 2017)

As indicated in the MP design section, a MP represents a section of homogeneous PA. Differences in, for instance, material qualities or layer thickness would indicate separate PA sections and would require individual MPs. Visual inspection is one of the primary methods to identify sections of different homogeneity as differences in color show differences in asphalt mixture. The drilling cores provided in the tender phase did not consider the different sections of homogeneity and were drilled at fixed intervals. This results in sections of PA on which no data is available (Figure 12).

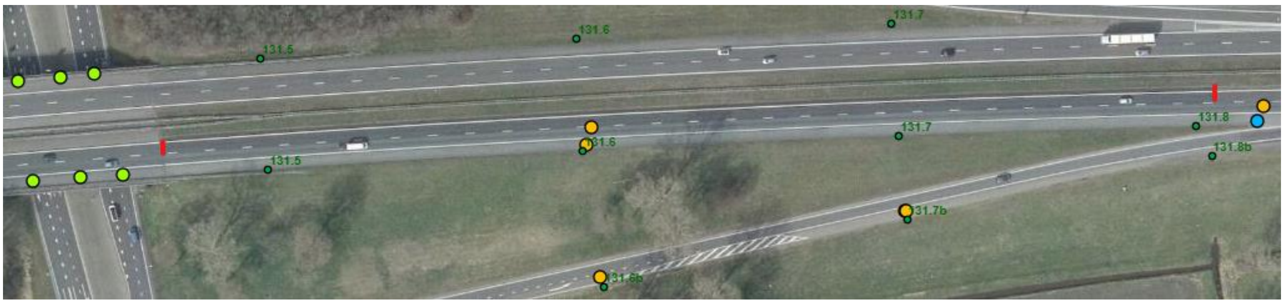

Figure 12: Drilling cores on a visually different top layer section. A1 100-meter marker 131.4 – 131.8 (Section of different color in between the red lines)

Analyzing the data provided in the tender phase indicates two main problems. The first problem is the incompleteness in terms of information types. Just a limited amount of the necessary PA MP information types are provided. The second problem is the lack of data on individual PA sections. Currently, data is collected based on a fixed interval rate of 250m or more, resulting in PA sections of which no data is available.

7.3. Material passport Information types obtainable for existing porous asphalt.

For new road pavement construction, information can be gathered as required for the designed PA MP. However, data on existing PA pavement is, in most cases, not available (as in this case study) and can only be gathered by performing research (e.g., drilling cores, inspecting visually, searching archives) on the existing pavement. This section indicates whether the data for each PA MP information type can still be obtained. Additionally, some research options are provided which enable obtaining such data.

7.3.1. Data obtainable through documentation

Contractors are legally obliged to deliver certain controlling documents when construction works on road pavement are finished. These documents are known as "as-built information." Included are legal documents stating asphalt mixture characteristics. However, these documents are based on batches and do not reflect the mixture as a whole. Additionally, the possible inaccuracy, the as-built information also includes the state of the material at the construction date. The penetration value of the bitumen will, for instance, differ as it degrades over time. As a result, data obtained through documentation can provide easy access to some data for the PA MP. However, the validity of the documents used should always be guaranteed, for instance, by performing field tests such as drilling cores.

7.3.2. Data obtainable through visual inspection

Visual inspection can be a valuable source of obtaining data and can be performed in two ways. A person can go to the project location and visually inspects aspects of the road pavement in situ, such as pavement color, cracks, and damages. The second option is a visual inspection based on images (e.g., street view and satellite imaging). The advantage of visual inspection in situ is the level of detail, whereas image-based visual inspection provides the advantage of comparing images throughout time. With a visual inspection, the physical boundaries of different PA sections can be found, for instance, by color differences in the asphalt or asphalt seams/joints at locations where two sections meet.

Visually inspecting the drilling cores allows researchers to identify the thickness of each asphalt layer. Therefore, a suitable method to provide data for the MP on layer thickness. However, drilling cores represent only the section that has been drilled, whereas the thickness of layers can vary in both directions. An alternative is using radar technology to create a complete image of the road's width and length, indicating the thickness of the asphalt layers. However, this technique is still under development, and its accuracy is still being investigated.

