CIR of surface courses
A Gap analysis of RAP gradation characteristics

BSc Civil Engineering
Bachelor Thesis

University of Twente supervisors: Dr. Ir. Seirgei Miller & Dr. Ir. João Santos
NTP supervisors: Pim Mulder & Jeroen Buijs

Author: Milan Arling

Department of Civil Engineering and Management
Faculty of Engineering Technology
Civil Engineering
University of Twente

February 13, 2025

Preface

This research was executed on behalf of NTP, a Dutch construction company active in the GWW-sector (Grond-, Weg- en Waterbouw). It serves as a Bachelor thesis graduation assignment for the program of Civil Engineering & Management. The thesis entails a gap analysis of RAP gradation characteristics and aims to provide insight into problems for applying CIR to surface layers alongside providing solutions for these problems.

During the execution of the assignment I have learned a thing or two about the asphalt industry, especially with respect to recycling. I want to thank NTP for the opportunity to visit multiple project sites and the asphalt plant A.C.B.

Apart from that, I would like to thank Henk Snoeijink from Freesmij for his knowledge and cooperation during the expert interview. Above all, I would like to thank my supervisors at both NTP and the University of Twente. Pim Mulder, Jeroen Buijs, Dr. Ir. Seirgei Miller and Dr. Ir. João Santos.

Enschede, February 2025

Milan Arling

Summary

Globally, the recycling of construction and demolition waste (CDW) has become an important element in the construction industry. The road industry, in particular, has adopted this element very well. In the Netherlands, recycling rates of up to 100% are reached regarding Reclaimed Asphalt Pavement (RAP). However, in the case of surface courses, this RAP material is mostly recycled in the form of Hot Mix Asphalt (HMA). This requires a considerable amount of energy compared to Cold Mix Asphalt (CMA), which is undesirable. However, partly due to the material properties of RAP, CMA's with 100% RAP are unsuitable for surface courses. NTP, a Dutch innovative and sustainable operating company in the Grond-, Weg- en Waterbouw (GWW) sector wants to find a way to ensure that cold in-situ recycling (CIR) can be applied to surface courses and potentially be able to define what asphalt pavement surfaces are eligible for this rehabilitation treatment.

This study focuses on improving the gradation characteristics of RAP material by performing a gap analysis. In this gap analysis, the state-of-practice regarding cold milling equipment and processes and their impact on RAP gradation is identified. This is done through a systematic literature review and a sieve analysis performed in accordance with NEN-EN 12697-2. This RAP gradation is then compared to the regulations defined in the NEN-Norms and the CROW Standaard RAW bepalingen 2020, to define the quality gap. Based on this quality gap, solutions for improving the RAP gradation and ultimately bridge the quality gap are identified. These solutions are then evaluated based on their potential effectiveness to bridge the quality gap. For the most suitable solution, an impact analysis was performed.

In this study, it was found that the current cold milling equipment and process caused high RAP clustering, leading to the material being too coarse graded compared to the regulations. CIR can either be applied with a single-unit train or a multi-unit train, with solutions including optimizing travel speed and drum configuration (pick spacing and cutting direction) for the single-unit train, and adding a mobile crushing and screening unit for the multi-unit train. Additionally, two other hypothetical solutions were identified: Ultrasonic vibrations and steam induced asphalt-aggregate segregations. However, these solutions were not tested and developed sufficiently to be applied in the field. Of the other two options, optimizing the operating parameters and the drum configuration appeared to be the best option based on expert opinion and equipment availability. Reducing the travel speed and the pick spacing while ensuring a down-cutting motion of the milling drum, can result in a finer graded RAP material. In the impact analysis, it was concluded that if the assumptions for the effect of the travel speed and the pick spacing are accurate, the gradation of RAP material will be in accordance with the regulations in most scenarios. This suggests that this solution can potentially effectively reduce the effect of clustering and thereby improve the RAP gradation.

To improve the accuracy of the results, the effect of the operating parameters and drum configuration has to be further researched. Additionally, it has to be determined if the resulting RAP gradations are of sufficient quality to create a CMA, which is in accordance with the required performance properties defined in the Standaard RAW bepalingen 2020.

Samenvatting

Wereldwijd is het recyclen van bouw- en sloopafval (CDW) een belangrijk element geworden in de bouwsector. Met name de wegenbouw sector heeft dit element goed omarmd. In Nederland worden recyclingpercentages van 100% bereikt voor freesmateriaal. Echter, in het geval van deklagen wordt dit freesmateriaal meestal gerecycled in de vorm van warme asfaltmengsels (HMA). Dit vereist een aanzienlijk hogere hoeveelheid energie in vergelijking met koude asfaltmengsels (CMA), wat ongewenst is. Echter is het 100% recyclen van freesmateriaal in CMA's voor deklagen, deels door de materiaal eigenschappen van het freesmateriaal, niet mogelijk.

NTP, een innovatieve en duurzame onderneming in de GWW-sector (Grond-, Weg- en Waterbouw), wil een manier vinden om ervoor te zorgen dat koud in-situ recycling (CIR) toegepast kan worden op deklagen en mogelijk bepalen welke asfaltverhardingen in aanmerking komen voor deze onderhoudstechniek.

Deze scriptie richt zich op het verbeteren van de gradatie-eigenschappen van freesmateriaal door het uitvoeren van een gap-analyse. In deze gap-analyse wordt de stand van zaken met betrekking tot koudfrezenapparatuur en processen en hun invloed op de RAP-gradatie geïdentificeerd. Dit wordt gedaan door middel van een systematische literatuurstudie en een zeefanalyse uitgevoerd volgens NEN-EN 12697-2. Deze RAP-gradatie wordt vervolgens vergeleken met de voorschriften gedefinieerd in de NEN-Normen en de CROW Standaard RAW bepalingen 2020, om de "quality gap" te definiëren. Op basis van deze quality gap worden oplossingen geïdentificeerd om de RAP-gradatie te verbeteren en uiteindelijk de quality gap te overbruggen. Deze oplossingen worden vervolgens geëvalueerd op hun potentiële effectiviteit om de quality gap te overbruggen. Voor de meest geschikte oplossing werd een impactanalyse uitgevoerd.

In deze scriptie werd vastgesteld dat de huidige koudfrezenapparatuur en het proces leidde tot hoge RAP-agglomeratie, waardoor het materiaal een te grove gradatie had in vergelijking met de voorschriften. CIR kan zowel met een single-unit train als een multi-unit train worden toegepast, met oplossingen zoals het optimaliseren van de rijsnelheid en de freeskop configuratie (lijnafstand en snijrichting) voor de single-unit train, en het toevoegen van een mobiele breek- en zeef unit voor de multi-unit train. Daarnaast werden twee andere hypothetische oplossingen geïdentificeerd: Ultrasone trillingen en stoom-geïnduceerde asfalt-steenslag segregatie. Deze oplossingen waren echter niet voldoende getest en ontwikkeld om in het veld toe te passen. Van de andere twee opties bleek het optimaliseren van de freesparameters en de freeskopconfiguratie de beste optie te zijn op basis van de mening van experts en de beschikbaarheid van apparatuur. Het verlagen van de rijsnelheid en de lijnafstand kan leiden tot een fijnere gradatie. In de impactanalyse werd geconcludeerd dat, als de aannames voor het effect van de rijsnelheid en de lijnafstand accuraat zijn, de gradatie van het RAP-materiaal in de meeste gevallen in overeenstemming zal zijn met de voorschriften. Dit suggereert dat deze oplossing mogelijk effectief de effecten van agglomeratie kan verminderen en daarmee de RAP-gradatie kan verbeteren.

Om de nauwkeurigheid van de resultaten te verbeteren, moet het effect van de freesparameters

en freeskopconfiguratie verder worden onderzocht. Daarnaast moet worden bepaald of de resulterende RAP-gradaties van voldoende kwaliteit zijn om een CMA te maken, die voldoet aan de vereiste prestatie-eigenschappen zoals gedefinieerd in de Standaard RAW bepalingen 2020.

Contents

List of Figures

List of Tables

Abbreviations and Terminology

AC Asphalt Concrete

ART Asphalt Recycling Train

BRL Beoordelingsrichtlijn

CART Cold Asphalt Recycling Train

CCPR Cold Central Plant Recycling

CDW Construction and Demolition Waste

CIR Cold In-situ Recycling

CMA Cold Mix Asphalt

CR Cold Recycling

FDR Full-depth Reclamation

GWW Grond-, Weg- en Waterbouw

HMA Hot Mix Asphalt

HR Hot Recycling

ITS Indirect Tensile Strength

OGFC Open-Graded Friction Course

PL Percentage-Loss

RAP Recycled Asphalt Pavement

SMA Stone Mastic Asphalt

SRQ Sub Research Question

WMA Warm Mix Asphalt

1 Introduction

Globally, the rate of urbanization has been increasing rapidly (Ritchie et al., 2018). This urbanization is fueled by the construction of all sorts of structures, including housing, infrastructure and facilities. In turn, this requires more and more building materials, which can result in scarcity of materials. Furthermore, the use of these materials has a negative impact on the environment. Consequently, CDW has become an important element in the construction industry.

In particular, the road industry has adopted this element very well. In the Netherlands, a leading country in this aspect, recycling rates of up to 100% percent are seen in different categories of materials. RAP, the material that is obtained after the removal of asphalt pavement, falls in this 100% recycling category (Holtz & Eighmy, 2000). RAP can be recycled in multiple pavement layers or courses, including base, binder and surface. This is done with either a CMA or a HMA. Surface courses are almost always paved in the form of a HMA. Otherwise, multiple problems arise such as low riding quality, performance and durability (Modarres et al., 2014). However, HMA is produced at a higher temperature, resulting in a higher energy consumption during production compared to CMA (Milad et al., 2022). It is therefore favorable to use CMA as frequent as possible for pavement construction.

1.1 Problem statement

NTP, a Dutch innovative and sustainable operating company in the GWW sector strives to handle raw materials carefully and responsibly and focus on the re-use of materials, which is embedded in their broader set of sustainability goals. One of their goals regarding this is to increase on-site recycling. As a part of this, NTP wants to find a way to ensure that CIR can be applied to surface courses and potentially be able to define what asphalt pavement surfaces are eligible for this rehabilitation treatment.

CIR of asphalt pavement is a widely recognized eco-friendly pavement rehabilitation practice (Jin et al., 2021). The main advantages of the practice are the re-use of materials and the elimination of hauling materials (the in-situ element), making it a timesaving and environmentally friendly technique. However, in most cases, this practice is used for binder- and base courses and not for surface courses. A difference between these courses lies in the gradation of the aggregates. The required aggregates in surface courses are often finer than in binder- and base courses. Furthermore, a higher degree of uniformity is required in surface course to ensure a smooth pavement surface. According to Yao et al., 2024, the main problems regarding RAP quality after cold milling are clustering and crushed aggregates. Many studies focus on elements of the CIR procedure related to binders, additives and compaction techniques. However, few studies focus on the quality of the RAP because it is seen as an uncontrollable factor. Modarres et al., 2014, listed several reasons on why CIR should not be performed for surface courses, including: low abrasion resistance against heavy vehicles, relatively high air void content, high permeability (will affect durability) and relative lack of smoothness. Currently, pavement layers produced with CIR practices almost always require a HMA course to be laid on top to solve the mentioned problems. These problems are mostly caused by the lack of quality of RAP. Ultimately, the problem is that the currently used cold milling techniques are not able to provide the required quality RAP material to be cold in-situ recycled as surface courses.

1.2 Research motivation

Globally, aspects such as sustainability and circularity are becoming increasingly important due to the resulting effects when these aspects are disregarded. As discussed in the introduction, incorporating CDW as materials in new structures and products can enhance the circularity of the industry. This would reduce the negative effects, such as climate change and material scarcity. As of now, the incorporation of 100% RAP in surface courses through CIR is not possible due to several challenges, resulting in the consumption of virgin materials. Furthermore, the need for HMA or warm mix asphalt (WMA) demands more energy consumption. It is therefore important to eliminate this need for virgin materials by investigating ways to overcome the challenges of CIR for surface courses.

1.3 Reading guide

In this reading guide, the structure of this study and the content of each section will be outlined. In the previous part of this section, the problem that this study aims to solve has been stated. In the next section, section 2, the theoretical framework will be discussed. This section will provide the necessary information to understand the concept of CIR, as well as the status of implementation in the Netherlands and the implications for surface courses. In section 3 the framework along which the study will be executed is discussed. This includes the research objective, the research questions that will be answered to achieve the research objective and the research scope. In section 4, the methods that will be used to answer each research question are discussed.

In section 5, the results of the research questions are discussed in five different subsections. In subsection 5.1, the first sub-research question will be answered by discussing the state-of-practice of cold milling equipment and process and their impact on RAP gradation. This will be followed by a regulation review in subsection 5.2. In subsection 5.3, the RAP gradations obtained in subsection 5.1 are compared to the regulations defined in subsection 5.2. Based on this comparison, potential solutions to solve the identified problem are discussed in subsection 5.4. This includes an assessment of the most suitable option and an impact analysis. In the last subsection, subsection 5.5, requirements for an asphalt surface course to be eligible for CIR rehabilitation treatment are identified.

In section 6, limitations in the execution of the methodology as well as the limitations of the results are discussed. In the conclusion (section 7), a final answer is given to each of the sub-research questions as well as the main research question. The study is concluded by giving recommendations to NTP, asphalt milling and paving companies and machine manufactures, as well as suggesting topics for further research (section 8).

2 Theoretical framework

This chapter provides a review of literature on relevant topics to give an overview of the elements involved in the problem and type of research already performed. This entails an explanation of the state of practice of CIR, including processes, recycling agents and re-using materials. Furthermore, the identified problems with using CIR practice for surface courses are also mentioned.

2.1 Asphalt recycling and rehabilitation

Essentially, asphalt recycling can be divided into two types based on temperature: Hot recycling (HR) and cold recycling (CR). Additionally, cold recycling can be further classified into three categories, being cold central-plant recycling (CCPR), CIR and full-depth reclamation (FDR) (Liu et al., 2022). This categorization is based on the concepts of construction technology (Xiao et al., 2018). The principle of CIR, which will be the focus of this research will be further discussed in subsection 2.2.

2.2 Basic principles of CIR

The CIR process is an on-site asphalt pavement rehabilitation technique that utilizes a train of specialized equipment possibly consisting of tanker trucks, milling machines, crushing/screening/sizing units, mixers, pavers and compaction rollers.

2.2.1 CIR process

Essentially, the process consists of the following steps: Milling and crushing of the existing pavement, mixing and addition of a recycling agent, paving, in-place compaction and placement of the surface course (Sebaaly et al., 2018).

1. Milling and crushing of the existing pavement
2. Mixing and addition of a recycling agent
3. Lay down
4. In-place compaction
5. Placement of the wearing course

This process is a continuous cycle, thus eliminating the need for hauling trucks, which is one of the major advantages of this technique. Typically, the CIR process is performed at a depth within the range of 50-125 mm (Bowers et al., 2022). According to Xiao et al., 2018, this range is typically 65-125 mm for partially depth reclamation (CIR). According to Bowers et al., 2022, CIR projects can be completed using a single-unit train and a multi-unit train. Xiao et al., 2018, distinguishes three types of CIR operations, which is displayed in Figure 1.

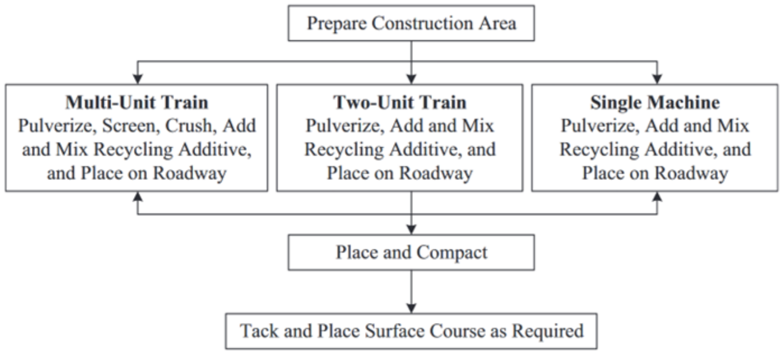


Figure 1: Categorization of CIR operations (Xiao et al., 2018)

A single-unit train includes a milling machine with a down-cut cutting head, meaning it rotates counterclockwise when moving left to right, to remove the pavement to a desired depth. The produced RAP is mixed with a recycling agent at the cutter head and this mixture is transferred into a paver. In this process, there is no crushing and screening unit. Multi-unit trains, on the other hand, do include a crushing/screening unit (Bowers et al., 2022).

2.2.2 Recycling agents

Extensive research has been performed on asphalt recycling agents. Liu et al., 2022, makes a distinction between stabilizing agents and rejuvenating agents. On the other hand, Xiao et al., 2018, only uses the term stabilizing agents and categorizes between bituminous stabilizing agents and cementitious stabilizing agents and these terms correspond to the terms used by Liu et al., 2022 respectively. The most frequently used stabilizing agents are emulsified asphalt and foamed asphalt, with the majority being emulsified asphalt (Liu et al., 2022)(Xiao et al., 2018). Emulsified asphalt is obtained by emulsifying bitumen and water using emulsifying agents and typically consists of 60% bitumen and 40% water. Recycling with foamed bitumen requires a process that adds small amounts of water to hot penetration-grade bitumen (Lewis & Collings, 1999). The most frequently used rejuvenating agents are cement and lime, although research is being done in the suitability of bio-based oils as rejuvenating agents (Ingrassia et al., 2019). Additionally, in some studies, researchers have examined the effects of incorporating cement into foamed- and emulsified asphalt mixtures (Liu et al., 2022). Xiao et al., 2018 also discusses the use of fly-ash as a cementitious stabilizing agent. Based on a study performed by the University of Kansas, it was concluded that the incorporation of fly-ash resulted in an increase of the strength of the mix, enhanced resistance to moisture damage, a decrease in permeability and lower potential for wheel path rutting (Cross & Fager, n.d.). Apart from bituminous and cementitious stabilizing agents, other additives are sometimes also incorporated in CIR mixtures. Jiang et al., 2020 explores the incorporation of three different polymers, being Styrene–butadiene rubber (SBR) latex, styrene-ethylene–butylene-styrene (SEBS) copolymer and chloroprene rubber (CR) latex. Modified emulsified asphalt has the potential to be used in layers closer to the surface as the temperature- and rutting resistance features are said to be improved.

2.3 Applications in the Netherlands

In the Netherlands, cold in-situ recycling is not applied frequently as a pavement rehabilitation technique. However, in the last couple of years, the method is becoming increasingly popular. In 2022, KWS, part of a Dutch construction company called VolkerWessels, executed a pilot project utilizing a cold asphalt recycling train (CART). In this project, the existing pavement was repaved as a base course. Beforehand, a mixture of cement and sand was spread on the pavement, after which it was milled with a in-situ foaming bitumen milling machine from Wirtgen. This machine mills the existing pavement, mixes the material with foaming bitumen and directly transfers it to a paver. The CART consisted of a water- and foaming bitumen tanker up front, followed by the foaming bitumen milling machine and an asphalt paver and roller (VolkerWessels, 2022). In early 2024, another construction company, BAM, applied an identical method. However, in this case, the existing pavement was repaved as a binder course (BAM, 2024). Rijkswaterstaat also initiated a pilot project in which it aims to use an ART (Asphalt Recycling Train) to rehabilitate surface courses. However, in contrast to the CART, the ART utilizes heat to soften the existing pavement, which ensures that the milled material has a sufficient gradation (Rijkswaterstaat, 2024). The use of heat in an in-situ pavement rehabiliation technique is undesirable as it increases the energy consumption relative to a cold recycling procedure.

2.4 Implications for surface courses

A common element of the mentioned literature on the CIR process and used recycling agents is that it is applied to sub-surface courses, mostly base/sub-base courses that experience low-volume traffic. Modarres et al., 2014, listed several reasons on why CIR should not be performed for surface courses, including: low abrasion resistance against impact of heavy vehicles especially during initial curing time, relatively high air void content, high permeability (will affect durability) and relative lack of smoothness. Furthermore, a higher content of water in mixtures and the initial stiffness caused by the addition of cement or pozzolanic additives both reduce the compactibility of the pavement layer, resulting in a higher air void content. Consequently, the roughness of the pavement layer could be increased. Vázquez et al., 2021, states that the reasons CIR is currently not frequently applied to surface courses, are the weak early-life strength and a relatively long curing time. Additionally, lower stability, lower ITS (Indirect Tensile Strength) values, and high risks of cracking and moisture damage are also limiting factors for using CIR for surface courses (Zhao et al., 2022). The list displayed below summarizes the possible limitations of CIR mixtures for surface courses.