7.3.3. Data obtainable through laboratory testing

In the laboratory, many of the data requirements of the PA MP can be fulfilled. The drilling cores taken from the existing road pavement can be used to perform tests to identify the mixture density, binder content, bitumen hardness, softening point, skid resistance, and aggregate fractions (grading). In the laboratory, tests can be performed to identify the qualities of the coarse aggregates, such as polished stone value, percentage of broken surface, shape, density, and resistance to fracturing. These tests are the same as performed for identifying characteristics of virgin coarse aggregates. When all characteristics of the coarse aggregates are found, the crushed stone class can be derived with certainty. Petrographic research can be executed to identify the type of stone (e.g., Dutch sandstone or Bestone). The name of the stone can provide certainty to a certain extent about what the origin is. However, this is never conclusive.

Identifying the different types of substances such as additives, sealants, fibers, fillers, or bitumen modifications used in the pavement can only be found through laboratory testing (assuming that it has not been documented which substances were used). The most commonly used test for determining a substance is gas chromatography-mass spectrometry (GCMS). This technique can be used to identify the type of additive, sealant, fiber, filler, and bitumen modification.

7.3.4. Data not obtainable

Most of the data can be obtained from the existing PA layers. However, some data cannot be achieved with retroactivity. The actual temperature bandwidth of the mixture during production and construction cannot be retrieved if not logged during production and construction. Since the PA of existing roads has already been produced and constructed, this data is considered lost. For bitumen, a comparable conclusion can be drawn. Bitumen is an oil-based substance, and oil is a natural product whose exact chemical composition changes slightly over the batches/years. Therefore, the exact type of bitumen is challenging to identify. Determining the brand is even considered impossible.

The consequences of unobtainable information are data gaps in the PA MP. Fortunately, the purpose of the unobtainable data in the MP is, in most cases, to analyze the effects of using such materials in multiple reuse cycles. However, missing out on essential data can reduce the potential circularity of PA as materials that are unsuitable for reuse in multiple cycles keep being used. Therefore, it is evident that future data gaps are prevented and that the proposed PA MP is used for new PA starting today.

7.4. Summary of obtainability of information types for existing porous asphalt

Almost all data requirements determined in the design of the PA MP can be met for existing PA layers. In Table 10, the information types are listed, indicating if the data can be obtained. Additionally, if possible and kown an option for determining how the data can be obtained provided.

Table 10: Summary of porous information types for asphalt material passport obtainable for existing porous asphalt layers

Information Type	**Possible**	**Data gathering option**
Date of construction	Yes	Documentation
Location (corners)	Yes	Visual inspection
Area	Yes	Based on location
Thickness	Yes	Drilling cores, Radar
Volume	Yes	Based on thickness and Area
Asphalt mixture	No	--
Density	Yes	Measuring the weight of a sample of known dimensions
Binder content	Yes	As described in NEN EN-12697-1
Additives	Yes	gas chromatography-mass spectrometry
Fiber type	Yes	gas chromatography-mass spectrometry
Sealing type	Yes	gas chromatography-mass spectrometry
Filling material	Yes	gas chromatography-mass spectrometry
Temperature bandwidth during production	No	--
Temperature bandwidth during application	No	--
Skid resistance	Yes	Friction after polishing test
Aggregate grading	Yes	Sieving aggregates into fractions
Origin	Yes	Petrographic research
Crushed stone class	Yes	Based on the stone qualities such as PSV and % broken surface
Polished stone value	Yes	Same as for new aggregates
% broken surface	Yes	Same as for new aggregates
Stone shape	Yes	Same as for new aggregates
Resistance to fracturing	Yes	Same as for new aggregates
Density stone	Yes	
Bitumen type	No	--
Bitumen Brand	No	--
Modification type	Yes	gas chromatography-mass spectrometry
Hardness	Yes	Penetration test
Softening point	Yes	Ring-ball test

8. Discussion

The MP defined in this research is a result of interviews with experts, literature study, and insights gathered during the execution of this thesis assignment. As there is still an ongoing debate about circularity, the data requirements for the PA MP can most likely change over time. Additionally, as more knowledge is gathered about the effects of materials on circularity, the need for data may shift. Therefore the PA MP designed in this research should be taken as a starting point and requires adaptation as knowledge increases.

Overall, the semi-structured interview approach seemed adequate for this research. The exploratory nature of this research required flexibility in the interviews. The semi-structured interviews allowed for deepening questions that explain the underlying mechanisms. This allowed the researcher to create a MP based on explicit interview data (actual data mentioned). However, the novelty of the topics discussed during the interviews posed a challenge. Themes such as circularity and high-value reuse are not uniformly interpreted as found during the interviews. Therefore, the understanding of underlying themes may have limited the answers provided by interviewees.

Time is one of the critical limitations of this study. Both interviews and the feedback round had to be planned on short notice, limiting the number of interviews taken. For this research, the decision was made to have a large set of interviews (14), considering the time available. Therefore, the thematic analysis of the interviews was done based on recordings instead of transcriptions. Analyses based on the records provided sufficient data to support the conclusion. However, analyses based on transcription would have allowed for a deeper understanding and may have revealed additional themes.

Unfortunately, no other work exists specifying the data requirements of a material passport for PA. Therefore, comparing the results for validation was not possible.

The proposed PA MP's success is bound by many factors which can significantly decrease the effect on increasing the potential circularity. The MP outlined in this research provides a framework that organizes all different data types necessary to close circularity loops for PA. However, using this framework requires different actors to take responsibility and actively work with the MP.

The first aspect impacting the effectiveness of the PA MP is data management. A MP is a dynamic document that includes data bound by events that occur in the lifespan of a PA section. A PA MP should not remain static after the construction of the pavement. Instead, it should be kept up to date. This requires effort from both contractor and client. Contractors should ensure that all actions affecting any PA MP data are logged and updated. On the other hand, clients should ensure that data is supplied correctly by the contractors and ensure the MP is complete at all times, as they are legally in the position to demand data as part of contractual agreements.

As PA degrades over time due to external factors which have nothing to do with contractor actions, data should be gathered at specific intervals to monitor the accuracy of the data in the PA MP compared to the actual situation. The client is, in most cases, the owner of a road and is the only party able to allow such testing on their property. Therefore, it is evident that clients should ensure tests are executed to monitor the data in the PA MP over time. However, clients will only perform such actions if a clear incentive is presented. This research has therefore provided that maintaining a PA MP is necessary to reuse materials and calculate circularity indicators. Clients who aim to become completely circular can therefore use that goal as an incentive for maintaining MPs.

The validity of MP data is a second impact that concerns both clients and contractors. In an ideal situation, the data supplied for inclusion in the PA MP is valid and represents the actual situation. However, contractors or clients should be responsible for the PA MP data in real life. Indicating who is responsible when data in the MP is incorrect. It should be made clear if, for instance, a contractor who supplied incorrect data is also responsible for any damage caused, whereas other contractors may base their work on the assumption that data in the MP is correct.

Decisions should be made with regards to digitalization, making the MP both manageable and usable in real projects. A MP on paper can include the same information as a digital MP. However, as indicated by RWS during the interviews, data on paper is challenging to manage and to make it accessible for multiple actors. The effectiveness of the MP is affected by how well the data is accessible and with which ease data can be interchanged between contractors and clients. Pavement information modeling systems such as PIM are a step in the right direction for a PA MP and can provide the digital basis for the data requirements of the PA MP.

9. Conclusion

This research presents a conceptual MP for PA, and has attempted to outline the data requirements that can enable the full circularity potential of PA. The different sub-questions posed in this research have been answered to provide the conceptual PA MP.

The MP is a novel theme, of which the effect is seen in the development of specific data requirements for MP in the road construction industry. The state-of-the-art of MPs in the road construction industry is an attempt to organize already known information into a single interchangeable format. However, it does not provide a covering framework that provides enough valuable data for contractors to unleash the full circularity potential of PA. Additionally, elements that are the foundation of pavement MPs, such as normalized road decompositions, are just starting to be formulated. Therefore, it can be concluded that MPs in the road construction industry are still in an early stage of development and are not ready to be applied yet.

Current data provided in tender phases of projects where PA is reused does not match the data requirements for increasing the potential circularity of this type of pavement. Not all the information types suggested in the PA MP design are provided, leaving gaps between the data supplied and the data required. Additionally, the data provided does not cover the different PA sections a road consists of, making many PA sections a black box regarding material composition and quality.