- Low abrasion resistance & indirect tensile strength, especially in early life
- High air void content
- High permeability
- Lack of smoothness/increased roughness
- Long curing time

3 Research framework

In this chapter, the research framework, along which the study will be executed, is discussed. This includes the research objective, the research questions that will be answered to achieve the research objective and the research scope.

3.1 Research objective

The research objective is to create an overview of the gradation characteristics of RAP produced through state-of-practice cold milling equipment and processes alongside the required gradation standards for surface course applications, to help identify innovative techniques and assess their effectiveness in improving RAP to be used in surface course applications.

3.2 Research questions

The main research question that will be answered in this by this study is listed below.

How can advancements in cold milling processes and equipment improve the gradation characteristics of Reclaimed Asphalt Pavement (RAP) to meet the requirements for surface course materials?

In order to answer this research question, the following sub-questions should be answered:

- What equipment and processes are currently used in cold milling, and how do they impact RAP gradation characteristics?
- What are the specific gradation requirements for RAP used in surface course material, and how do current RAP characteristics compare?
- What new techniques are available that can improve the gradation characteristics of RAP and what impact do these techniques have on meeting the required gradation standards for surface courses?
- What factors should be considered to determine if a specific surface course is eligible for CIR?

3.3 Research scope

In order to ensure that the study can be completed within the timeframe of 10 weeks, it is important to define the research scope. In the process of recycling RAP, several material properties are important to consider. This includes, among others, gradation, bitumen content and angularity. However, in this study, only the gradation characteristics will be examined. Additionally, design requirements and relevant regulations will be based on NEN-norms and CROW Standaard RAW bepalingen 2020 (CROW, 2020). The design requirements are based on allowed grading envelopes and not on performance properties.

4 Methodology

This section will elaborate on the research methods that will be utilized to answer the sub research questions and ultimately the main research question. First, the general research methodology, which is structured in a research model, will be discussed. After this, a more detailed description will be given for the different research steps.

4.1 Research model

A research model will help ensure that all steps necessary to achieve the research objective are defined properly and incorporated in the right manner. The model is displayed in Figure 2.

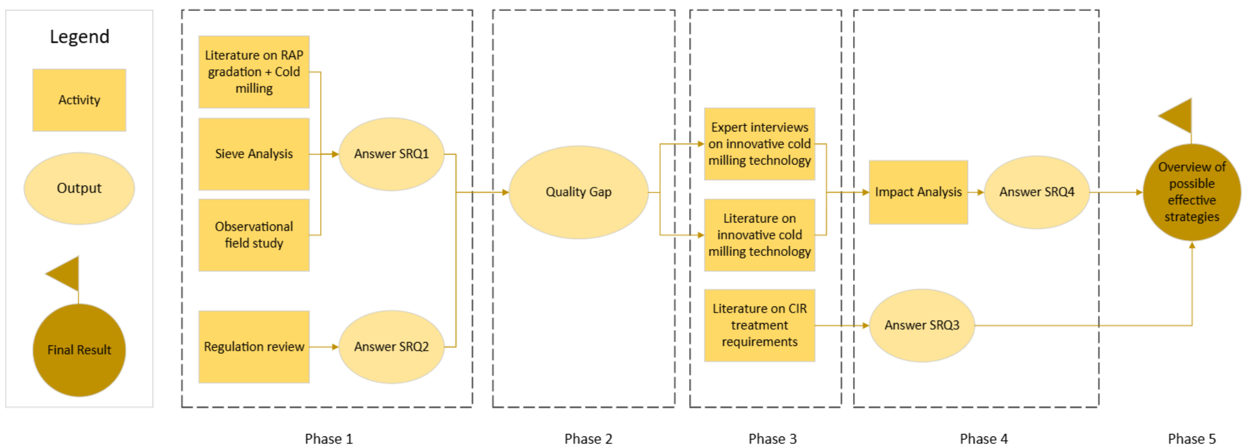


Figure 2: Research Model

The model is composed of five phases, which will be completed in the defined order with some overlap between them. In phase 1, sub-research question (SRQ) 1 will be answered, while SRQ2 will be partly answered. In phase 2, the remaining part of SRQ2 will be answered by comparing the results from SRQ1 and SRQ2. In phase 3, information from phase 2 is used to fuel a search for answers on SRQ4. Additionally, in this phase, information will be gathered to answer SRQ3, which will ultimately be done in phase 4. In phase 4, the solutions found in phase 3 will be evaluated with an impact analysis to ultimately give a final answer on SRQ4. In phase 5, the answers to SRQ3 and SRQ4 will be used to construct an overview of recommendations for possible effective strategies.

4.2 Phase 1: Defining the state-of-practice and the regulations

In this phase, the state-of-practice regarding the cold milling equipment and process will be identified and defined. Additionally, the gradation characteristics of RAP acquired through the current cold milling equipment and process will be analyzed and described. As displayed in the research model, SRQ1 will be answered using three research techniques. First, an observational field study will be performed to gain information about the currently used cold milling equipment and process, which will be complemented with a systematic literature study. Simultaneously, RAP samples from a cold milling procedure will be analyzed with a sieve analysis. The procedure of the sieve analysis shall be conforming the procedure defined in NEN-EN 12697-2. Lastly, the obtained results shall be compared to results from other similar studies for validation and get an image of the general situation regarding RAP gradation.

Furthermore, in this phase the required gradation characteristics, according to the regulations, for surface courses of different type of asphalt mixes and the incorporation of RAP in these courses will be defined. The regulations that will be reviewed are the NEN-norms, in particular the NEN-EN 13108 series and the CROW Standaard RAW bepalingen 2020 (CROW, 2020). The NEN- norms can be accessed with the University's access through NEN-connect, while the CROW Standaard RAW bepalingen 2020 is provided by NTP.

4.3 Phase 2: Defining the quality Gap

In this phase, the results of phase 1 will be used to identify the "quality gap". The quality gap corresponds to the difference in gradation between the regulations and the RAP material from the sieve analysis and literature. For this the gradation requirements according to the regulations will be compared to the results from the sieve analysis and literature study. This will be done based on general gradation requirements, but also RAP homogeneity.

4.4 Phase 3: Search for solutions

The "Quality Gap" defined in phase 2 forms the basis for an exploratorive study for innovative cold milling techniques in the form of a semi-systematic literature study. Furthermore, expert interview(s) (listed in Appendix A) on cold milling equipment and processes will provide additional information on innovative techniques. The combination of these research strategies will likely ensure that adequate information is acquired. If the execution of one of the strategies fails to provide information, the other strategy will likely compensate for this. Ultimately, the effectiveness of the identified techniques will be assessed on their ability to bridge the defined quality gap. Additionally, a semi-systematic literature study on factors influencing the effectiveness and performance of a CIR rehabilitated pavement will be performed. This literature study will be complemented with the findings from the expert interview(s) (listed in Appendix A).

4.5 Phase 4: Impact analysis

In the fourth phase, an impact analysis of the proposed solution(s) will be performed. This impact analysis will be in the form of a scenario analysis. In this scenario analysis, multiple possible scenarios based on different combinations of parameter values and their possible influence on gradation, will be tested for their effectiveness in bridging the quality gap.

4.6 Step 5: Overview of strategies

In the last phase, the findings from phase 4 will be presented. In this phase, the main research question will be answered. This will be discussed in section 7 and section 8.

5 Results

5.1 State-of-practice

In this section, aspects of the state-of-practice of the cold milling process and technology and its impacts on RAP gradation will be discussed. In subsubsection 5.1.1, the current cold milling technology and process will be discussed. This will be followed by a discussion on RAP gradation characteristics obtained through literature study (subsubsection 5.1.2) and a sieve analysis (subsubsection 5.1.3).

5.1.1 Current milling equipment and process

As discussed in subsubsection 2.2.1, CIR can either be performed with a single-unit recycling train or a multi-unit recycling train. However, both of these methods utilize a cold milling machine to remove the existing asphalt pavement course. The equipment and process that is currently used for this in the Netherlands is discussed in this section.

Equipment

In the Netherlands, leading asphalt milling companies, such as Freesmij, Aduco and Freesverhuur Ommen, only use cold milling machines from Wirtgen. Wirtgen is a leading manufacturer of cold milling machines and distinguishes between three types of regular cold milling machines: small, compact and large. Additionally, Wirtgen also offers cold recyclers. In the case of cold in-situ recycling either large cold milling machines or cold recyclers are used. The large cold milling machines have a wide range of applicability, which extends from complete removal up to a depth of 35 cm in a single pass, rehabilitation of concrete pavements and airport runways as well as fine milling to improve pavement skid resistance (WIRTGEN, 2024). In total, there are five different large cold milling machines: the W200 Fi, the W200 Hi, the W210 Fi, the W220 XF and the W250 Fi. Between these configurations, there is a distinction in milling width, maximum milling depth, maximum power and operating weight. In addition to the capabilities of a cold milling machine, cold recyclers are equipped with mixing unit, which can create a CMA using foaming bitumen or bitumen emulsion (WIRTGEN, n.d.-b). In total there are 2 different cold recyclers: the W240 CRi and the W380CRi. Between these types, there is a distinction between milling width and operating weight.

A typical cold milling machine (Figure B.1) consists of at least the following components: a powerful engine, steerable crawler units, a milling drum, an operator platform, and a conveyor belt often equipped with a vacuum cutting system for the extraction of fine material particles (WIRTGEN, n.d.-a). As discussed, a cold recycler (Figure B.2) is also equipped with a mixing unit in addition to the mentioned components (WIRTGEN, n.d.-b). According to Wirtgen, the key technologies to remove pavement efficiently are the cutting technology, machine control technology, and leveling technology. The milling drum, displayed in Figure 3, is attached with pick holders, which in turn are attached with picks. These round shaft picks are equipped with carbide pick tips to increase the hardness of the picks. This is said to increase the milled surface quality and the longevity of the picks. Furthermore, a range of different configured milling drums allows for the use of a milling drum tailored to the requirements of the job. According to expert 1 (Table A.1), milling machines are normally equipped with a milling drum with an 18 mm spacing between the picks. In the different configurations, there is a distinction in milling depth, milling width and spacing between the picks. Furthermore, machine control is an important factor in the production of quality RAP. Ensuring that machine parameters are consistent throughout the milling process will increase the uniformity of RAP material, since a change in parameters influences the size and composition of the material (Zaumanis et al., 2021). The innovative “Mill Assist”, only available on the F-series generation of machines, automatically optimizes the speed of the diesel engine, the milling drum, the travel drive, the water system and the machine’s advance speed. Lastly, proper leveling technology is also important to ensure uniformity, because changes in depth throughout the milling process can influence the composition of the RAP material (Zaumanis et al., 2021).

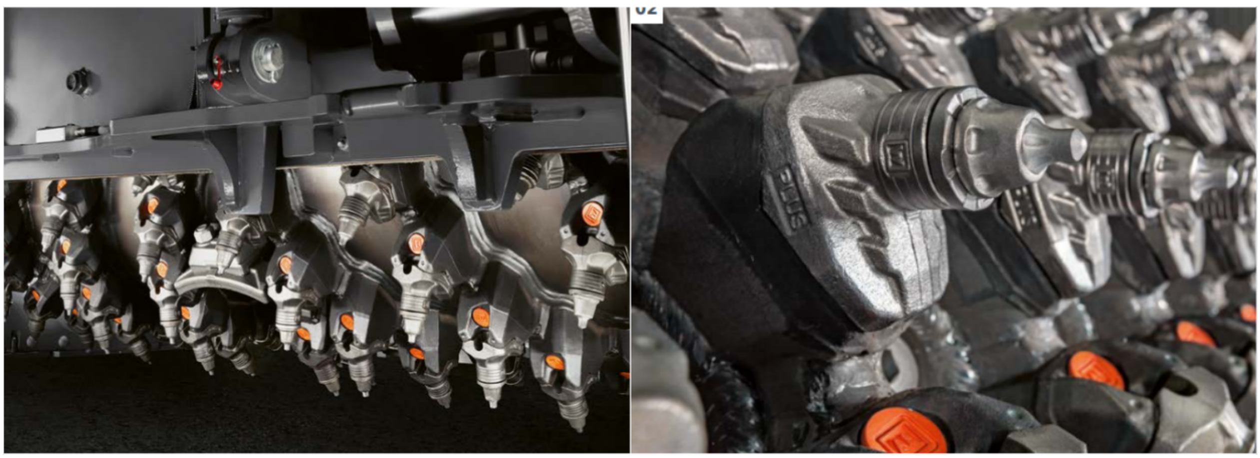


Figure 3: Milling drum of a cold milling machine (WIRTGEN, n.d.-a)

Process

The asphalt milling process is relatively simple: the milling machine is positioned on the to be milled road section. In front of the machine, a hauling truck captures the RAP material. Furthermore, the milling machine moves at a constant travel speed if the milling depth is consistent. If the required milling depth changes, the travel speed is adjusted accordingly. Apart from the milling depth and travel speed, other parameters that can be adjusted during the milling process are the drum rotational speed, the water injection and conveyor speed. According to expert 1 (Table A.1), the focus during cold milling currently lies mostly on the quality and quantity. In this, the quality means the condition, in terms of smoothness and uniformity, of the remaining layer after cold milling. Quantity denotes the productivity of the operation in square meters of pavement milled in a certain time metric. However, upon request, emphasis can be placed on other aspects, which also includes a focus on the quality of the RAP.

Yao et al., 2024, visualized the trajectory of the milling picks attached to the milling drum. This visualization gives an overview of the cutting path and cutting area of each pick and is displayed in Figure 4(a). The impact of the milling drum picks and its specific trajectory can cause aggregate breakage, which changes the structure of the original aggregates. This phenomenon is visualized in Figure 4(b) and is further discussed in subsubsection 5.1.2.

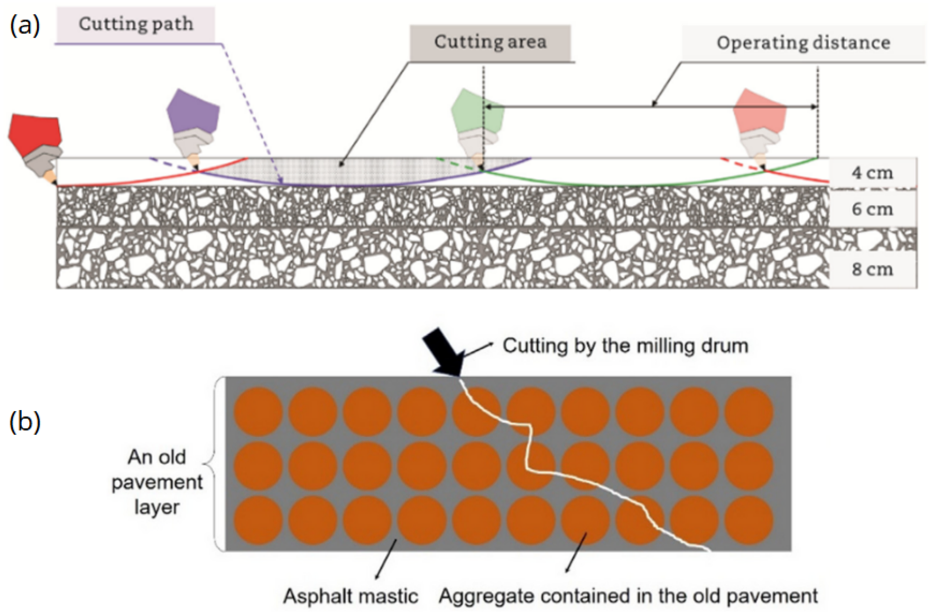


Figure 4: (a) Cutting area and cutting path of as single cutter during the milling process (Yao et al., 2024); (b) Schematic diagram of the breakdown during milling operation (Yang et al., 2021)

5.1.2 RAP gradation characteristics: literature

RAP consists of two components (Sebaaly et al., 2018):

- RAP aggregate, which is the aggregate part of the reclaimed asphalt.
- RAP binder, which consists of the asphalt cement of the reclaimed asphalt.

Typically, these two components are clustered and form larger sized chunks than the initial aggregates. The RAP aggregates present in these clustered chunks are often partially or completely crushed. Consequently, the type of aggregate breakage from the RAP chunks can be categorized into two classes (Figure 5). The partially crushed RAP aggregates do not significantly differ from the original morphology of the aggregate. In contrast, completely crushed RAP aggregates will have a different morphology compared to the original aggregate. This typically leads to a reduce in volume, while the particles often consist of a substantial amount of binder. Ultimately, this causes implications for the utilization of RAP in new asphalt mixtures (Yao et al., 2024). Various studies performed on the effect of cold milling on the gradation characteristics of RAP are reviewed in the sections below.

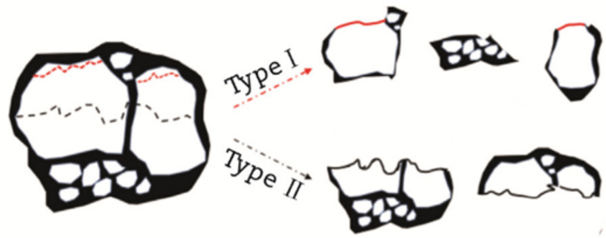


Figure 5: Classification of the type of breakage of RAP chunks (Yao et al., 2024)

In this study, Yao et al., 2024 examined RAP clustering and RAP aggregate breakdown during a cold milling procedure executed on an expressway in Southeast China. The original pavement structure consisted of three layers, including a 4 cm AC-16 upper layer, 6 cm AC-20 middle layer, and 8 cm AC-25 lower layer, employing basalt aggregate in the upper layer and limestone aggregate in the middle and lower layers. The AC-16 upper layer was milled using the Wirtgen W 2000 cold milling machine, with a milling rotation of 100 rounds per minute. The obtained RAP samples were examined in two forms. First RAP particles were examined, which is the original material obtained from the milling procedure. Consequently, from this material, the individual RAP aggregates are extracted from the binder through a centrifugal separation method. Both materials are compared to the original pavement gradation, which was determined by core drilling sampling. In Figure B.5, the resulting particle and aggregate gradation obtained through a sieving analysis is displayed. From this figure, it becomes evident that RAP particle gradations were lower than the RAP aggregate gradations. Furthermore, the aggregate gradation of RAP is generally closer to the gradation of the original pavement. However, there is a slight difference as the grading curves of the RAP aggregates are suggesting an overall finer gradation compared to the original aggregates. A cause for this could be aggregate breakage, of which the concept is discussed in subsubsection 5.1.1 and earlier in this section. The position of the grading curves of the RAP particle gradation indicates the effect of clustering.

Yang et al., 2021, performed a similar study on RAP clustering and RAP aggregate breakdown. In this study, RAP samples obtained from a milling procedure off another expressway located in Southeast China were examined. The original pavement's structure consists of a 4 cm AC-13 diabase upper layer, a 6 cm AC-16 limestone middle layer, and an 8 cm AC-16 lower layer. The pavement was milled using a Wirtgen W 2000 cold milling machine. Similar to the research performed by Yao et al., 2024, Yang et al., 2021, also distinguishes between RAP particles and RAP aggregates using the same definitions and a similar sieve analysis procedure. First the sieve analysis is performed on the RAP particles, after which the aggregates are extracted from the RAP particles using a centrifugal extraction method. The gradation of both materials were compared to the gradation of the original pavement. The results of the sieve analysis of the AC-13 upper layer is displayed in figure Figure B.6. From this figure, it can be concluded that the gradation of RAP particles are significantly higher than the gradation of the RAP aggregates. Additionally, the RAP aggregates have a similar grading curve to the original gradation. These results correspond to the results obtained by Yao et al., 2024. According to Yang et al., 2021, approximately 0.1%–1.8% more filler, 0.2%–8.7% more fine aggregate, and 2.4%–9.1% less coarse aggregate is produced by milling when compared to the original materials. This is the effect of aggregate breakdown and applies to the RAP aggregates, thus the material obtained after binder extraction. On the other hand, approximately 30%-50% of the RAP particles are clustered. This indicates that the current cold milling process and equipment causes the production of more fines, while also producing clustered RAP aggregates.