The PA MP designed in this research closes the gap between the current data supplied and data demand in tender phases. It provides a framework that can be used to identify the complete material composition of exiting PA layers when fully supplied with data. Moreover, it provides the input data for circularity indicators necessary to make supported decisions to improve the circularity of PA.

Finally, from the analysis of current knowledge (interviews and literature), the conclusion can be drawn that the different actors in PA construction do not agree yet on what circularity is. Knowledge of circularity, both on the side of the client and contractor, has to be further developed to ensure that both actors speak the same language. Only when clients and contractors agree upon a uniform definition can the development of a PA MP to increase the potential circularity of PA be completed.

9.1. Theoretical implications

This research has set out to provide a definition (as to the author's knowledge, for the first time) in terms of data requirements for a PA MP. Additionally, the provided definition can set a basis for further debate among scholars about what data requirements MPs should have to increase the potential circularity of road pavements, as the concepts described in this research are tangible. Furthermore, the PA MP designed in this research can be further explored.

9.2. Practical implications

A MP is often specified as a digital location storing information required by contract or as an automated tool to calculate the ECI (MKI). However, the MP, as developed in this research, can significantly increase the potential circularity of PA by providing detailed data on which materials are present in existing PA pavements, including the quantity and quality. Additionally, the MP enables clients and contractors to identify the effect of PA materials over multiple cycles, hence identifying the potential circularity of certain materials and providing the ability to optimize circularity based on MP data. The MP, as provided in this research, can be seen as a guidance document for clients and contractors when it comes to defining which data is relevant and, more importantly, which data should be gathered in retroactivity for the existing PA pavements.

10. Recommendations for further research

Based on the results gathered and the discussion of this report, the following research items are worth exploring in the future.

Identify what circularity implies for porous asphalt

Defining a PA MP that increases the circularity potential requires a uniform definition among clients and contractors for what circularity means in terms of PA, indicating what can be considered circular PA. Additionally, obstacles that prevent PA from becoming circular should be discussed. For example, currently, bitumen is not circular as downcycling always occurs. However, the implications on end goals, such as 100% circularity, are yet unknown. Making the concept of circularity more tangible in the road construction sector, and providing a feasible end goal, can help the development of the PA MP.

Applying the PA MP to different types of asphalt

Different types of asphalt are primarily produced with the same type of materials. Therefore, future research should identify how the PA MP should be adapted to be applied to different types of asphalt, possibly indicating information types that must be added or removed.

Validating the PA MP

This research aimed to validate the proposed PA MP. However, more extensive validation is advised. Using case studies to quantify the effect of PA MPs on the potential circularity. Additionally, the MP PA information types should be tested to verify if sufficient data is kept to provide the necessary inputs for the CB'23 (2022) circularity indicators.

PA MP sections

As designed in this research, PA MPs represent a homogeneous PA section. However, a clear definition of what homogeneous is in road construction is currently lacking. This may result in the segmentation based on homogeneity being unsuitable for MPs. Different ways of segmenting roads, such as by a grid system, should be investigated. Different ways of segmenting are already in use in existing pavement information modeling (PIM) systems. The way these systems decompose roads is similar to the method used for the proposed PA MP and supports coordinate-based sections to which data can be added. Therefore a logical step would be to investigate if the data requirements for the PA MP can be included in the existing PIM systems.

Guideline on managing PA MPs

As indicated in the PA MP conceptualization, each different PA section with a different composition should have its own MP considering existing rules and regulations. However, this would imply that every repair requires a new MP, regardless of size. Additionally, as PA materials degrade gradually over time, the PA MP should be updated daily to hold the actual data on material qualities. Future research should establish explicit guidelines on when PA sections are significant enough to have their own MP. Additionally, the proposed yearly interval for updating data for degraded materials should be validated.

Retaining PA MP data from multiple cycles

Reusing PA in new PA layers is relatively new, where only a handful is produced with RPA. However, in the future, as more RPA is applied and PA layers produced with RPA are reused again, MPs from different cycles of the material become available. As this has not yet occurred, no knowledge is available on managing such a process. Therefore, different scenarios such as mixing material and in-situ recycling should be investigated, indicating how the MP from different cycles can be retained and still be related to the material it belongs to.