Zhu et al., 2020 performed a study on the clustering of reclaimed asphalt pavement for cold recycling, with the aim of making a characterization. In this study, three different types of RAP materials collected from stockpiles at three different sources, were tested. The original compositions of the three RAP materials are dense graded AC, SMA and open-graded friction course (OGFC). The gradation curves of the three RAP materials before and after extraction are displayed in Figure B.7. In this study, Zhu et al., 2020, utilized three different tests to evaluate the clustering properties. These tests include the asphalt extraction test, a modified Los Angeles abrasion test, and a mixing test, which all reflected the clustering characteristics effectively. All three RAP samples tested in this study exhibited signs of clustering, indicated by the loss of original sized aggregates. Furthermore, the RAP material was classified into three categories: strong RAP, weak RAP and aggregate, of which weak RAP showed a significantly higher clustering degree. According to the findings, this type of RAP material should be minimized in the cold recycling process.

Cadar et al., 2022, analyzed RAP material from a secondary road in Romania (country road DJ109), based on the following characteristics: particle size, binder content, material variability and uniformity, and the clustering phenomena. The used RAP was obtained by a cold milling procedure applied to the surface course with a thickness of 5 − 10 cm. For the milling procedure, a Wirtgen W200, was used at a moving speed of 10 m/min and a milling depth of 5 cm. In total, 9 piles of RAP material, each consisting of milled material of a segment of approximately 1 km, were collected. Furthermore, the samples were collected from each stockpile using the sampling method as specified in SR EN 932-1. The results of the sieve analysis are displayed in Table B.1. The visual analysis conducted in this study indicated the phenomenon of RAP particle clustering.

Xu et al., 2019 researched the phenomena of particle clustering in RAP particles. In particular, the particle composition, clustering degree, crushing properties and clustering stability of RAP were studied. Two RAP materials were investigated in this study; one of the materials was obtained during the process of cold milling, while the other material was collected from crushing material of plant. The original mixture was of the type AC-13. The RAP particles gradation curve was obtained through a sieving experiment and is displayed in Figure B.8. In this study, it was found that the particle of sizes 16 mm and 19 mm were mainly composed of 9.5 mm and 4.75 mm aggregates, indicating the presence of RAP particle clustering. According to Xu et al., 2019, this is because the RAP was not broken sufficiently during the milling procedure. Furthermore, the Percentage-Loss (PL) rate after extraction, used as an evaluation index, indicated that the larger the RAP particle size, the more severe the clustering degree.

In Table 1, an overview is given on the original pavement mix and course of the RAP studied in the sources.

Source	Yao et al. (1)	Yang et al. (2)	Zhu et al. (3)	Cadar et al. (4)	Xu et al. (5)
Asphalt Mix	AC-16	AC-13	AC & SMA	-	AC-13
Pavement Layer	Surface	Surface	-	Surface	-
Sample preparation	-	-	-	-	Dried at 60 °C

Table 1: Overview of the original pavement mix and layer of the sources

5.1.3 RAP gradation characteristics: sieve analysis

As discussed in the introduction of this chapter, the results of the literature study on RAP gradation characteristics will be compared to the results obtained from a sieve analysis of RAP material gathered through cold milling. The RAP used for this sieve analysis was collected from stockpiles at the asphalt plant of NTP. Due to a lack of availability, the only mix types that were used are SMA-NL 11 and AC Surf. In the AC Surf stockpile, RAP materials from AC-8-, AC-11- and AC-16 pavement were present. As mentioned in section 4, the sieve analysis was carried out in part in accordance with the procedure defined in NEN-EN 12697-2, as the RAP material was sieved without the washing procedure defined in Section 7.1 of NEN-EN 933-1. Furthermore, the RAP material was sieved without drying. The reason for this is the fact that in a cold in-situ operation, the RAP material will not be washed and dried. In this way, the situation is represented as accurately as possible. However, as a consequence, the 0.063 mm sieve was not included. Because of this, the results from the literature study for the 0.063 mm sieve can not be compared to the results from the sieve analysis. Additionally, it is possible that the presence of water in the RAP samples increased the weight of the particles due to water retention. The sieving procedure was executed in several steps:

1. Sample collection
2. Sample division
3. Execution of sieve analysis

The content and execution of these steps are elaborated in subsection B.2. The results of the sieve analysis are displayed in Table 2.

	AC Surf (Sample #)					SMA-11 (Sample #)				
Through sieve	1	2	3	4	Avg	1	2	3	4	Avg
	Percentage passing (%)									
45 mm	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
31.5 mm	96%	98%	96%	98%	97%	98%	99%	97%	97%	98%
22.4 mm	89%	91%	87%	90%	89%	94%	95%	93%	92%	93%
16 mm	79%	81%	78%	78%	79%	85%	86%	83%	84%	85%
11.2 mm	66%	65%	63%	65%	65%	66%	67%	61%	61%	64%
8 mm	51%	50%	47%	48%	49%	39%	41%	39%	37%	39%
5.6 mm	37%	34%	31%	33%	34%	25%	27%	26%	23%	25%
4 mm	25%	23%	20%	22%	23%	16%	16%	17%	15%	16%
2 mm	13%	11%	10%	11%	11%	8%	6%	8%	7%	7%

Table 2: Results of the sieve analysis

5.1.4 Conclusion

The results from subsubsection 5.1.2 and subsubsection 5.1.3, can be combined to give an overview of the gradation characteristics of RAP material obtained through current cold milling practices. The test results of the sieve analysis and the data gathered through the literature are combined into graphs displaying each of the grading curves. These graphs are displayed in Figure 6 and Figure 7. In these graphs, it can be seen that the grading curves of the sieve analysis and the grading curves extracted from literature studies generally follow similar trajectories. However, the differences are greater for the SMA-NL 11 RAP materials than for the AC Surf RAP materials. From the sieve analysis, it can be concluded that the AC surf RAP material had a finer gradation than the SMA-NL 11 RAP material. However, a higher percentage of coarse particles ($\geq 22.4mm$) was retained for the AC Surf RAP material. This could suggest that the AC Surf samples had a higher rate of clustering or relatively more severe clustering. The results from the literature study can not support this statement as most of the RAP material originates from AC surface courses.

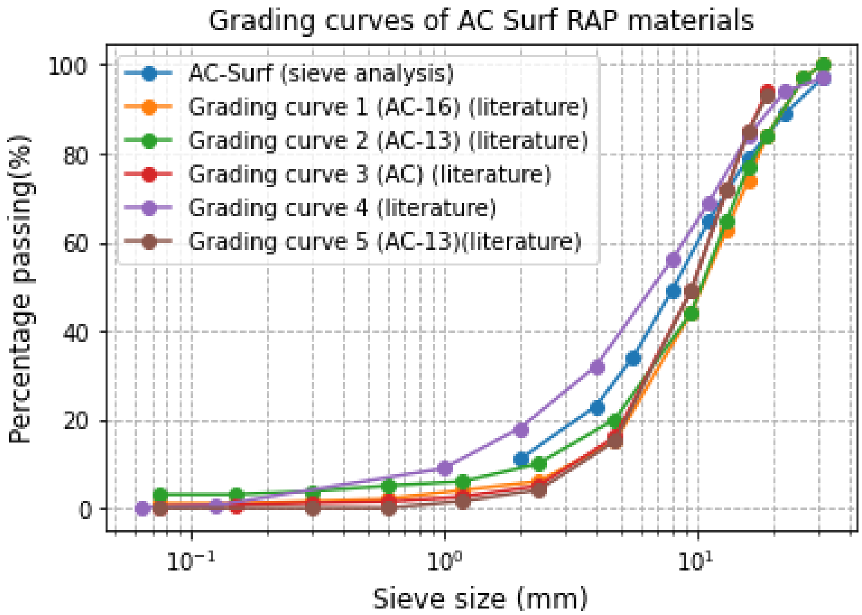


Figure 6: Grading curves of AC-Surf RAP material from the sieve analysis compared to literature

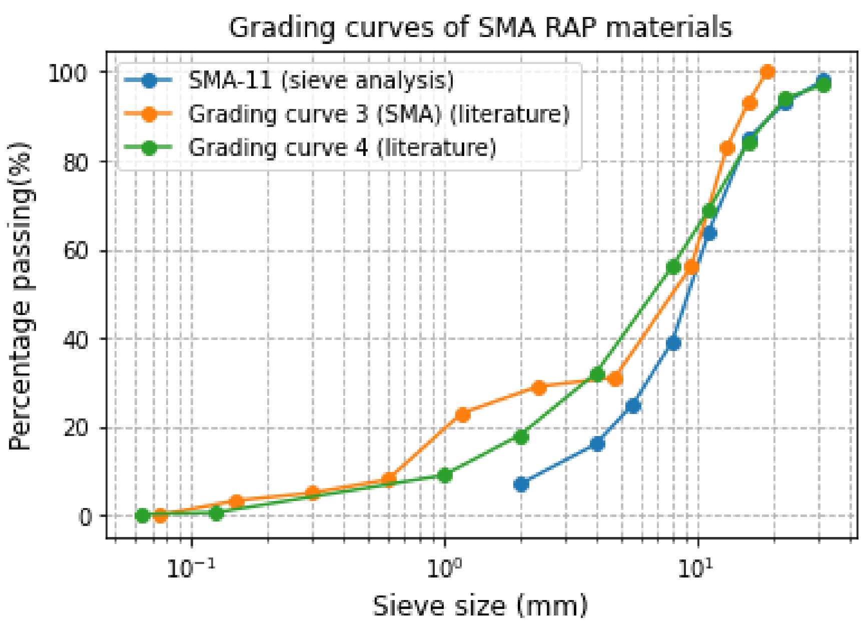


Figure 7: Grading curves of SMA RAP material from the sieve analysis compared to literature

5.2 Regulations

In the case of this project, the target asphalt mix type will be Asphalt Concrete (AC), while Stone Mastic Asphalt (SMA) will also be considered. This can be explained by the fact these are among the most used mix types for asphalt surface courses in the Netherlands (Rijkswaterstaat, 2022). Additionally, this was proposed by NTP. Considering this, the gradation requirements of RAP will be based on the gradation requirements of these mixes. On top of that, RAP material itself also has certain requirements, specifically in terms of homogeneity.

5.2.1 Asphalt Concrete

AC is defined as asphalt in which the aggregate particles are continuously graded or gap-graded to form an interlocking structure. Furthermore, it is used for surface courses, binder courses, regulating courses, and bases (Netherlands Standardization Institute, 2016a).

In chapter 81 of the CROW Standaard RAW bepalingen 2020, all requirements regarding bituminous pavements are listed (CROW, 2020). Section 81.26.02 specifically discusses the requirements of AC mixes. In this section, it is first stated that AC must comply with the requirements of NEN-EN 13108-1, while taking into account the provisions described in the other paragraphs of the section. NEN-EN 13108-1 specifies the requirements for mixtures of the mix group AC for use on roads, airfields and other trafficked areas. According to section 5.2.2.1, the requirements for the overall grading limits of the target composition are given in two tables, distinguishing between two basic sieve sets. In the CROW Standaard RAW bepalingen 2020, it is stated in paragraph two of section 81.26.02 that the aggregate gradation should be determined with the basic sieve set plus set 1. The corresponding table is displayed in Table C.1. In this table, D denotes the upper sieve size, while the numbers in this table are a representation of the percentage of mass retained on the corresponding sieve size from the entire mass of the sample.

It has to be noted that according to paragraph 05 of section 81.26.02, the maximum allowed percentage of mass of asphalt granulate applied in surface courses is 30%. However, with CIR, all RAP material will be included in the mixture. Hence, an inclusion of 100% is achieved, which is why this regulation will be ignored.

5.2.2 Stone Mastic Asphalt

SMA is an asphalt mixture defined as a gap-graded asphalt mixture with bitumen as binder, composed of a coarse crushed aggregate skeleton bound with a mastic mortar. The asphalt mixture is mainly used for surface courses, while it can also be used for regulating and binder courses (Netherlands Standardization Institute, 2016b).

In section 81.26.03 of the CROW Standaard RAW bepalingen 2020, all requirements regarding SMA mixes are listed. The first paragraph of this section states that SMA must comply with the requirements of NEN-EN 13108-1, while taking into account the provisions described in the other paragraphs of the section. NEN-EN 13108-5 specifies the requirements for mixtures of the mix group SMA for use on roads, airfields and other trafficked areas. According to section 5.2.2.1, the requirements for the overall grading limits of the target composition are given in two tables, distinguishing between two basic sieve sets. In the CROW Standaard RAW bepalingen 2020, it is stated in paragraph two of section 81.26.02 that the aggregate gradation distribution should be determined with the basic sieve set plus set 1. The corresponding table is displayed in figure Table C.2. In this table, D denotes the upper sieve size, while the numbers in this table are a representation of the percentage of mass retained on the corresponding sieve size from the entire mass of the sample. On top of the grading requirements for SMA according to NEN-EN 13108-1, section 81.26.03 of the RAW standaard 2020 bepalingen also enlists a table (table 81.2.9) with grading requirements of different SMA mixes, displayed in Table C.3. In general, these requirements correspond with the requirements of the NEN-EN 13108-1. However, a more specified percentage range is given in the RAW standard 2020 bepalingen. In total there are five different SMA mixes; SMA-NL 5, SMA-NL 8A, SMA-NL 8B, SMA-NL 11A and SMA-NL 11B. The number in this notation denotes the upper sieve size. Furthermore, for upper sieve sizes 8 and 11, a distinction is made between type A and B. This denotes the content of material smaller than 2 mm, which is lower for type B. The numbers in this table are a representation of the percentage of mass retained on the corresponding sieve size from the entire mass of the sample.

It has to be noted that according to paragraph 07 of section 81.26.03, it is prohibited to incorporate RAP into new SMA mixes. However, with CIR, all RAP material will be included in the mixture. Hence, an inclusion of 100% is achieved, which is why this regulation will be ignored.

5.2.3 RAP material

In addition to the requirements of both types of asphalt mixes, there are also requirements regarding RAP itself. These requirements are discussed in section 81.26.11 of the CROW Standaard RAW bepalingen 2020, as well as in the NEN-EN 13108-8. In section 81.26.11, paragraphs 04 t/m 07 discuss the requirements of RAP regarding gradation. Especially the homogeneity of the material is of importance. Paragraph 04 states that RAP material should be homogeneous, on which it will be assessed. If the material is not assessed as homogeneous, it should be homogenized. In addition, in paragraph 05, it is stated that if asphalt granulate is used as a continuously available raw material in the production process, a batch is stored separately and assessed by the producer at regular intervals. From this stored RAP, five samples of 2,5 kg each will be examined based on binder content, particle gradation and penetration of the reclaimed bitumen. The RAP is deemed as homogeneous if the standard deviation calculated on the results of the five samples is within the limit defined in table 81.2.15, which is displayed in Table C.4.

5.2.4 Conclusion

The regulations can be outlined based on the findings discussed in subsubsection 5.2.1, subsubsection 5.2.2 and subsubsection 5.2.3, which collectively provide an overview. This overview of the gradation requirements of the asphalt mixes used in surface courses and included in the scope of this study is given in Table 3. It can be seen that the composition of a mix type, in terms of gradation, is based on four sieve sizes at the minimum. For the AC mixes, the range of the percentage of mass retained on the 2 mm sieve is relatively broad. If RAP is added to these mixtures, it should comply with the homogeneity requirements as defined in Table C.4.

Through sieve	SMA-NL 5	SMA-NL 8A	SMA-NL 8B	SMA-NL 11A	SMA-NL 11B	AC-8 Surf	AC-11 Surf	AC-16 Surf
	Percentage of mass retained on sieve in terms of mass of entire sample (%(m/m))							
22.4 mm								100
16 mm				100	100		100	90-100
11,2 mm		100	100	92-100	92-100	100	90-100	
8 mm	100	92-100	92-100	DV	DV	90-100		
5,6 mm	92-100	DV	DV					
4 mm	DV							
2 mm	28-38	21-31	18-28	18-28	17-27	10-72	10-60	10-50
0,5 mm	DV	DV	DV	DV	DV			
0,063 mm	9,5-13,5	8,0-12,0	7,0-11,0	7,0-11,0	6,0-10,0	2,0-13,0	2,0-12,0	0-12,0

Table 3: Gradation requirements of different asphalt mixtures used in surface courses

5.3 Quality gap

In this section, the results from subsection 5.1 and subsection 5.2 will be compared to define and visualize the quality gap. This will be done based on the general gradation and the homogeneity of the RAP material. It has to be noted that for the comparison of SMA-NL 8 and SMA-NL 11 the "B" type was selected, as these are suggested by Rijkswaterstaat (Rijkswaterstaat, 2022).

5.3.1 Gradation

In subsection 5.1, the gradation characteristics of RAP materials were analyzed and discussed. In this section, it was concluded that the effect of clustering caused the RAP material to be relatively coarse graded. This is reflected in Figure 8 and Figure 9, where the gradation requirements of both AC-Surf mixes and SMA-NL mixes are compared to the results from the sieve analysis.

Asphalt Concrete

The grading curves of the AC-Surf RAP material analyzed in the sieve analysis lies outside the boundaries of all AC-Surf mixes, except for the 2mm sieve. According to the grading requirements of the AC-surf mixes defined in NEN-EN 13108-1, the maximum aggregate size of the AC-8 Surf, AC-11 Surf and AC-16 Surf mixes is 8mm, 11mm and 16 mm respectively. However, in the AC-Surf sample used in the sieve analysis, RAP particles of at least 32 mm in diameter were present as some of the material was retained on the 31.5 mm sieve.

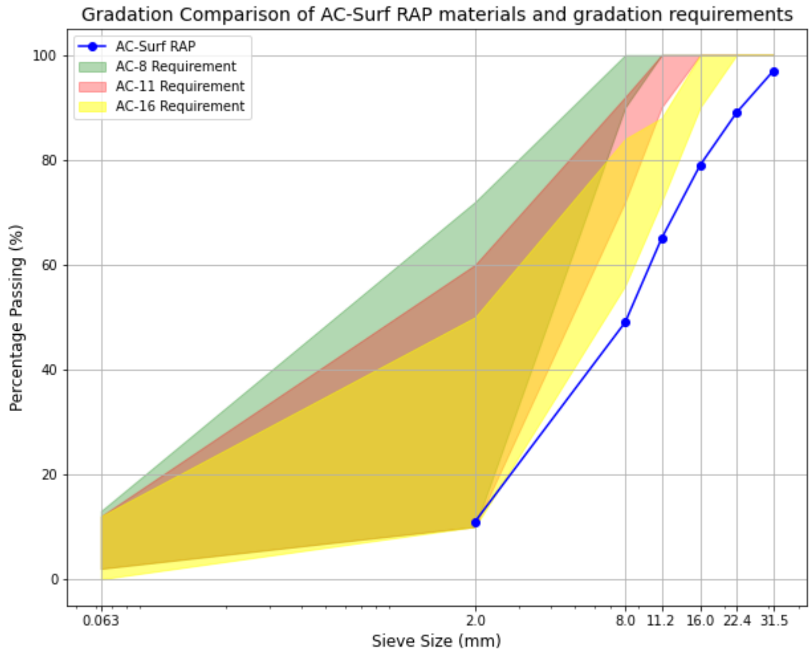


Figure 8: Graph of gradation requirements of different AC Surf mixes and the gradation of AC Surf determined with the sieve analysis

In Table 4, the gradation of the AC-Surf RAP material obtained through the sieve analysis is compared to the required gradation of different AC-Surf mixes. In this table, the differences are expressed as percentage points. It can be seen that for all AC-Surf mixes, there is a positive difference between the lower passing limit and the percentage passing in the AC-Surf RAP material. An exception for this is the 2 mm sieve, on which the percentage of RAP material retained is within the required limits. This indicates that the AC Surf RAP material is too coarse graded.