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Appendix

Appendix A: Circularity indicators

Table A1: Parameters for calculating circularity adapted from Platform CB'23 (2022)

Parameter	**Unit**	**Relevant to indicators (indicator number)**
Mass of object	kg	1
Mass percentage of primary materials in a single object	Percentage	1
Mass percentage of non-renewable primary materials in a single object	Percentage	1
Mass percentage of renewable materials in a single object	Percentage	1
Mass percentage of primary sustainably produced materials in a single object	Percentage	1
Mass percentage of secondary material in a single object	Percentage	1
Mass percentage of reused input materials in a single object	Percentage	1
Mass percentage of recycled input materials in a single object	Percentage	1
Mass percentage of socio-economic scares materials	Percentage	1
Mass percentage of socio-economic non scares materials	Percentage	1
Mass percentage for which reuse is most realistic	Percentage	2
Mass percentage for which recycling is most realistic	Percentage	2
Mass percentage for which energy production is the most realistic end-of-life	Percentage	3
Mass percentage for which landfill is the most realistic end-of-life	Percentage	4
Product functional technical value	-	5
Product functional quality	-	5
Product technical quality	-	5
Product degradation	-	5
Product ability to adapt	-	5
Product economic value	Euro	6
Product remaining value	Euro	6
Value of materials in product	Euro	6
Product disassembly cost	Euro	6
Product transport cost	Euro	6
Product waste disposal cost	Euro	6
Product transformation cost	Euro	6

Appendix B: Supporting documents literature review

Table B1: Keywords employed for identifying publications

(exemplary) keywords, keyword combinations
“product passport”
“material passport”
“material passport” AND asphalt

Appendix C: Additional insights from the interviews

Table C1: How would you define circularity in the road construction sector

No primary materials should be used. The materials that miss should be provided in a bio-based way.
Make the production of asphalt circular by using energy from alternative sources. In addition, the temperature during production should be lowered.
Process the asphalt using electric machines.
Provide asphalt with longer lifespans. Hence, fewer replacements have to be performed.
Design asphalt that increases the fuel efficiency for traffic.
Remove asphalt from existing pavements, do something with it, and put it back. Asfalt uit de weg halen, er iets mee doen, en dan weer terug brengen.
The circular economy is a means to become more sustainable. Some key elements can be named, such as: 1) Availability of materials, 2) Environment, 3) Biodiversity.
You want to keep as much material in the "loop."
Trying to keep all materials in the loop as much as possible. Where circularity is the means to become sustainable.
It depends on how to define circularity. Some define circularity only in terms of material streams, whereas others also consider the energy transition.
Create asphalt mixtures with as much reuse as possible, replace bitumen as a binder and extend the lifespan.
Electrify all the machines.
Asphalt is already a product that is recycled on a large scale. Recycling is, however, not the same as circularity. Recycling is when existing asphalt is reused for new asphalt. Circularity is broader as, in circularity, materials with functions outside of asphalt can be used in new asphalt.
There are a few critical elements to circularity. Most importantly, all materials coming free during milling should have a useful application. Every material coming free must have a proper destination, so no material must be thrown away (zero waste). So also, materials with a lower quality than required will find a way to a useful application. This means that for all the products created, someone must have thought about aspects that could obstruct reuse, and such obstruction may not occur. Lastly, circularity implies reducing primary construction materials and using as much material from secondary sources as possible.

Table C2: What are difficulties or circularity in the road construction industry

Most developments concerning circularity are done in the Netherlands. Therefore, everything is new.
More asphalt is produced than is milled. Therefore, new material is still required.
Asphalt is a great product. It is very cheap and lasts a long time. However, if something needs to change, it is always more expensive as prices are always compared to the low prices of current asphalt.
Currently, many extensions of the road network take place; hence more material is required than is available for reuse.
The end goal of circularity is still unclear, and no techniques have been identified that can close the loop.
If it is unknown what materials have been used on road sections, it is unclear which sections can be reused and which not.
There are boundaries to the reuse of asphalt materials. Bitumen can only be reused for some cycles.
The problem is that if 80% RPA is used in PA, using a conventional method, 100% control over the new product cannot be achieved. This leads to a lower quality PA which has to be replaced earlier. Therefore this is less sustainable.
Asphalt plans have a problem concerning emissions due to the reuse of asphalt. During heating of the RA, toxic substances are released into the air, restricting the maximum amount of reuse. 100% of the application of RA is therefore not possible.