Through sieve	**AC-Surf**	**AC-8 Surf**		**AC-11 Surf**		**AC-16 Surf**	
	Percentage passing (%)						
		Lower limit	Δ	Lower limit	Δ	Lower limit	Δ
45 mm	100%	100%	0%	100%	0%	100%	0%
31.5 mm	97%	100%	3%	100%	3%	100%	3%
22.4 mm	89%	100%	11%	100%	11%	100%	11%
16 mm	79%	100%	21%	100%	21%	90%	11%
11.2 mm	65%	100%	35%	90%	25%		
8 mm	49%	90%	41%				
5.6 mm	34%						
4 m	23%						
2 mm	11%	10%	-1%	10%	-1%	10%	-1%
0.063 mm	-	-	-	-	-	-	-

Table 4: Gradation of current state-of-practice AC-Surf RAP material compared to gradation from the regulations expressed as difference in percentage points

Stone Mastic Asphalt

Similar conclusions can be made for the SMA-NL mixes, where the grading curve of the SMA-NL 11 mix used in the sieve analysis also lies outside the boundaries of the SMA-NL 8 and SMA-NL 11 mixes. However, in this case, the difference between the gradation of the RAP material and the required gradation is larger than the differences in the AC-Surf mixes. This can be attributed to finer gradation requirements for the different SMA mixes and lower passing percentage for the finer sieve apertures ($\leq 11.2mm$) compared to the AC-Surf material. The maximum aggregate size for the SMA-NL 8 and the SMA-NL 11 mixes are 8mm and 11mm respectively. In the SMA-NL 11 sample used in the sieve analysis, aggregates of at least 32 mm in diameter were present.

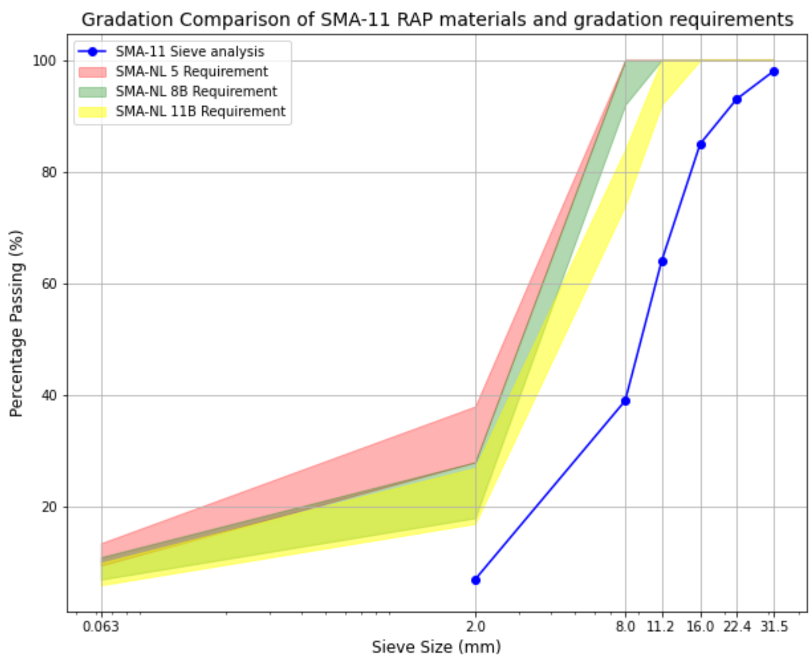


Figure 9: Graph of gradation requirements of different SMA mixes and the gradation of SMA-11 determined with the sieve analysis

In Table 5, the gradation of the SMA-NL 11 RAP material obtained through the sieve analysis is compared to the required gradation of different SMA-NL mixes. In this table, the differences are expressed as percentage points. It can be seen that for all SMA-NL mixes, there is a positive difference between the lower passing limit and the percentage passing in the SMA-NL 11 RAP material. This indicates that the SMA-NL 11 RAP material is too coarse graded.

Through sieve	SMA-NL 11	SMA-NL 5		SMA-NL 8B		SMA-NL 11B	
	Percentage passing (%)						
		Lower limit	Δ	Lower limit	Δ	Lower limit	Δ
45 mm	100%	100%	0%	100%	0%	100%	0%
31.5 mm	98%	100%	2%	100%	2%	100%	2%
22.4 mm	93%	100%	7%	100%	7%	100%	7%
16 mm	85%	100%	15%	100%	15%	100%	15%
11.2 mm	64%	100%	36%	100%	36%	92%	28%
8 mm	39%	100%	61%	92%	53%		
5.6 mm	25%	92%	67%				
4 m	16%						
2 mm	7%	28%	21%	18%	11%	17%	10%
0.063 mm	0%	95%	95%	7%	7%	6%	6%

Table 5: Gradation of state-of-practice SMA-NL 11 RAP material compared to gradation from the regulations expressed as difference in percentage points

Clustering

Overall, it can be said that the gradation of RAP of both SMA-NL and AC-Surf mixes obtained through the current state-of-practice are too coarse graded. As mentioned in subsubsection 5.1.4, RAP particles retained on sieves with aperture 22.4 mm and above generally consist of clustered aggregates and bitumen. This causes the percentage passing of the RAP material to be too low for most of the sieves. If the clustered particles would be separated into smaller fragments, the percentage passing the larger aperture sieves ($\geq 22.4mm$) would increase. As the total sample size of the finer graded RAP material increases due to the seperation of coarser fragments, the percentage passing the sieves with smaller apertures ($\leq 11.2mm$) will also likely increase.

5.3.2 Homogeneity

In subsubsection 5.2.3, it is stated that RAP material should be assessed as homogeneous if it is to be used for new asphalt mixes. The material is assessed through the standard deviation of five samples at different recycling percentages of RAP. Table 81.2.15 of the CROW Standaard RAW bepalingen 2020, displayed in Table C.4, specifies these requirements. In Table 6, the standard deviation of both RAP materials used in the sieve analysis and the maximum standard deviation allowed are displayed. It has to be noted that in the sieve analysis, only four samples are used instead of the required five. Furthermore, the standard deviations are compared to the standard deviation of a recycling percentage larger than 50 %.

Through sieve	Standard deviations		
	Maximum	AC-Surf	SMA-11
11.2 mm	5.5	1.51	3.02
5.6 mm	4.5	2.21	1.45
2 mm	3.5	1.52	0.72
0.063 mm	0.8	-	-

Table 6: Required homogeneity of RAP material to be used in new asphalt mixes and homogeneity of AC-Surf and SMA-NL 11 tested in the sieve analysis, expressed in standard deviation.

From this table, it can be concluded that the standard deviation of the both RAP materials are within the maximum allowed limits. This conclusion can not be made for the sieve of aperture 0.063 mm, because it was not incorporated in the sieve analysis.

5.4 Bridging the quality gap

As mentioned in subsubsection 2.2.1, CIR can be performed in two ways: with a single-unit recycling train or a multi-unit recycling train. In subsection 5.3, it was concluded that with the a standard cold milling procedure, the RAP material is too coarse graded. In this section, methods for improving the RAP gradation characteristics for both of the CIR methods will be discussed. Additionally, hypothetical solutions that are purely based on theory are discussed.

5.4.1 Single-unit train: Adjusting milling operating parameters

One of the ways to influence the properties of RAP in a single-unit CIR operation, is to change the milling parameters and the milling machine configuration. As briefly discussed in subsubsection 5.1.1, parameters that could be changed during the process of milling are the travel speed, rotational speed of the milling drum, milling depth, water injection and conveyor speed. These parameters can influence the properties of RAP material after a milling procedure. However, the most researched and prominent parameters are the travel speed of the milling machine, the rotational speed of the milling drum and the milling depth. Another influential operating parameter is the drum configuration, expressed in cutting motion and pick spacing.

Travel speed

The travel speed of the milling machine has a significant influence on the gradation properties of RAP. Yao et al., 2024 found that milling at a lower travel speed significantly reduces the gradation of RAP material (Figure B.5). Additionally, Yang et al., 2021, reported comparable findings in a similar study (Figure B.6). In both studies, the milling procedure was performed at three different travel speeds: 10 m/min, 14 m/min and 18 m/min. For all these travel speeds, the clustering rate of the RAP material was calculated using different evaluation methods.

Yao et al., 2024, used the grader-retained percentage method, Modulus of fineness method, the fineness degree method, the loss percentage method and the grading curve area difference method. All these evaluation methods indicated that a lower travel speed results in a lower RAP particle gradation. Yang et al., 2021, evaluated the phenomena using the grader-retained percentage method and reported similar results. The clustering rate of the RAP material from the AC-13 pavement was 30% at 10m/min, while 18 m/min yielded a clustering rate of 50%. The RAP material from the AC-16 pavement, however the differences were lower between the travel speeds.

Zaumanis et al., 2021, used the grading-curve area difference method to characterize the clustering of RAP. The findings support the findings from Yao et al., 2024 and Yang et al., 2021 and suggests that reducing travel speed also reduces the clustering rate. The dataset obtained from the experiments can be publicly accessed. This dataset also includes the black grading curves (without binder extraction), which can be used to analyze the impact of the operating parameters of the milling operation on the grading curve of the RAP material. In this analysis, the different configurations of the milling operation for each milling site were compared. For this, the grading curve data of the different configurations for each milling site, is plotted in a graph. These graphs are displayed in Figure D.1. In these graphs, it can be seen that the grading curves of the configuration with the lowest travel speed generally has the finer graded grading curve. Collectively, these results all indicate that milling at a lower travel speed can significantly reduce the RAP particle gradation. This might be explained by the fact that if the milling machine moves slower, the number of impacts of the milling picks on the same surface area increases.

Milling drum rotational speed

Similar to the travel speed of the milling machine, the rotational speed of the milling drum can also influence the gradation of RAP material. However, the correlation between the rotational speed of the milling drum and the gradation properties of the RAP material is opposite compared to the travel speed. If the rotational speed of the milling drum increases, the gradation of the RAP material is generally higher, meaning that the material becomes finer graded (Song et al., 2024). This might be explained by the fact that the number of contacts of the milling picks with the asphalt layer in the same surface area increases.

In contrast, Zaumanis et al., 2021, concluded that the rotational speed of the milling drum did not significantly influence the gradation properties of the RAP material. However, in this study, the differences in rotational speeds that were tested were approximately -11.0% and +16.5% from a base value of 109 rounds per minute. On the other hand, Song et al., 2024, tested differences of -40% and +40%, from a base value of 150 rounds per minute. This suggests that a relatively larger change in rotational speed is needed to significantly to influence the RAP material gradation. However, Yao et al., 2024 tested different rotational speeds with a deviation of approximately -33% and +33% from a base value of 75 rounds per minute, of which it was concluded that the rotational speed did not significantly influence the RAP gradation. Based on this information, it is unclear whether the rotational speed of the milling drum has a significant influence on the RAP gradation.

Milling depth

Apart from the speed parameters, the milling depth also influences the gradation of RAP material. A higher milling depth generally leads to a higher clustering ratio, and therefore a coarser graded RAP material. Yao et al., 2024, found that an increase of milling depth from 40 mm to 60- and 80 mm, led to a reduction of 39.1% and 50.4% in parallel bonding keys broken between particles. If more parallel bonding keys are broken, the clustering rate will be reduced and will therefore lead to a finer graded material. This indicates that a smaller milling depth leads to a lower clustering ratio and a finer graded RAP material.

Milling drum configuration

In addition to the operating parameters, the configuration of a milling machine can also be changed. Especially the configuration of the milling drum has an impact on RAP gradation characteristics. The main changes in configuration of the milling drum relate to the cutting direction and the distance between picks on the cutting drum.

A conventional milling operation operates with a milling drum milling in an up-cutting motion. However, in single-unit CIR trains, milling drums of the milling machines are configured to cut in a down-cutting motion. This gives the milling machine operator more control over the RAP size by adjusting the forward moving speed (Cross & Jakatimath, 2007). This means that this option is most effective when combined with changes in milling parameters.

Additionally, decreasing the distance between picks on the milling drum results in finer graded RAP material (Lombardo, 2022). This can be explained by the fact that more picks will lead to more impacts with the asphalt pavement. As a result, the milled material will experience more impacts, thus is more likely to de-agglomerate. As discussed in subsection 5.1, Wirtgen offers a range of milling drums differentiating between width and distance between milling picks. Apart from Wirtgen, most other milling machine manufacturers also offer a range of different milling drums. The specific effects of pick spacing has not been studied.

5.4.2 Multi-unit Train: Mobile crushers

In multi-unit CIR trains, mobile crushing and screening units are added to improve the gradation characteristics of RAP material. These mobile units can crush RAP material to a desired top size, which depends on the target asphalt mixture. The machine operates in a closed-loop system where the material is continuously processed until it meets the required top size. If the material has reached the required top size, it passes through a screening unit and is transferred into a pugmill. This technique can effectively separate clustered RAP particles, which is the main problem as discussed in subsection 5.3. This makes crushing and screening units an effective technique for ensuring that RAP material suffices to the gradation requirements of surface courses (Cross & Jakatimath, 2007).

Roadtec, a subsidiary of Astec Industries, offers such a crushing and screening unit, which is displayed in Figure 10. The RT-500 Cold-in-Place Recycle trailer is equipped with a screener that processes the material fed into its hopper. All materials that do not pass through the screener are transported to a crushing chamber where the material is crushed and transported back to the screener. The material passing the screening unit is transported to a pugmill mixer, which mixes the RAP material with foaming bitumen to form a new asphalt mixture (Roadtec, n.d.).

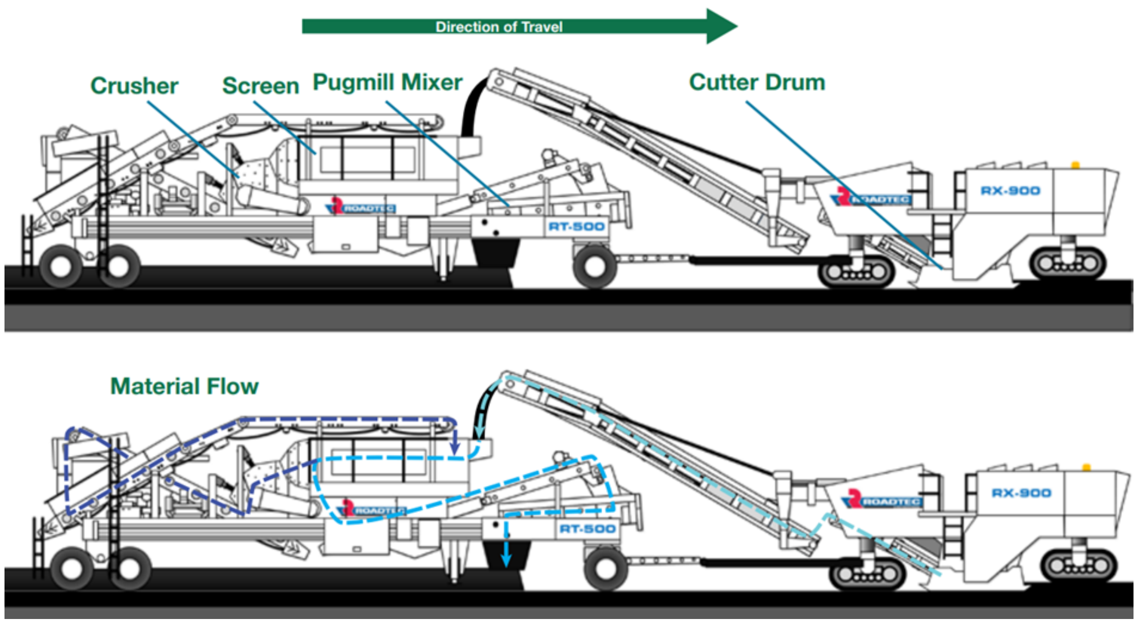


Figure 10: RT-500 Cold-in-Place recycling trailer (Roadtec, n.d.)

5.4.3 Hypothetical solutions

In this section, other solutions that are purely based on theory are discussed. This implies that these solutions have not yet been applied to asphalt pavement reclamation.

Ultrasonic vibration treatment

In the oil industry, extensive research has been done to reduce the viscosity of heavy oils, including asphalt. Viscosity can be defined as a fluid's resistance to flow, which in the case of bitumen is relatively high. If this viscosity is reduced, the bitumen will exhibit more fluid type properties. In a study performed by Galimzyanova et al., 2024, mixtures of bitumen and oil were subjected to ultrasonic vibrations of 22 kHz for different time intervals. In this study, it was found that subjecting these mixtures to ultrasonic vibrations can reduce the viscosity. Oil sample AKB-6, consisting of 40 % mass fraction of bitumen and 60 % mass fraction of oil, displayed a viscosity reduction rate of approximately -17 %, -29% and -30 % after a treatment time of 1, 2 and 3 minutes respectively. Wang et al., 2022 performed a similar study where they subjected a 90# petroleum matrix asphalt to different ultrasonic frequencies (40 kHz, 28 kHz, 55 kHz) at different temperatures ranging from $90 - 150\,°C$. In this study, they defined three ultrasound stages, being ultrasound preparation stage (0-300 seconds), ultrasonic irradation stage (300-900 seconds) and the viscosity recovery stage (900+ seconds). At the end of the ultrasonic irradation stage, maximum viscosity decrease is achieved. This applied to all applied frequencies, while a ultrasonic frequency of 40 kHz resulted in the biggest reduction.

A limitation for this solution is that it has only been tested in laboratory setting. Additionally, neither of the studies were performed on pure bitumen at a normal temperature range (ambient conditions). It is therefore unclear if the same effect will be achieved if applied to asphalt pavement or RAP material, as this material is in a solid state. However, if the same effect will be achieved, ultrasonic transducers can be integrated in a cold recyclers mixing chamber. If this can be successfully applied, the bitumen on the RAP material will likely become less viscous. As a result, clustered RAP particles can be separated during the mixing procedure.

Steam induced asphalt-aggregate segregation

Another possible hypothetical solution could be steam induced asphalt-aggregate segregation. One of the primary causes of asphalt pavement deterioration is water damage. Water damage can occur in the presence of liquid or gaseous water and can occur in the form of stripping, loosening, raveling, and water erosion (Sun et al., 2024). In essence, this is caused by a decrease in adhesion between asphalt and aggregates. Tu et al., 2022 performed a study to determine the effect of different concentrations of water vapor on the surface energy of both asphalt and aggregates. The lower the surface energy, the lower the adhesion between asphalt and aggregates. In this study, it was found that exposure to water vapor of different concentrations and different exposure times had no significant effect on the surface energy of asphalt. On the other hand, it did have a significant effect on the surface energy of aggregates, indicating that exposure to water vapor can lower the adhesion between asphalt and aggregates.

While water vapor is not the same as steam, both are gaseous forms of water. The difference lies in the temperature, which is much higher with steam. This adds the effect of heat, which reduces the viscosity of bitumen (Galimzyanova et al., 2024). Both the effects of a decrease in adhesion between asphalt and aggregates and viscosity of bitumen could result in a better graded RAP material, exhibiting a lower clustering rate. However, the effect of steam has not been tested on asphalt pavements. It is therefore unknown how effective the measure could be in reducing the clustering of RAP. Additionally, creating steam requires a significant amount energy, which could make it economically and environmentally infeasible.

5.4.4 Assessment of options

From the solutions mentioned in the previous sections, the solutions discussed in subsubsection 5.4.3 can currently not be applied due to the several limitations mentioned. On the other hand, the other two solutions could be viable options for ensuring the RAP gradation characteristics are close to or within the boundaries of applicability. However, each of the solutions have advantages and disadvantages. The first solution, changing the milling parameters and drum configuration, is easy to implement. The milling parameters can be precisely monitored and regulated using the “Mill Assist” function, while the different drum configurations can be provided by Wirtgen. Furthermore, since no additional equipment will be added to the recycling train, the recycling train will be relatively more maneuverable. Lastly, the initial investment costs will be relatively low as no additional equipment is needed. However, a lower travel speed will result in a lower productivity. A lower travel speed will also result in more impacts per meter. A smaller pick spacing will increase the number of picks, thus the number of picks requiring maintenance will also increase. Both of these aspects could result in a higher wearing rate of the picks.

On the other hand, with the use of a mobile crusher, these negative effects will not be experienced. Furthermore, the maximum RAP particle size can be more precisely controlled in comparison with the other solution. However, the addition of this piece of equipment will result in a larger recycling train, leading to a reduction in maneuverability. This limits the applicability of the solution, as it can not be applied to smaller roads. Furthermore, an extra piece of equipment will require initial investment costs.

Apart from the advantages and disadvantages of both options, the expert opinions indicated that the solution of changing the operation parameters and drum configuration would be the better option. This can be attributed to the fact that the mobile crushing machinery is not yet available in the Netherlands. Therefore, the first solution will be further elaborated upon in the remaining part of this report.

5.4.5 Scenario development

In order to evaluate the effectiveness of the proposed solution, some possible scenarios will be tested. These scenarios are based on the influence of different combinations of values for the travel speed and distance between picks on the milling drum. As discussed in subsubsection 5.4.1, it is unclear whether the rotational speed of the milling drum has a significant influence on the RAP gradation. It is therefore excluded as a parameter in the scenarios and is assumed to be a constant value of 100 rounds per minute. Although the milling depth has a significant influence on the gradation of RAP material, it will not be accounted for in this scenario analysis. This can be explained by the fact that the RAP material on which this analysis is based, originates from a 40 mm thick surface course. In the Netherlands, the minimum recommended thickness for AC surf courses is 30 mm for AC-11 and 40 mm for AC-16 (Rijkswaterstaat, 2022). This means that a reduction in milling depth is not feasible as it is already at the lower range in this scenario analysis. Both the values for the rotational speed and the milling depth are based on the values used by Yao et al., 2024 and Yang et al., 2021, on which the effect of the travel speed parameter is based. In these studies, AC-16 Surf and AC-13 Surf mixes were analyzed, which is why in the scenario calculation, only these two mixes will be used. For this, the AC-13 Surf mix roughly corresponds with an AC-11 Surf mix and will therefore be compared to the AC-11 Surf regulations. This means that the AC-8 Surf, SMA-NL 11 and SMA-NL 8 will be excluded from the impact analysis

A CIR project has a minimum productivity for it to be a profitable operation compared to other rehabilitation operations. With this minimum productivity, the lower boundary value for the travel speed can be computed. This can be done using Equation 1.

$$P = W \times S \times 60 \tag{1}$$

Where:

- P: Productivity in m^2/hour
- W: Milling width in meters (m)
- S: Forward moving travel speed in m/min

In this equation, the values of W are based on the width of the milling drum, whose values were discussed earlier. According to expert 1 (Table A.1), the minimum productivity for a CIR operation to be profitable is approximately 1000 m^2/hour. Based on this value and the values for the width (W), the travel speed (S) can be computed for all scenarios.

In order to compute the grading curves of the different proposed scenarios, it is necessary to determine the influence of both parameters on the RAP gradation. For both parameters, a different method was applied. The influence of the travel speed parameter was determined mathematically, while the influence of the pick spacing parameter was based on expert consultation. As discussed in subsubsection 5.1.2, both Yao et al., 2024 and Yang et al., 2021 constructed grading curves of RAP gathered from a milling operation under three different travel speeds: 10 m/min, 14 m/min and 18 m/min. Based on these values, a gradient was calculated for each sieve size, which is displayed in Table D.1 and Table D.2. Based on this gradient, the grading curves of RAP material gathered at a lower travel speed, were extrapolated. This method relies on the assumption that the change in grading curves resulting from the change in travel speed is a linear relationship.

As discussed in subsubsection 5.1.1, equipment manufacturer Wirtgen has two cold recyclers available, the W240 CRi and the W380 CRi. With these machines there is a distiction between, among others, the width of the milling drum. The W240 CRi is equipped with a 2.35 meter (198 picks) wide milling drum, while the W380 CRi has four options for the milling drum width: a 3.2 meter (239 picks), a 3.5 meter (258 picks) and two different 3.8 meter (277 picks & 294 picks) wide drums (WIRTGEN, n.d.-b). All these milling drums have a slightly different pick spacing. Therefore, the values for the pick spacing parameter will be based on the different milling drum configurations. Specifically, it will be calculated by dividing the width of the milling drum by the number of picks. As briefly discussed in subsubsection 5.4.1, the specific effect of pick spacing is not known, which is why it is approximated in an expert consultation session. Furthermore, due to this uncertainty in effect, two possible effect scenarios per parameter combination will be explored. In this session, it was determined that the first scenario (W240 CR(i) FB2350 198), with a pick spacing of approximately 11.87 mm, will experience an improvement of 10% and 20%. The improvements for the other scenarios are relative to the first scenario. In this method, a base case of a pick spacing of 15 mm was used to calculate the relative improvements. In Table 7, all scenarios including information about the configuration of the milling machine, travel speed, pick spacing, and the effect of the pick spacing are displayed.

Scenario	1	2	3	4	5	6	7	8	9	10
Cold Recycler	W 240 CR(i)	W 240 CR(i)	W 380 CR(i)	W 380 CR(i)	W 380 CR(i)	W 380 CR(i)	W 380 CR(i)	W 380 CR(i)	W 380 CR(i)	W 380 CR(i)
Drum Configuration	FB235 0 198	FB235 0 198	FB320 0 239	FB3200 239	FB350 0 258	FB3500 258	FB380 0 277	FB380 0 277	FB380 0 294	FB380 0 294
Drum width(m)	2.35	2.35	3.2	3.2	3.5	3.5	3.8	3.8	3.8	3.8
speed (m/min)	7.09	7.09	5.21	5.21	4.76	4.76	4.4	4.4	4.4	4.4
Spacing (mm)	11.87	11.87	13.39	13.39	13.57	13.57	13.72	13.72	12.93	12.93
Effect of pick spacing (%)	**10%**	**20%**	**5.2%**	**10.3%**	**4.6%**	**9.2%**	**4.1%**	**8.2%**	**6.6%**	**13.3%**
Productivity (m^2/h)	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**	**1000**
Maintenance (# number of picks)	198	198	239	239	257	258	277	277	294	294

Table 7: Analyzed scenarios based on different values for parameters

In this table, the effect of pick spacing and the productivity can be changed. Productivity is directly related to travel speed through Equation 1. As discussed, the initial grading curves are based on the studies of Yao et al., 2024 and Yang et al., 2021. In these studies, a sieve set different than the set used in the Netherlands is utilized. To make a comparison between the improved grading curves and the regulations, the results were linearly interpolated.

5.4.6 Calculation and assessment

As discussed in the previous section, 10 different scenarios were explored. The combination of the travel speed and pick spacing parameters resulted in different improved grading curves. Similar to Figure 8 and Figure 9, these grading curves are plotted in graphs together with the gradation requirements of the different asphalt mix types (Appendix D). In Figure D.2 and Figure D.3 , it can be seen that the grading curves of the majority of scenarios lie within the gradation requirements for AC-16 Surf mixes. However in scenario 3, 5 and 7, the percentage passing the 22.4 mm sieve is 99% instead of the required 100%. Overall, this indicates that, if the assumptions used are correct, the parameter values should be sufficient to bridge the quality gap in the majority of scenarios.

Similarly, the grading curves of the scenarios of the AC-11 mixes do not all lie within the gradation requirements for AC-11 Surf mixes (Figure D.5 & Figure D.4). This specifically applies to scenario 1, 3, 5 and 7. In these scenarios, the percentages passing the 16 mm and 11.2 mm sieves are lower than the requirements. This means that with the used parameter values, clustering of RAP particles is still a problem. In these cases, AC-11 Surf mixes can be rehabilitated into an AC-16 Surf mix. By doing this, the gradations are in accordance with the regulations.

5.5 CIR treatment requirements

An important factor in the effectiveness of a CIR treatment using the techniques described and evaluated in the previous section, is project selection. CIR is not universally applicable, but it can be highly effective in specific situations. As Stephen. A. Cross notes, "CIR treatments are a tool in the toolbox and it does not work everywhere, but in some cases it works exceedingly well" (Cross, n.d.). In this section, the project selection guidelines will be outlined. This includes important factors such as pavement distress, climatic conditions and geometrical properties. In the end, a flowchart will constructed and visualized.

5.5.1 Important factors

Pavement condition and composition

One of the most important considerations when evaluating whether CIR can be applied, is the condition of the original pavement. Cracked pavements of which the bases and subbases are structurally sound and well-drained are generally eligible for CIR treatment. However, pavements exhibiting the following failure mechanisms are less successful when rehabilitated with a CIR treatment (Modarres et al., 2014):

- Rutted pavements caused by too high asphalt content
- Failure cause by wet, unstable base, subbase or subgrade
- Failure caused by heaving or swelling occurring in underlying soils
- Pavements that exhibit stripping of the asphalt from the aggregates

Furthermore, pavements with rutting caused by deep structural issues are not eligible for CIR treatment. Additionally, deformations in the form of shoulder drop off should not be rehabilitated with CIR, while deformation in the form of shoving could be rehabilitated with CIR if additives are used (Federal Highway Administration, 2018). When CIR is applied to pavements with severe deterioration, the service life of the pavement is expected to significantly decrease.

On the other hand, pavements with surface defects including bleeding, potholes, raveling and skid resistance are qualified for CIR. Furthermore, pavements with deformations in the form of corrugations and rutting caused by wear are also eligible for CIR treatment. If rutting occurs due to mix instability, it can be applied if it is corrected with additives. CIR can also be applied to all pavements with non-load associated cracking. Furthermore, pavements with rutting caused by deep structural issues are not eligible for CIR treatment.

Apart from the state of the pavement, the composition is also of importance. In particular, the presence of foreign matter in the RAP material. Paragraph 02 of the CROW Standaard RAW bepalingen 2020 states that the content of foreign matter, impurities and cold asphalt prepared with liquid bitumen in RAP for binder- and surface courses must comply with category F1 (NEN-EN 13108-8). If this condition is not met, applying CIR rehabilitation treatment is not possible without extraction of these materials from the obtained RAP material.

Another requirement for applying CIR treatment to a surface course is that the composition of the original pavement must be consistent or at least divided in consistent sections. If this is not the case, the calculations for the mix design will be wrong for sections that deviate from the sections for which the calculations were made. These differences can be in terms of water content, asphalt content and aggregate gradations.

Climatic conditions

In most cases, the climatic conditions do not significantly influence the expected service life of a CIR rehabilitated pavement (Chesner et al., 2011). However, the minimum temperature for recycling method utilizing bitumen emulsion or foam bitumen is 10 °C. Furthermore, in wet conditions, it is recommended to not use foam bitumen. Instead, bitumen emulsion is proven to be more successful, because it is a water-based binder. On the other hand, foam bitumen is a hot mixture, which cools down on wet surfaces. This results in poor bonding compared to bitumen emulsion (Modarres et al., 2014).

Geometrical properties

Another factor influencing the applicability of CIR treatments are the geometrical properties of the pavement. One of such properties is the thickness of the pavement. Pavements constructed with a thicker base, base plus subbase, and total pavement thickness exhibited longer CIR treatment service lives (Chesner et al., 2011). Furthermore, the total thickness of the asphalt layers should be between 15-25 cm. In addition, the minimum asphalt pavement thickness to be cold recycled should be approximately 5 cm (Modarres et al., 2014). Not only technical considerations need to be considered for this aspect, but also the economic aspects. In particular, the size of the project is of importance for this. According to Modarres et al., 2014, projects of a total size of 40.000 m^2 or more are economically more beneficial. This can be explained by the fact that CIR operations require a relatively high setup cost, which is spread out more per area unit on larger projects.

5.5.2 Project selection flowchart

Based on the information of important factors that play a role in CIR project selection, a flowchart was constructed (Figure E.1). In this flowchart, project size is not taken into account as this is to be evaluated by the contractor based on economic and environmental feasibility. Furthermore, wet conditions are also excluded since the binder agent of choice is different for different contractors. The flowchart first goes through the climatic conditions and geometrical properties. If these requirements are met, the condition of the pavement will be evaluated. First, the presence of foreign matter has to be evaluated, after which the flowchart moves on to the condition of the base and subbase layers. If these conditions are sufficient, the state of the pavement regarding failure mechanisms, will be evaluated. If there are only surface defects and/or non-load associated cracking, CIR is recommended. However, if there are other failure mechanisms, CIR applicability can be further evaluated with the remaining part of the flowchart.

6 Discussion

In this section, the limitations of the methods used and results obtained during the execution of this study, will be discussed.

6.1 Limitations in the methodology

The first limitation with respect to the methodology arises in determining the current RAP gradation characteristics. First of all, the RAP material from both the literature review and the sieve analysis was obtained from standard cold milling procedures. These procedures do not entirely reflect the cold milling procedure performed in a CIR operation. Additionally, the conditions during which the RAP material was obtained is unknown for some of the sources. Both limitations result in the analyzed RAP material not reflecting the actual situation completely accurate. More representative results would have been obtained if RAP material was obtained from a controlled experiment using a cold recycler. In this way, the effects of operating parameters such as travel speed and drum rotational speed could have been measured, which would likely yield a more accurate result. However, due to limited availability of such machines in the Netherlands, this was not possible. In addition, this study was executed in a period of the year when cold milling is not performed. Consequently, obtaining RAP material in an experimental setting was not feasible.

In the execution of the sieve analysis, it was calculated that the laboratory sample was to be divided into four subsamples. However, for the determination of the homogeneity of RAP material, five samples are required according to section 81.26.11 of the CROW Standaard RAW bepalingen 2020 (CROW, 2020). Although this might not have a big impact, it is not in accordance with the regulations. Another possible limitation of the sieve analysis is the fact that it was executed using a manual sieving-shaking procedure. With this, it is possible that material that would normally pass a specific sieve, is now retained on that sieve. Additionally, due to overloading, the subsamples had to be sieved in parts. This caused some spillage of RAP material. Both factors have an effect on the results obtained from the sieve analysis.

In this study, the expertise of only one expert was utilized. Although this was a highly experienced expert, more expert interviews could have been conducted. The input from other experts could have provided different views on the cold milling process and equipment, influential milling parameters and specific values for these parameters, and more innovative techniques to improve RAP gradation characteristics.

In the impact analysis, the effect of the travel speed and pick spacing on the RAP gradation are compounded. This means that the effect applied on the gradations is slightly higher than what it should be. However, since the effects applied are relatively low, this difference should be minimal.

6.2 Limitations in the results

As a result of the fact that the impact analysis relies heavily on assumptions, the gradations obtained in the different scenarios might not be accurate representations of what would be obtained in reality. If the assumptions appear to be inaccurate, the results obtained from the impact analysis are also inaccurate. However, if representative values for these assumptions are found, a similar methodology can be applied to determine the RAP gradation in different scenarios. Apart from that, the impact analysis is also only performed on the AC-11 Surf and AC-16 Surf material, while the AC-8 Surf, SMA-NL 5 SMA-NL 8 and SMA-NL 11 are excluded. This reduces the completeness of the results. Lastly, the initial RAP gradation on which the impact analysis was applied originated from studies performed by Yao et al., 2024 and Yang et al., 2021. In these studies, the grading curves of the RAP material were constructed with a different sieve set than the one used in the Netherlands. In order to make a comparison between the gradations obtained through the impact analysis and the regulations, the results from the impact analysis had to be interpolated. This possibly has an effect on the results.

Another limitation arises in defining the quality gap. In this part of the study, the RAP material analyzed in the sieve analysis was compared to the regulations. However, in the sieve analysis, only RAP material originating from AC Surf and SMA-NL 11 pavements were analyzed. As a consequence, a direct comparison between RAP material gradation and regulations for the specific AC Surf mixes and the SMA-NL 5 & SMA-NL 8 mix types was not possible. However, in subsection 5.3, this comparison is made, which makes it less accurate.

The requirements for an asphalt pavement to be eligible for rehabilitation using CIR, defined in subsection 5.5, are based on literature about sub-surface (binder and base) courses. However, this study focuses on the surface course.

7 Conclusion

In this section, conclusions will be drawn based on the results of the study. This is done by answering the sub-research questions, followed by the main research question.

- *What equipment and processes are currently used in cold milling, and how do they impact RAP gradation characteristics?*

In the Netherlands, asphalt milling contractors mostly use Wirtgen equipment. In the case of CIR either large cold milling machines or cold recyclers are used. The key technologies of these machines are the cutting technology, the machine control technology and the leveling technology. All of these factors play a significant role in the control of RAP gradation. The cold milling machines are normally equipped with a milling drum with a 18 mm pick spacing. In the new generation of these machines, the "F-series", a feature called "Mill Assist" is available. With this feature, milling parameters can be controlled to improve the milling process based on chosen objectives. In the current cold milling process, the objectives are the smoothness and uniformity of the remaining (underlying) layer after cold milling and the productivity of the operation in terms of surface area milled in a certain time period.

Based on the results obtained from the sieve analysis and the systematic literature study, it can be concluded that grading curves for AC Surf RAP material generally followed similar trajectories. For SMA RAP material, this conclusion cannot be made with the same certainty as only one source in the literature study provided a grading curve for SMA RAP material. Despite this, it can be said that for both RAP materials, clustering of aggregates and bitumen was present. This can be explained by the fact that material with a coarser gradation than the original mixture was present. According to Yao et al., 2024 and Yang et al., 2021, the RAP material also showed signs of aggregate breakage, as the percentage of filler and fine aggregates after bitumen and aggregate separation increased.

- *What are the specific gradation requirements for RAP used in surface course material, and how do current RAP characteristics compare?*

In this study, only AC Surf (AC-8, AC-11 & AC-16) and SMA-NL (SMA-NL 8A&B & SMA-NL 11A&B) are analyzed . The gradation requirements of RAP are evaluated based on the requirements defined in NEN-EN 13108-1 (AC) and NEN-EN 13108-5 (SMA) and the CROW Standaard RAW Bepalingen 2020. According to these regulations, both the general grading requirements and the homogeneity of RAP material is of importance for the application to surface courses. In the regulations, the grading boundaries of every asphalt mixture type is based on four sieve sizes.

When compared to the regulations, the RAP gradation determined by answering the first sub research question is too coarse graded. In Figure 8 (AC) and Figure 9 (SMA), it can be seen that the grading curves for both asphalt mix types lies outside the boundaries according to the regulations. Due to stricter boundaries, the difference between the grading curve of the SMA RAP material and the regulations is larger compared to the AC RAP material. Apart from the general grading requirements, the homogeneity of the RAP analyzed in the sieve analysis was within the allowed limit, suggesting that this is not a problem.

- *What new techniques are available that can improve the gradation characteristics of RAP and what impact do these techniques have on meeting the required gradation standards for surface courses?*

CIR operations are executed either with a single-unit recycling train or a multi-unit recycling train. In the single-unit recycling train the quality of the RAP material relies on the parameters travel speed and pick spacing, while the effect of drum rotational speed is uncertain. In multi-unit recycling trains, a mobile crusher is added to ensure RAP meets the required gradation. Apart from this, two other techniques have been identified: Ultrasonic vibrations and steam induced asphalt-aggregate segregation. However, both of these techniques have not been tested and developed sufficiently to be applied in the field. Of the other two options, controlling the operating parameters and the drum configuration appeared to be the better option due to availability of equipment and expert opinion. Decreasing the travel speed and reducing the pick spacing leads to a finer graded RAP material. However, these parameters should be carefully monitored to ensure that RAP breakage is not excessive. In the impact analysis, scenarios with different parameter values were tested on their impact to the gradation of RAP material. Based on this impact analysis, it can be said that all scenarios resulted in a RAP material gradation within the gradation requirements for the AC-16 Surf RAP material. For the AC-11 Surf RAP material, the scenarios with the lower value for the pick spacing effect also resulted into the RAP grading curves being within the gradation requirements. This suggests that based on the assumptions, changing the operating parameters and the milling drum configuration could be an effective way of ensuring that RAP material is properly graded to be used in a CMA for surface courses.

- *What factors should be considered to determine if a specific surface course is eligible for CIR?*

Based on literature, important factors to consider when evaluating whether application of CIR as a rehabilitation practice is an effective measure, are pavement condition and composition, climatic conditions and geometrical properties. Regarding pavement condition and composition, pavements with structurally sound and well-drained bases and subbases are generally eligible for CIR. In terms of climatic conditions, taking moisture and temperature into consideration is of importance. In the design of an asphalt mixture, the moisture index is taken into account, which is why it is important that this index is in line with the design index. Additionally, the use of foam bitumen is not recommended in wet conditions because it cools down when in contact with the wet aggregate surfaces. Apart from this, the recommended minimum temperature is 10 °C. Lastly, the geometrical properties, pavement thickness and project size, are also of importance. For this, the pavement thickness is related to the performance of a CIR layer, as thicker bases plus subbases result in longer CIR treatment service lives. The project size is related to the economic feasibility.

How can advancements in cold milling processes and equipment improve the gradation characteristics of RAP to meet the requirements of surface course materials?

By getting a better understanding of influential factors during the milling process, the gradation characteristics of RAP material can be improved. In this study, it was found that reducing the travel speed of the milling machine and decreasing the pick spacing on the milling drum can effectively reduce the clustering of RAP. As a result, the gradation of AC-11 Surf and AC-16 Surf RAP material was found to be in accordance with the regulations in the majority of the explored scenarios. Innovative technologies, such as the "mill assist" feature on modern Wirtgen cold milling machines can help optimize these influential factors. Additionally, mobile crushing & screening units, used in multi-unit recycling trains, can be used to control the maximum aggregate size more precisely. However, this technology is not yet available in the Netherlands.

8 Recommendations

In this section, the final recommendations will be given to NTP, asphalt milling and paving companies, and milling machine manufacturers. Additionally, recommendations for further research are given.

8.1 Recommendations to NTP, asphalt milling and paving companies, and milling machine manufacturers

This study serves as a starting point to achieving the desired result of creating a CIR process that can be applied to surface courses. The results can be used to get a better understanding of the influence of the cold milling process and equipment on the gradation of RAP material. During the CIR operation, it is best to use a cold recycler with the lowest pick spacing from a RAP material quality perspective. On top of that, it is best to keep the travel speed as low as possible, while still operating with sufficient productivity. According to expert 1, the minimum productivity for a CIR operation to be economically and environmentally profitable is approximately 1000 $m^2/hour$.

CIR is most suitable for pavements with stable, well-drained bases and subbases whose surface defects are not in the form of: rutting caused by too high asphalt content, stripping of asphalt from aggregates and shoulder drop-off. Furthermore, it is important that the presence of foreign matter is in accordance with NEN-EN 13108-8 and must comply with category F1. It is also important that composition of the original surface course is consistent. Apart from that, the minimum ambient temperature for CIR using foam bitumen or bitumen emulsion is 10 °C, while it is recommended to not use foam bitumen in wet conditions.

Notwithstanding, an attempt should be made by milling machine manufacturers, especially Wirtgen, to integrate a mobile crusher into the recycling train as this allows for the gradation of RAP material to be controlled more accurately. Another option would be to try to get the RT-500 Cold-in-Place recycling trailer from Roadtec to the Netherlands to test it's feasibility for implementation.

8.2 Recommendations for further research

Effect of the milling parameters and drum configuration

In this study, the effects of the milling parameters and the drum configuration are heavily based on assumptions. To improve the accuracy of the results, the effect of the milling parameters and the drum configuration on the gradation characteristics must be determined. This can be done either in an experimental setting or by creating a simulation of the milling process.

In an experimental setting, different variations of milling parameters and drum configurations can be explored. For this, it is important to keep the conditions regarding pavement composition, milling depth, temperature, moisture index consistent. Apart from that, the effect of the milling parameters can also be evaluated using simulations. Currently, several

Discrete Element Method (DEM) simulations regarding the influence of operating parameters and milling drum configuration on asphalt pavement during the milling process, have been constructed (Song et al., 2024), (Petrescu et al., 2024), (Dumitru et al., 2022). However, these DEM simulations do not directly relate these parameters to the RAP material gradation. In most instances, the influence of these parameters is expressed in terms of the impact force or, in certain cases, the particle bonding ratio (PBR), which represents the proportion of particles that remain bonded to one another. These metrics do relate to the gradation of RAP material and can therefore possibly be used to determine the influence of operating parameters on RAP gradation. If a relationship between these metrics and RAP gradation can be derived, the effect of operating parameters and drum configuration could potentially be effectively simulated.

These methods can also be used together by first determining the effect of a selective set of parameter values. These effects can then be used to construct relationships between the parameters and the RAP gradation. Ultimately, this relationship can be used to explore parameter values outside the initial set. These simulations can be performed with multiple different software applications, such as EDEM (Altair Engineering, 2023) and PFC (Itasca Consulting Group, 2023). Yao et al., 2024 used PFC software in which they first modeled the asphalt mixture by specifying a particle size distribution and using a contact bonding model to simulate the bonds between asphalt mortar and aggregates. This contact bonding model is based on a list of fixed parameters. Secondly, the actual milling process can be modeled by first creating a 3D solid model of a milling pick and importing this into PFC for the simulation analysis. To simulate the crushing effect of the milling process on the aggregate, the coarse aggregate units were comprised of smaller aggregates. A similar methodology can be used to construct a DEM model to simulate the impact of milling parameters on the RAP gradation.

Explore different aspects of CMA

This study focused solely on the gradation of RAP material. However, other aspects of the CIR process are also important. With proper compaction techniques, high void ratios, which is a significant problem for cold asphalt mixes designated for surface courses, can be reduced. According to expert 1, foamed bitumen does not coat the RAP material in the same way as new or hot asphalt mixture. With foamed bitumen, small bitumen points are formed on the aggregates and these points need to connect to each other. This results in a significantly lower adhesion of the mixture compared to a hot mix. Ultimately, this means that the mixture is not strong and stiff enough to be used as a surface course. It is therefore important to find a way to increase the adhesion properties of CMA.

Testing the performance properties

Although the grading curves of the majority of the scenarios are within the gradation requirements, the obtained RAP material might still not be of sufficient quality. In order to verify this, CMA with the specific RAP gradations must be constructed to test the performance based on at least the void content (V), Indirect Tensile Strength Ratio (ITSR), the stiffness (S), the creep rate (f_c) and the fatigue resistance (ε_6) (CROW, 2020).

Determining field applicability of hypothetical solutions

Both hypothetical solutions mentioned in subsubsection 5.4.3 can potentially improve the gradation of RAP material by reducing the clustering rate. However, the effect of these solutions has not yet been tested on asphalt pavement or RAP material. Understanding this effect is crucial in determining whether or not they have the potential of being good solutions. Additionally, their field applicability has to be tested.

References

Altair Engineering, I. (2023). Edem: Discrete element modeling software. https://altair.com/edem

BAM. (2024, April). *Bam introduceert techniek om asfalt ter plekke koud te recyclen tot volwaardige deklaag* [Accessed: 2024-06-17]. https://www.bam.com/nl/pers/persberichten/2024/4/bam-introduceert-techniek-om-asfalt-ter-plekke-koud-te-recyclen-tot

Bowers, B. F., Diefenderfer, B. K., & Cross, A. V., S. A.and Nordcbeck. (2022). *Construction of cold central plant recycling and cold in-place recycling of asphalt pavements best practices guide* (tech. rep.). The National Academies of Sciences, Engineering, and Medicine.

Cadar, R. D., Boitor, R. M., & Dragomir, M. L. (2022). An Analysis of Reclaimed Asphalt Pavement from a Single Source—Case Study: A Secondary Road in Romania. *Sustainability*, *14*(12), 1–14. https://ideas.repec.org/a/gam/jsusta/v14y2022i12p7057-d834841.html

Chesner, W. H., Stein, C. W., Justus, H. G., Kearney, E. R., & Cross, S. A. (2011). Evaluation of factors affecting long-term performance of cold in-place recycled pavements in new york state. *Transportation Research Record: Journal of the Transportation Research Board*, *2227*(1), 13–22. https://doi.org/10.3141/2227-02

Cross, S. A. (n.d.). Introduction to cold in-place recycling [Recorded Lecture, Asphalt Recycling & Reclaiming Association]. https://www.youtube.com/watch?v=wsUpHteP_XA&t=47s

Cross, S. A., & Fager, G. A. (n.d.). Fly ash in cold recycled bituminous pavements.

Cross, S. A., & Jakatimath, Y. (2007, December). Evaluation of cold in-place recycling for rehabilitation of transverse cracking on US 412. https://rosap.ntl.bts.gov/view/dot/23099

CROW. (2020). *Standaard raw bepalingen 2020*.

Dumitru, T., Ilincă, C., & Tănase, M. (2022). Influence of technological parameters on the behaviour in operation of the asphalt milling equipment. *IOP Conference Series: Materials Science and Engineering*, *1262*(1), 012018. https://doi.org/10.1088/1757-899X/1262/1/012018

Federal Highway Administration. (2018, February). *Overview of project selection guidelines for cold in-place and cold central plant pavement recycling*. https://www.fhwa.dot.gov/pavement/asphalt/pubs/hif17042.pdf

Galimzyanova, A. R., Gataullin, R. N., Stepanova, Y. S., Marfin, E. A., Khelkhal, M. A., & Vakhin, A. V. (2024). Elucidating the impact of ultrasonic treatment on bituminous oil properties: A comprehensive study of viscosity modification. *Geoenergy Science and Engineering*, *233*, 212487. https://doi.org/https://doi.org/10.1016/j.geoen.2023.212487

Holtz, K., & Eighmy, T. T. (2000). Scanning european advances in the use of recycled materials in highway construction. *Public Roads*.

Ingrassia, L. P., Lu, X., Ferrotti, G., & Canestrari, F. (2019). Renewable materials in bituminous binders and mixtures: Speculative pretext or reliable opportunity? *Resources,* *Conservation and Recycling*, *144*, 209–222. https://doi.org/10.1016/j.resconrec.2019.01.034

Itasca Consulting Group, I. (2023). Pfc: Particle flow code. https://www.itasca.fr/en/software/pfc

Jiang, J., Ni, F., Zheng, J., Han, Y., & Zhao, X. (2020). Improving the high-temperature performance of cold recycled mixtures by polymer-modified asphalt emulsion. *International Journal of Pavement Engineering*, *21*(1), 41–48. https://doi.org/10.1080/10298436.2018.1435882

Jin, D., Ge, D., Chen, S., Che, T., Liu, H., Malburg, L., & You, Z. (2021). Cold in-place recycling asphalt mixtures: Laboratory performance and preliminary m-e design analysis. *Materials*, *14*(8), 2036. https://doi.org/10.3390/ma14082036

Lewis, A. J. N., & Collings, D. C. (1999). Cold in place recycling: A relevant process for road rehabilitation and upgrading. *7th Conference on Asphalt Pavements for Southern Africa, CAPSA (Vol. 29).*

Liu, Z., Sun, L., Zhai, J., & Huang, W. (2022). A review of design methods for cold in-place recycling asphalt mixtures: Design processes, key parameters, and evaluation. *Journal of Cleaner Production*, *370*, 133530. https://doi.org/10.1016/j.jclepro.2022.133530

Lombardo, J. (2022). Milling best practices improve the quality of RAP. *For Construction Pros*. https://www.forconstructionpros.com/asphalt/article/21590915/milling-best-practices-improve-the-quality-of-rap

Milad, A., Babalghaith, A. M., Al-Sabaeei, A. M., Dulaimi, A., Ali, A., Reddy, S. S., Bilema, M., & Yusoff, N. I. M. (2022). A comparative review of hot and warm mix asphalt technologies from environmental and economic perspectives: Towards a sustainable asphalt pavement. *International Journal of Environmental Research and Public Health*, *19*(22), 14863. https://doi.org/10.3390/ijerph192214863

Modarres, A., Rahimzadeh, M., & Zarrabi, M. (2014). Field investigation of pavement rehabilitation utilizing cold in-place recycling. *Resources, Conservation and Recycling*, *83*, 112–120. https://doi.org/10.1016/j.resconrec.2013.12.011

Netherlands Standardization Institute. (2016a). *Bituminous mixtures: Material specifications - part 1: Asphalt concrete* (tech. rep. No. NEN-EN 13108-1). Netherlands Standardization Institute. Delft, Netherlands. https://connect.nen.nl/Standard/Detail/221161?compId=16755&collectionId=0

Netherlands Standardization Institute. (2016b). *Bituminous mixtures: Material specifications - part 5: Stone mastic asphalt* (tech. rep. No. NEN-EN 13108-5). Netherlands Standardization Institute. Delft, Netherlands. https://connect.nen.nl/Standard/Detail/221157?compId=16755&collectionId=0

Petrescu, M. G., Dumitru, T., Laudacescu, E., & Tănase, M. (2024). Experimental investigation and numerical analysis regarding the influence of cutting parameters on the asphalt milling process. *Materials*, *17*(14). https://www.mdpi.com/1996-1944/17/14/3475

Rijkswaterstaat. (2022). *Verificatie geschiktheid wegenbouwmaterialen en - technieken (vgw)* (tech. rep.). Rijkswaterstaat.

Rijkswaterstaat. (2024, June). *Rijkswaterstaat en provincie gelderland starten pilotprogramma met asphalt recycling train* [Accessed: 2024-06-17]. https://www.rijkswaterstaat.nl/

nieuws/archief/2024/06/rijkswaterstaat-en-provincie-gelderland-starten-pilotprogramma-met-asphalt-recycling-train

Ritchie, H., Samborska, V., & Roser, M. (2018). Urbanization; the world population is moving to cities. why is urbanization happening and what are the consequences? *Our World in Data*.

Roadtec. (n.d.). Cold-in-place recycling equipment brochure [Retrieved from http://roadtec.com.ua/images/media/literature-eng/CIR_Equipment_Brochure.pdf].

Sebaaly, P. E., Castro, J., & Hajj, E. (2018). *Development of in-place density method for cold in-place recycling* (tech. rep.). Solaris University Transport Center.

Song, C., Cheng, H., Fan, K., Wu, W., Wang, X., & Li, L. (2024). Influence of operating parameters of a multi-cutter milling rotor on particle size. *Powder Technology*, *438*, 119651. https://doi.org/10.1016/j.powtec.2024.119651

Sun, E., Zhao, Y., & Cai, R. (2024). Characterization of microstructural evolution of asphalt due to water damage using atomic force microscopy. *Construction and Building Materials*, *438*, 137175. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2024.137175

Tu, C., Xi, L., Luo, R., Huang, T., & Luo, J. (2022). Effect of water vapor concentration on adhesion between asphalt and aggregate. *Materials and Structures*, *55*(9). https://doi.org/10.1617/s11527-022-02073-w

Vázquez, V., García-Hoz, A., Terán, F., Gil-Abarca, A., & Paje, S. (2021). Functional characterization of a cold-in place-recycled pavement at different stages of the curing process. *Science of The Total Environment*, *789*, 148065. https://doi.org/10.1016/j.scitotenv.2021.148065

VolkerWessels. (2022, June). *Kws maakt eerste meters met innovatieve koud-asfaltrecyclingtrein* [Accessed: 2024-06-17]. https://www.volkerwessels.com/nl/nieuws/kws-maakt-eerste-meters-met-innovatieve-koud-asfaltrecyclingtrein

Wang, L., Song, Z., & Gong, C. (2022). Power ultrasound on asphalt viscoelastic behavior analysis. *Case Studies in Construction Materials*, *16*, e01012. https://doi.org/https://doi.org/10.1016/j.cscm.2022.e01012

WIRTGEN. (n.d.-a). *Cost-efficient and compact professional machine cold milling machine w 200 f i*. https://www.wirtgen-group.com/binary/full/o229549v77_W200Fi_Brochure_Datasheet_enGB.pdf

WIRTGEN. (n.d.-b). *High-quality cold in-place recycling*. https://www.wirtgen-group.com/binary/full/o296515v77_W240CRW380CRi_BrochureDatasheet_ENGB.pdf

WIRTGEN. (2024). Cold milling | Removal of road pavements | Wirtgen. https://www.wirtgen-group.com/ocs/en-nl/wirtgen/cold-milling-machines-61-c/

WIRTGEN. (n.d.-a). *Efficient removal and granulation of road surfaces* (tech. rep.). WIRTGEN GROUP. https://www.wirtgen-group.com/binary/full/o229466v77_ColdMillingMachines_Brochure_Datasheet_enGB.pdf

WIRTGEN. (n.d.-b). *W240cr/w380cri brochure datasheet* (tech. rep.) (Accessed: January 15, 2025). WIRTGEN GROUP. https://www.wirtgen-group.com/binary/full/o296515v77_W240CRW380CRi_BrochureDatasheet_ENGB.pdf

Xiao, F., Yao, S., Wang, J., Li, X., & Amirkhanian, S. (2018). A literature review on cold recycling technology of asphalt pavement. *Construction and Building Materials*, *180*, 579–604. https://doi.org/10.1016/j.conbuildmat.2018.06.006

Xu, G., Ma, T., Fang, Z., Huang, X., & Zhang, W.-g. (2019). The evaluation method of particle clustering phenomena in rap. *Applied Sciences*. https://api.semanticscholar.org/CorpusID:117316423

Yang, J., Tao, W., Gao, J., Yu, D., Zhou, J., He, L., & Yao, Y. (2021). Measurement of particle agglomeration and aggregate breakdown of reclaimed asphalt pavement. *Construction and Building Materials*, *296*, 123681. https://doi.org/10.1016/j.conbuildmat.2021.123681

Yao, Y., Yang, J., Gao, J., Zheng, M., Song, L., Xu, J., & Sun, C. (2024). RAP chunks produced in cold milling operation of asphalt pavement: Evaluation, mechanism, and engineering investigation in china. *Journal of Traffic and Transportation Engineering (English Edition)*, *11*(5), 972–1000. https://doi.org/10.1016/j.jtte.2024.03.004

Zaumanis, M., Loetscher, D., Mazor, S., Stöckli, F., & Poulikakos, L. (2021). Impact of milling machine parameters on the properties of reclaimed asphalt pavement. *Construction and Building Materials*, *307*, 125114. https://doi.org/10.1016/j.conbuildmat.2021.125114

Zhao, H., Su, J., Ma, S., Su, C., Wang, X., Li, Z., Wei, J., & Cui, S. (2022). Study on cold recycled asphalt mixtures with emulsified/foamed asphalt in the laboratory and on-site. *Coatings*, *12*(7), 1009. https://doi.org/10.3390/coatings12071009

Zhu, J., Ma, T., & Fang, Z. (2020). Characterization of agglomeration of reclaimed asphalt pavement for cold recycling. *Construction and Building Materials*, *240*, 117912. https://doi.org/10.1016/j.conbuildmat.2019.117912

A Appendix: Methodology

A.1 Interview structure

1. General questions

- What is your function at the company you work at?
- How many years of experience do you have with cold milling?
- Do you have experience with cold in-situ recycling?

2. Substantive questions

- What is/are the main objectives of a standard cold milling procedure? Is this speed of operation, maintenance of milling equipment, quality of RAP, etc.?
- Which components of a milling machine have a big influence on the RAP gradation?
  - Are there variations of these components that reduce the RAP particle size?
- What changeable parameters have a big influence on RAP particle gradation?
  - How do these parameters influence the RAP particle gradation?
- How do the different configurations of milling drums influence the RAP particle gradation?
- What configurations of milling drums are used most often in the Netherlands?
- What is your opinion on the, through literature gathered solutions, regarding possible success of implementation?
- Are there other ways to ensure that RAP material has the right gradation to be in-situ recycled?
- What factors should be considered to determine if a specific surface course is eligible for CIR?

A.2 Expert information

Expert	Expertise	Company	Function
1	Cold milling procedure	Freesmij	Regional Manager (North)

Table A.1: Information on interviewed experts

B Appendix: State-of-practice

B.1 Current cold milling equipment and process

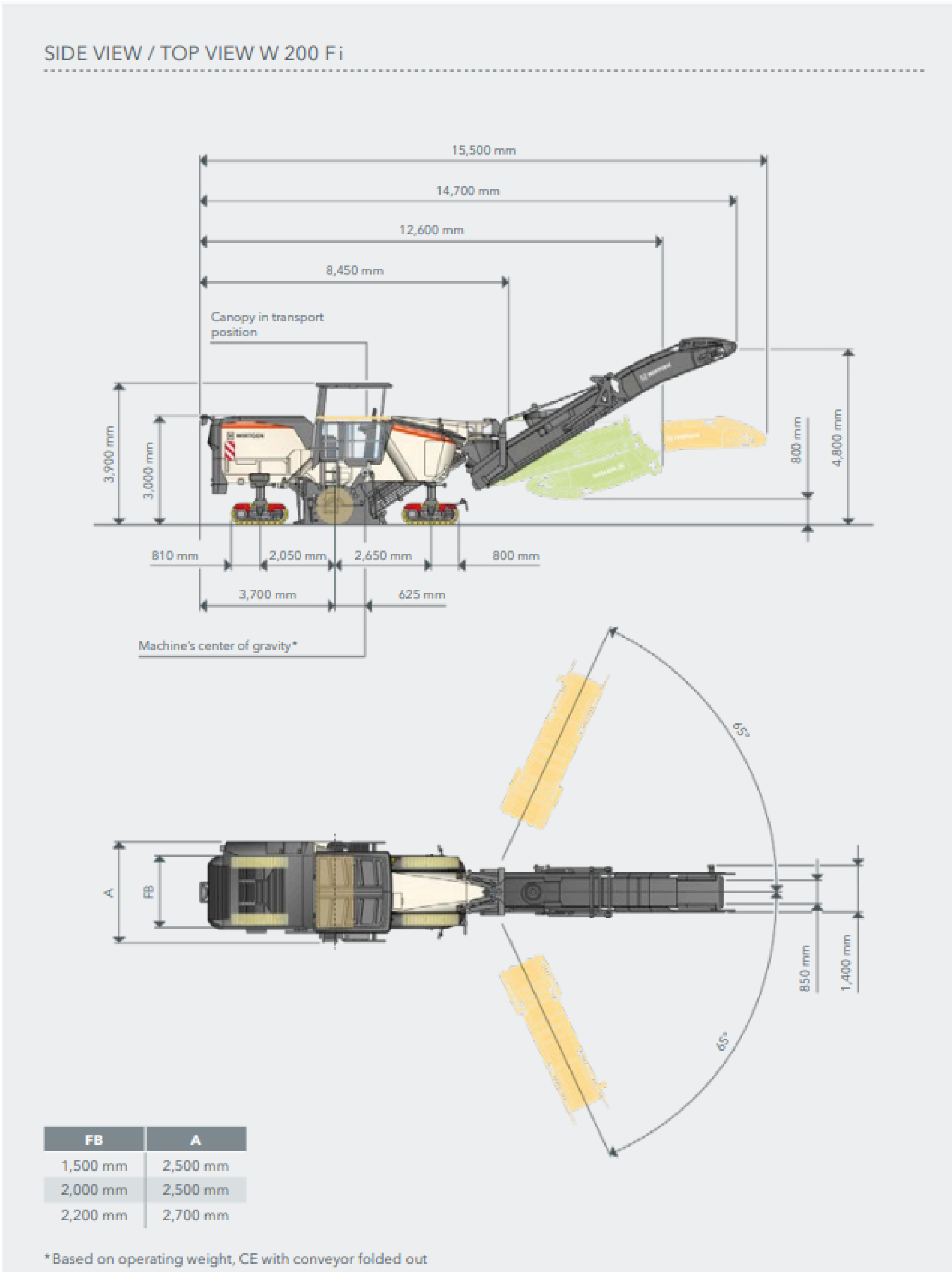


Figure B.1: Specifications of the 200 Fi cold milling machine (WIRTGEN, n.d.-a)

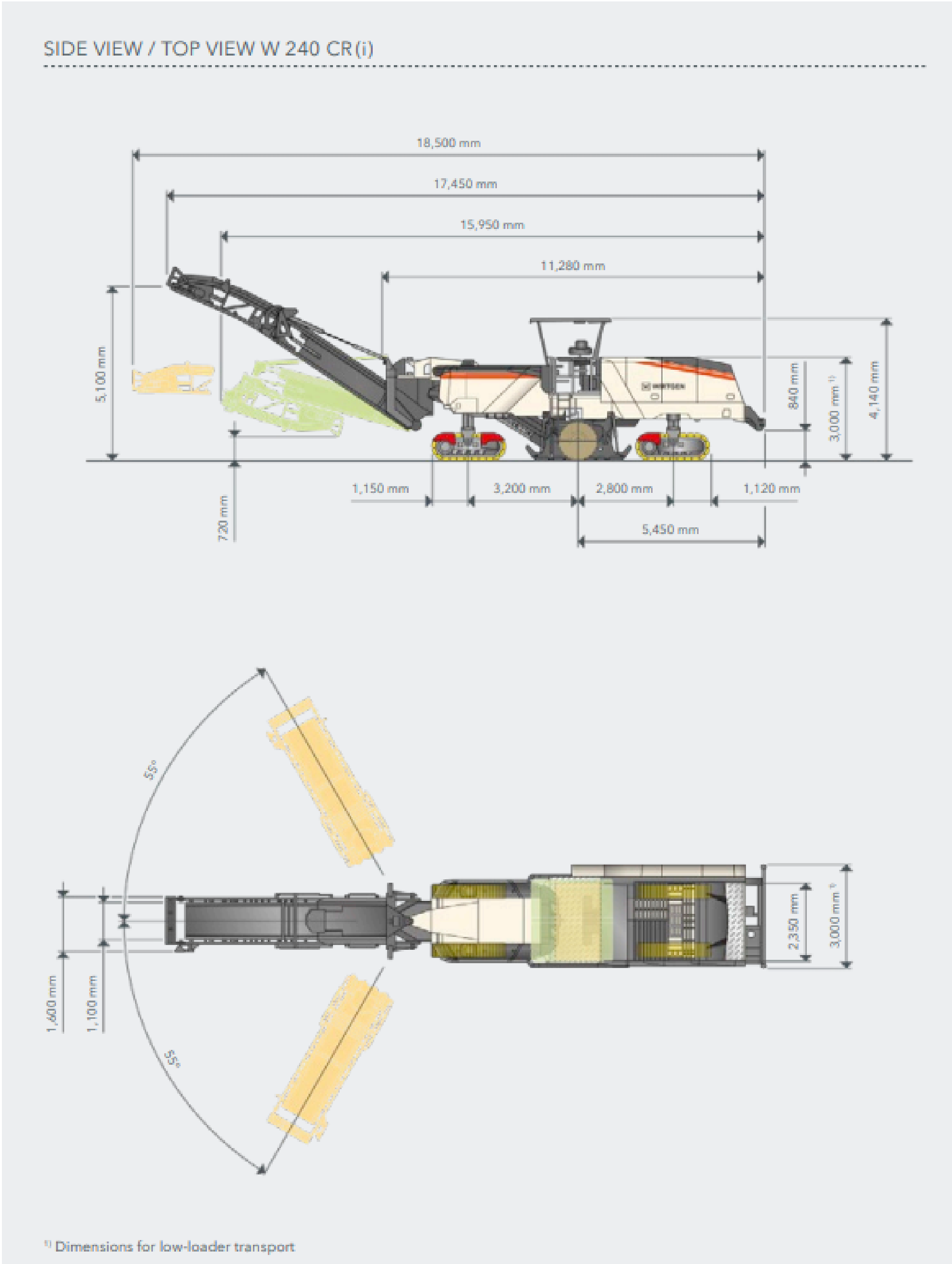


Figure B.2: Specifications of the W240 CR(i) cold recycler (WIRTGEN, n.d.-b)

B.2 Sieve analysis

The method for performing the sieve analysis, including preparations and calculations will be discussed in this appendix. This will be done according to the steps defined in subsubsection 5.1.3.

1. Sample collection

The stockpiles of RAP on the asphalt plant were prepared for taking a sample by creating an even "plateau", which are displayed in Figure B.3(c) and (d). This was done using a shovel loader, shown in Figure B.3 (a). From these plateaus, samples for the AC Surf and SMA-NL 11 mix types were collected using a sampling scoop and a wheelbarrow, which are shown in Figure B.3 (b). Furthermore, the size of the initial sample corresponded to a full wheelbarrow. The dimensions of the sampling scoop were in accordance with the required dimensions specified in NEN-EN 932-1.

((a)) Shovel loader used to prepare the RAP stockpiles for sample collection

((b)) Sampling equipment used, including a sampling scoop and a wheelbarrow

((c)) Plateau of SMA-NL 11 stockpile

((d)) Plateau of AC Surf stockpile

Figure B.3: Overview of equipment used during the sample preparation and collection

2. Sample division

The next step in the followed procedure was the division of the collected samples into appropriate subsamples. Due to the absence of appropriate size sample division equipment, fractional shoveling as defined in NEN-EN 932-2 was used as the sample reduction technique. In this method, the number of subsamples which the entire sample needs to be divided in, is determined with Equation 2.

$$n = m_L/m_T \quad (2)$$

For this, both m_L and m_T have to be determined. m_L can be determined with Equation 3 , while m_T can be determined using table 1 of NEN-EN 933-1.

$$m_L = 6 \times \sqrt{D} \times \rho_b \quad (3)$$

In this equation, D denotes the maximum aggregate size in mm, while ρ_b denotes the bulk density of the RAP material. The bulk density can be calculated with Equation 4, discussed in NEN-EN 1097-3.

$$\rho_b = \frac{m_2 - m_1}{V} \quad (4)$$

In this equation, m_1 denotes the mass (kg) of the empty barrel, while m_2 indicates the mass (kg) of the barrel including the RAP material. In this case, a bucket was used instead of a barrel. Furthermore, V denotes the volume of the bucket in liters. To apply this formula, at least three measurements should be performed.

AC Surf

Using Equation 4, the bulk density was determined. In this, the following information applies:

- m_2 - m_1 average is 15.64 kg
  - Measurement 1: 15.66 kg
  - Measurement 2: 15.45 kg
  - Measurement 3: 15.81 kg
- V is 12.5 L

Inserting these values leads to a bulk density of:

$\rho_b = \frac{m_2 - m_1}{V} = \frac{15.64}{12.5} \approx 1.25\ Mg/m^3$

The maximum aggregate size D was determined by sieving the largest RAP particles in each sample, which resulted in a D of 32 mm. Inserting the values for D and ρ_b in Equation 3, results in the following m_L:

$m_L = 6 \times \sqrt{D} \times \rho_b = 6 \times \sqrt{32} \times 1.25 \approx 42.47\ kg$

From table 1 in NEN-EN 933-1, m_T can be extracted. A maximum aggregate size D of 32 mm, yields a m_T of 10 kg. Inserting the determined m_L and m_T in Equation 2, yields following sample division:

$n = m_L/m_T = 42.47/10 = 4.25$

Using the assumption that the test portion mass is to be within 85% to 115% of m_T, n is rounded to the nearest whole number, which is 4. This results in a test portion size of $42.47/4 \approx 10.62kg$. The laboratorium sample, m_L, is divided into four subsamples of approximately 10.62 kg, which are stored buckets.

SMA-NL 11

Using Equation 4, the bulk density was determined. In this, the following information applies:

- m_2 - m_1 average is 16.77 kg
  - Measurement 1: 16.39 kg
  - Measurement 2: 17.00 kg
  - Measurement 3: 16.92 kg
- V is 12.5 L

Inserting these values leads to a bulk density of:

$\rho_b = \frac{m_2 - m_1}{V} = \frac{16.77}{12.5} \approx 1.34\ Mg/m^3$

The maximum aggregate size D was determined by sieving the largest RAP particles in each sample, which resulted in a D of 32 mm. Inserting the values for D and ρ_b in Equation 3, results in the following m_L:

$m_L = 6 \times \sqrt{D} \times \rho_b = 6 \times \sqrt{32} \times 1.34 \approx 45.48\ kg$

From table 1 in NEN-EN 933-1, m_T can be extracted. A maximum aggregate size D of 32 mm, yields a m_T of 10 kg. Inserting the determined m_L and m_T in Equation 2, yields following sample division:

$n = m_L/m_T = 45.48/10 = 4.48$

Using the assumption that the test portion mass is to be within 85% to 115% of m_T, n is rounded to the nearest whole number, which is 4. This results in a test portion size of $45.48/4 \approx 11.37kg$. The laboratorium sample, m_L, is divided into four subsamples of approximately 11.37 kg, which are stored buckets.

3. Execution of sieve analysis

The subsamples were sieved using the following sieve apertures: 45 mm, 31.5 mm, 22.4 mm, 16 mm, 11.2 mm, 8 mm, 5.6 mm, 4 mm, 2 mm. Because the RAP material was sieved without washing and drying, sieves of aperture size lower than 2 mm were excluded from the sieve set. To avoid overloading the sieves, the subsamples were sieved in multiple parts for sieves of aperture size 11.2 mm and lower. Additionally, the material passing the 5.6 mm sieve was collected before sieving due to overloading. The sieving column used in this sieve analysis is shown in Figure B.4. The results of the sieve analysis are displayed in Table 2.

((a)) 31.5 mm - 5.6 mm

((b)) 4 mm - 2 mm

Figure B.4: Sieving column used for the sieve analysis

B.3 Gradation extracted from literature

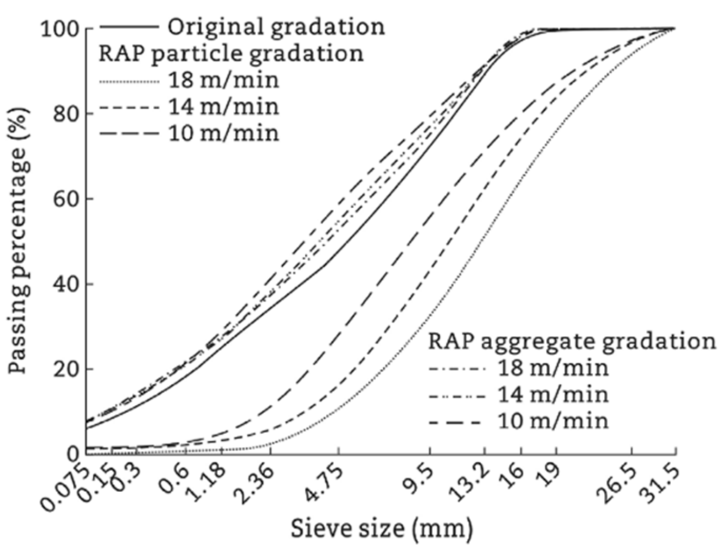


Figure B.5: Gradation curves of original asphalt pavement, RAP particle gradation, and RAP aggregate gradation resulting from research performed by (Yao et al., 2024)

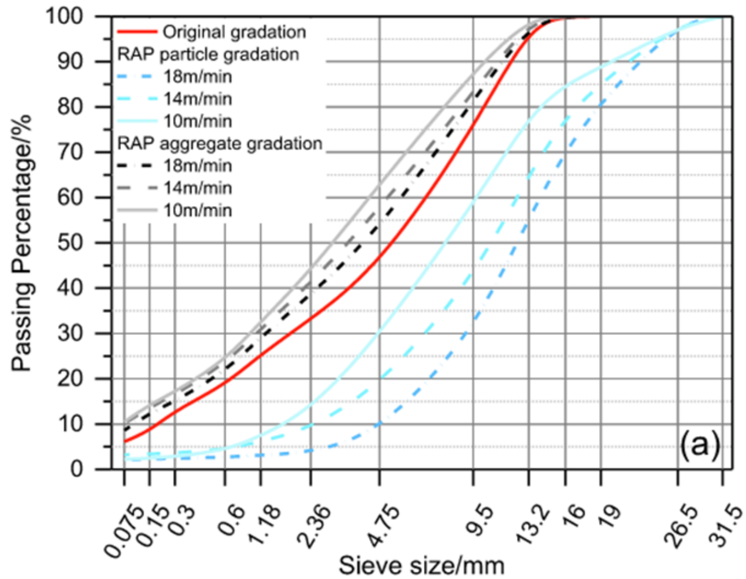


Figure B.6: Gradation curves of original asphalt pavement, RAP particle gradation, and RAP aggregate gradation resulting from research performed by (Yang et al., 2021)

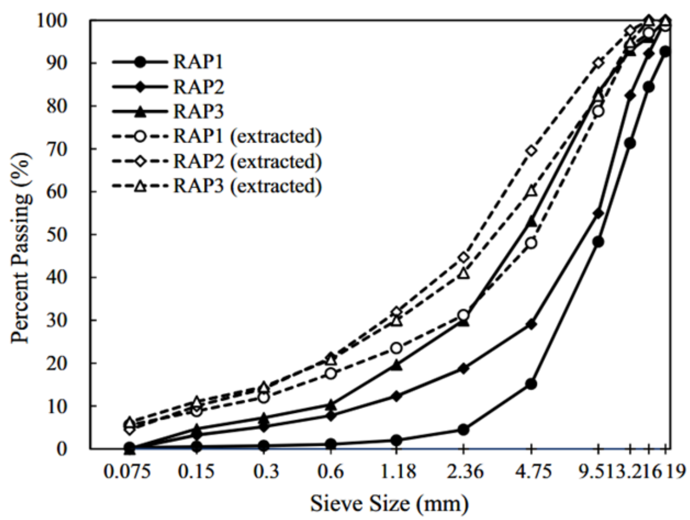


Figure B.7: Gradation curve of three types of RAP material, being AC (RAP 1), SMA (RAP 2) and OGFC (RAP 3) (Zhu et al., 2020)

Sieve (mm)	31.5	22.4	16	11.2	8	4	2	1	0.125	0.063
Mean	96.90	93.60	84.08	69.36	56.12	31.67	17.73	8.99	0.52	0.17
Variance	8.13	12.94	43.82	89.42	122.42	84.49	41.58	18.09	0.11	0.02
St dev	2.85	3.60	6.62	9.46	11.06	9.19	6.45	4.25	0.33	0.13
Cv (%)	3	4	8	14	20	29	36	47	63	79
St error	0.95	1.20	2.21	3.15	3.69	3.06	2.15	1.42	0.11	0.04
T-stat 95%	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31
Confidence interval (%)	94.70	90.83	78.98	62.07	47.60	24.59	12.77	5.71	0.27	0.06
	99.10	96.37	89.18	76.64	64.64	38.74	22.70	12.26	0.77	0.27

Table B.1: Statistical values of percent passing (%) of the statistical model for the entire road section (Cadar et al., 2022)

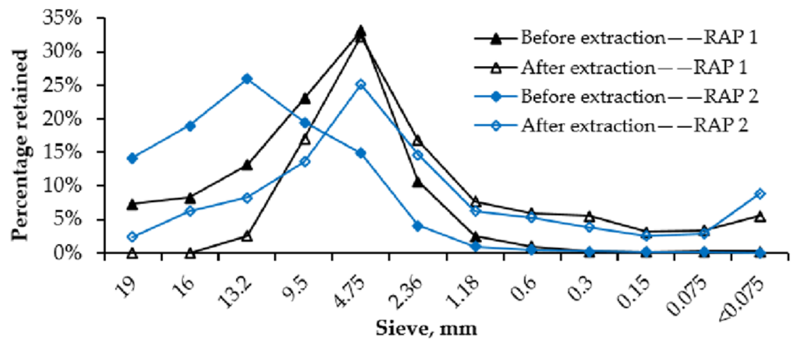


Figure B.8: Percentage retained of reclaimed asphalt pavement RAP 1 and RAP 2 before and after extraction (Xu et al., 2019)

C Appendix: Regulations

C.1 Grading requirements Asphalt Concrete

Table 1 — General grading requirements of target composition — Basic sieve set plus set 1

D	4	5 (5,6)	8	11 (11,2)	16	22 (22,4)	32 (31,5)
Sieve mm	Percentage passing by mass						
1,4 *D*[a]	100	100	100	100	100	100	100
D	90 to 100	90 to 100	90 to 100	90 to 100	90 to 100	90 to 100	90 to 100
2	50 to 85	15 to 72	10 to 72	10 to 60	10 to 50[b]	10 to 50[b]	10 to 65
0,063	5,0 to 17,0	2,0 to 15,0	2,0 to 13,0	2,0 to 12,0	0 to 12,0	0 to 11,0	0 to 11,0

[a] Where the sieve calculated as 1,4 *D* is not an exact number in the basic set plus set 1 series then the next nearest sieve in the set shall be adopted.

[b] For application on airfields the maximum percentage passing 2 mm may be increased to 60 %.

Table C.1: Table 1 of NEN-EN 13108-1, displaying the general grading requirements of a target composition

C.2 Grading requirements Stone Mastic Asphalt

Table 1 — General grading requirements of target composition — Basic sieve set plus set 1

D	4	5 (5,6)	8	11 (11,2)	16	22 (22,4)
Sieve mm	Passing sieve % by mass					
1,4 *D*[a]	100	100	100	100	100	100
D	90 to 100	90 to 100	90 to 100	90 to 100	90 to 100	90 to 100
2	20 to 45	15 to 40	15 to 40	15 to 35	15 to 30	15 to 30
0,063	5,0 to 14,0	5,0 to 14,0	5,0 to 14,0	5,0 to 13,0	5,0 to 12,0	5,0 to 12,0

[a] Where the sieve calculated as 1,4 *D* is not an exact number in the ISO 565- series/R20 then the next nearest sieve in the set shall be adopted.

Table C.2: Table 1 of NEN-EN 13108-5, displaying the general grading requirements of a target composition

Table 81.2.9 Grain size distribution of stone mastic asphalt (%(m/m))

Through sieve	SMA-NL 5	SMA-NL 8A	SMA-NL 8B	SMA-NL 11A	SMA-NL 11B
16 mm				100	100
11,2 mm		100	100	92-100	92-100
8 mm	100	92-100	92-100	DV	DV
5,6 mm	92-100	DV	DV		
4 mm	DV				
2 mm	28-38	21-31	18-28	18-28	17-27
0,5 mm	DV	DV	DV	DV	DV
0,063 mm	9,5-13,5	8,0-12,0	7,0-11,0	7,0-11,0	6,0-10,0

DV: Declared Value; value to be specified by the producer

Note: As a characteristic coarse sieve, in deviation from the provisions of NEN-EN 13108-5, sieve D/2 is not prescribed

Table C.3: Table 81.2.9 of the CROW Standaard RAW bepalingen 2020 displaying the grain size distribution of stone mastich asphalt

C.3 Grading requirements of RAP material

Table 81.2.15 Homogeneity of asphalt granulate/RAP

	Maximum standard deviation for five samples at recycling percentages of RAP		
	≤ 30	30-50	>50
Grain size distribution			
Through sieve 11,2 mm (see note 1)	6,5	6,0	5,5
Through sieve 5,6 mm (see note 2)	5,5	5,0	4,5
Through sieve 2 mm	4,5	4,0	3,5
Through sieve 0,063 mm	1,2	1,0	0,8
Binder content (%)	0,5	0,4	0,3
Penetration	5 (0,1 mm)	4 (0,1 mm)	3 (1 mm)

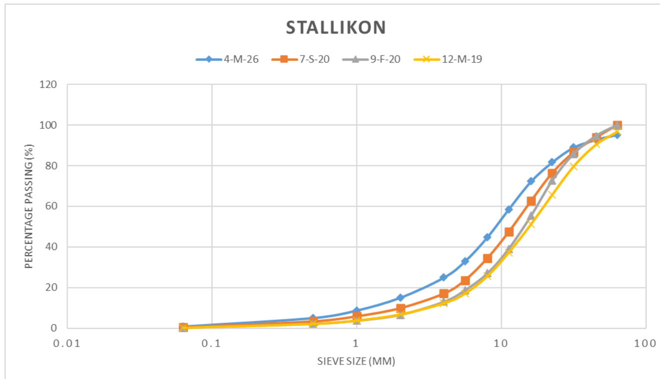
Note 1: Only for surface courses of asphalt concrete

Note 2: Only for binder courses and surface courses of asphalt concrete

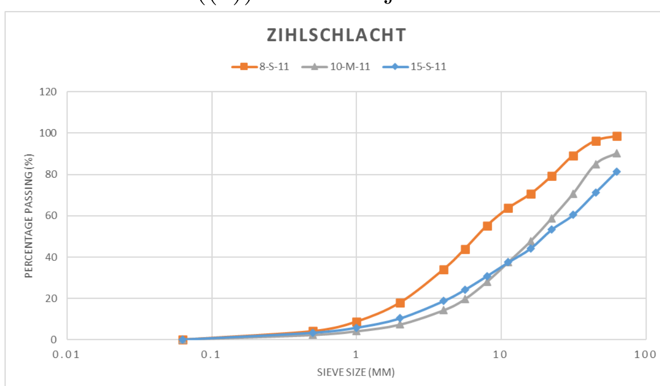
Table C.4: Table 81.2.15 of the CROW Standaard RAW bepalingen 2020 displaying the homogeneity of RAP

D Appendix: Innovative milling techniques

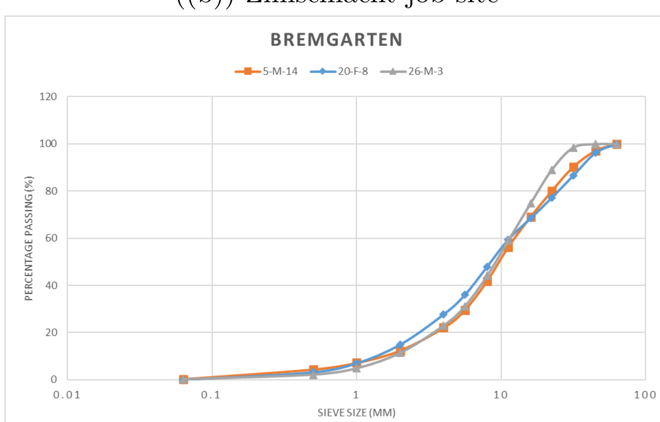
D.1 Influence of operating parameters



((a)) Stallikon job site



((b)) Zihlschlacht job site



((c)) Bremgarten Job site

Figure D.1: Grading curves of different configurations of milling machine operating parameters at all job sites (Zaumanis et al., 2021)

D.2 Scenario development

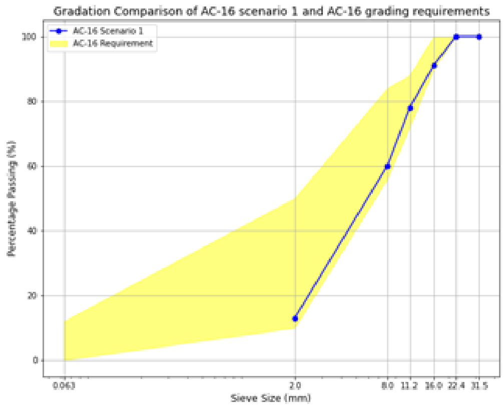
(AC-16) (Yao et al.)				
Sieve	Percentage passing (%)			
	10 m/min	14 m/min	18 m/min	RC (%/(m/min))
31.5	100	100	100	0.00
26.5	98	97	94	0.50
19	87	84	76	1.38
16	78	74	64	1.75
13.2	72	63	52	2.50
9.5	56	44	33	2.88
4.75	27	15	10	2.13
2.36	11	6	2	1.13
1.18	5	4	1	0.50
0.6	3	2	0.8	0.28
0.3	1.5	1.5	0.3	0.15
0.15	1	1	0	0.125
0.075	1	1	0	0.125

Table D.1: Speed parameter effect AC-16

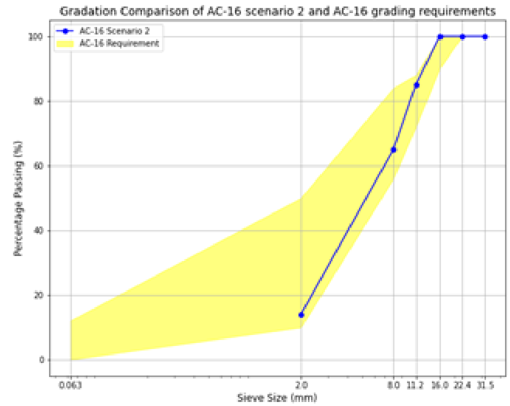
(AC-13) (Yang et al.)				
Sieve	Percentage passing (%)			
	10 m/min	14 m/min	18 m/min	RC (%/(m/min))
31.5	100	100	100	0.00
26.5	97	97	97	0.00
19	89	84	80	1.13
16	84	77	70	1.75
13.2	77	65	55	2.75
9.5	59	44	33	3.25
4.75	30	20	10	2.50
2.36	14	10	4	1.25
1.18	8	6	3	0.63
0.6	5	5	2	0.38
0.3	2.3	3.8	1.5	0.10
0.15	1.5	3	1.5	0.00
0.075	1.5	3	1.5	0.00

Table D.2: Speed parameter effect AC-13 (AC-11 Surf)

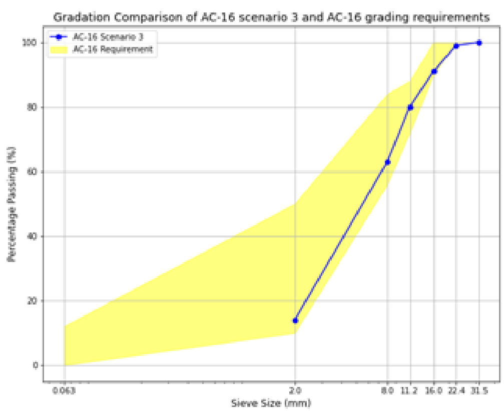
D.3 Grading curves scenarios (AC-16 Surf)



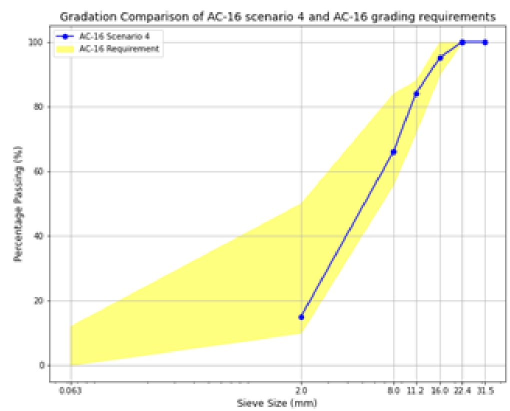
((a)) Scenario 1



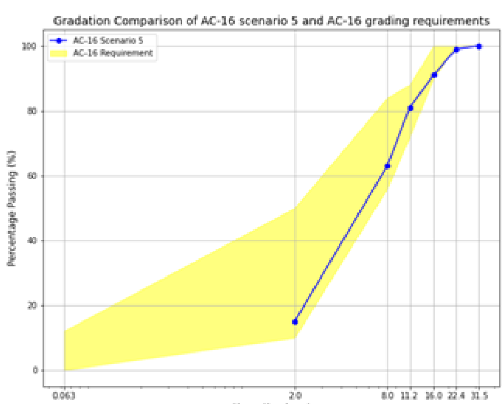
((b)) Scenario 2



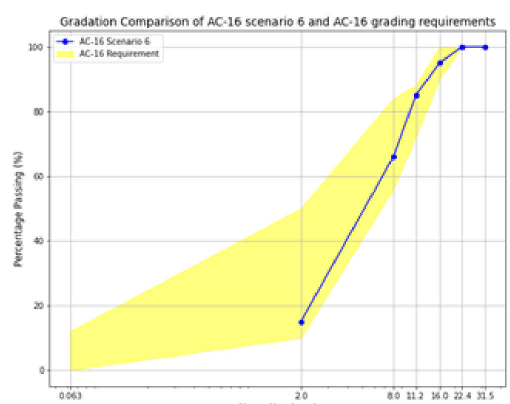
((c)) Scenario 3



((d)) Scenario 4

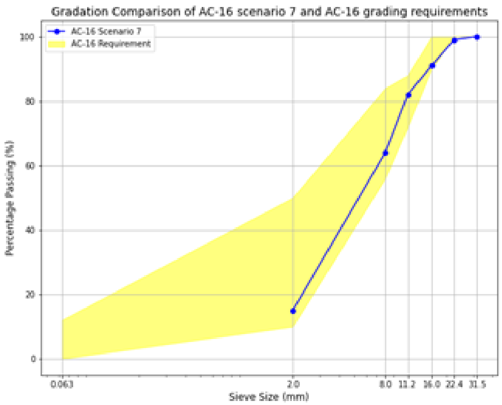


((e)) Scenario 5

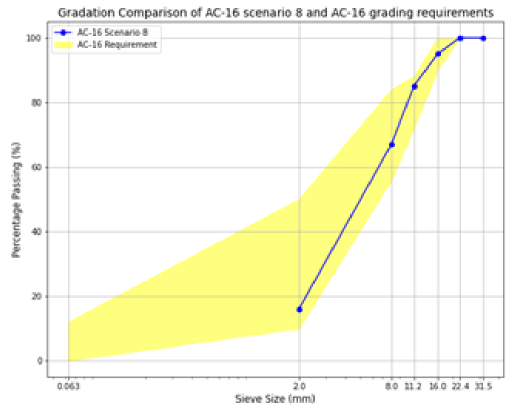


((f)) Scenario 6

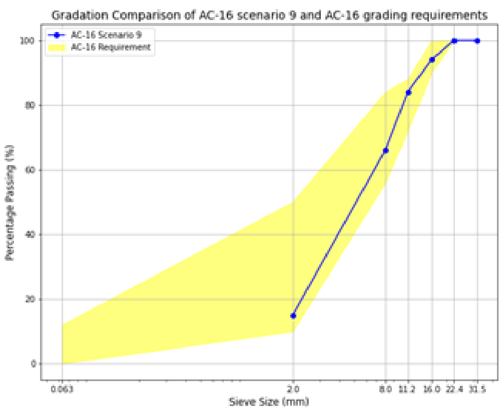
Figure D.2: Grading curves of different configurations of milling machine operating parameters across various scenarios.



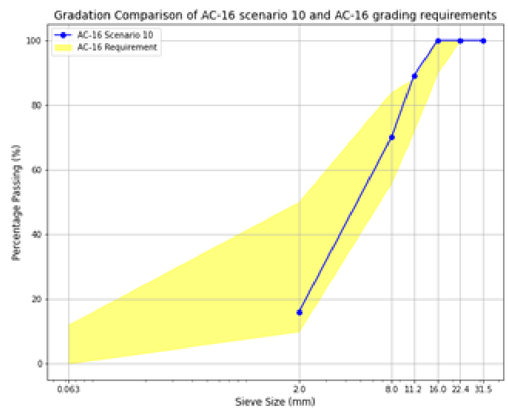
((a)) Scenario 7



((b)) Scenario 8



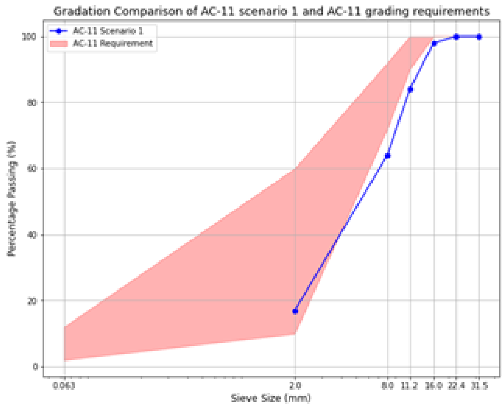
((c)) Scenario 9



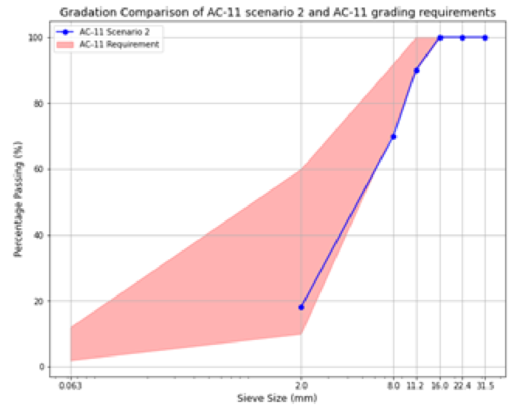
((d)) Scenario 10

Figure D.3: Grading curves of different configurations of milling machine operating parameters across various scenarios compared to AC-16 Surf regulations.

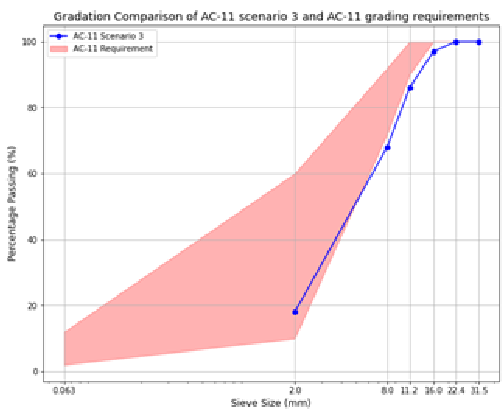
D.4 Grading curves scenarios (AC-11 Surf)



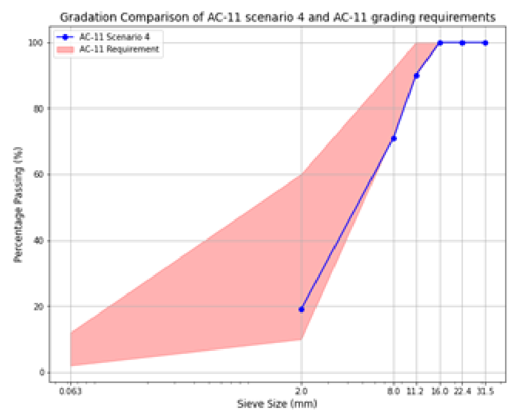
((a)) Scenario 1



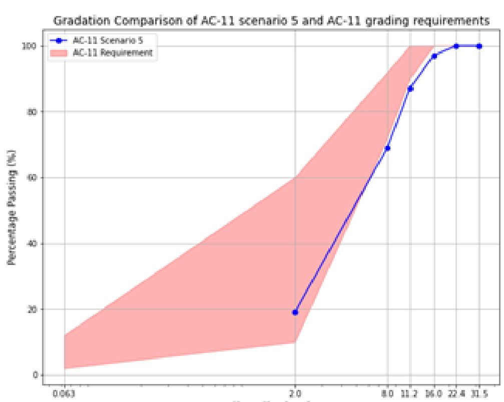
((b)) Scenario 2



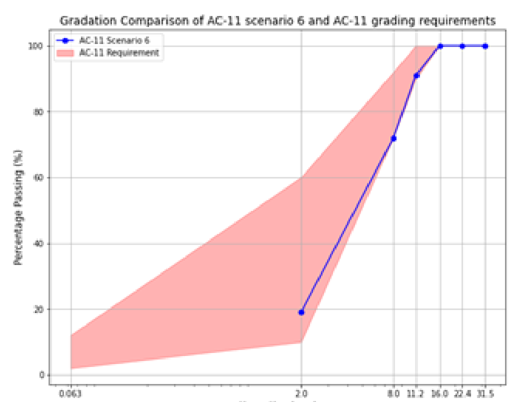
((c)) Scenario 3



((d)) Scenario 4

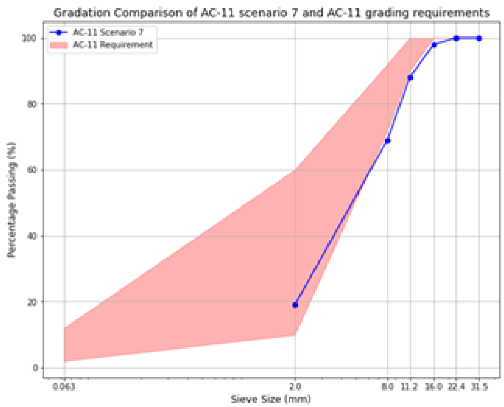


((e)) Scenario 5

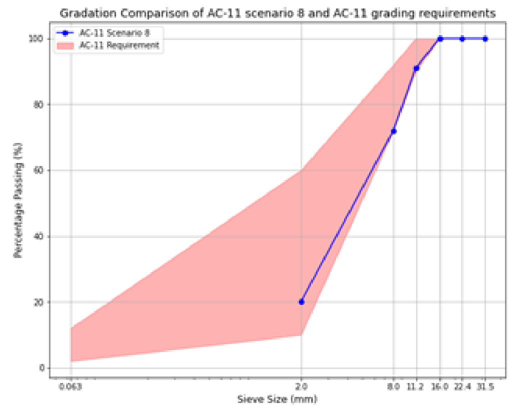


((f)) Scenario 6

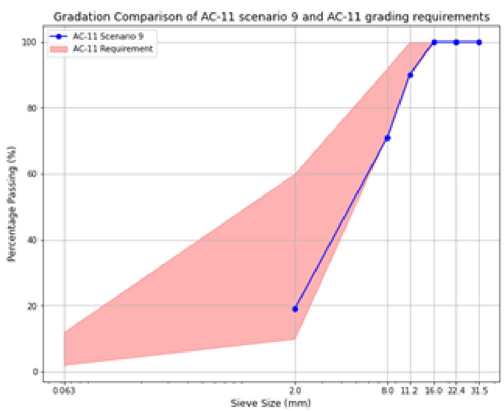
Figure D.4: Grading curves of different configurations of milling machine operating parameters across various scenarios.



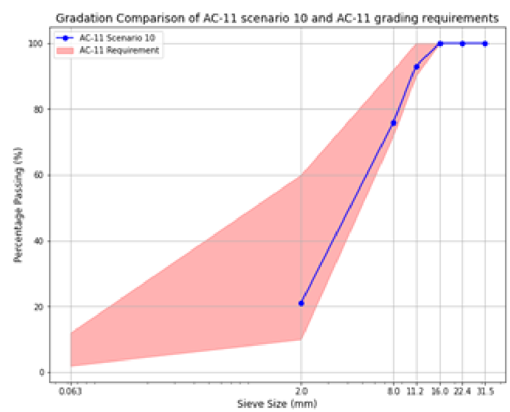
((a)) Scenario 7



((b)) Scenario 8



((c)) Scenario 9



((d)) Scenario 10

Figure D.5: Grading curves of different configurations of milling machine operating parameters across various scenarios compared to AC-11 Surf regulations.

E Appendix: CIR treatment requirements

E.1 Project selection flowchart

Figure E.1: Guideline for CIR project selection in the form of a flowchart