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IMPROVED AND SUSTAINABLE ASPHALT MIXES



Ballast Nedam

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BACHELOR THESIS

Improved and Sustainable Asphalt Mixes

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Declaration of Authorship

I, Abidemi Olosunde, declare that this thesis titled, "Improved and Sustainable Asphalt Mixes" and the work presented in it are my own. I confirm that :

- This work was done wholly or mainly while in candidature for a bachelor degree at this University.
- Where I have consulted the published work of others, this is always clearly attributed.
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- I have acknowledged all main sources of help.

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Summary

The overriding purpose of the thesis research is to develop new design concepts for improved and sustainable asphalt mixes. To accomplish this goal, it became necessary to reach some prerequisite goals. Determining what a sustainable asphalt means, and how that ideal is connected with the field of asphalt mix production assumed a high degree of importance during the literature review conducted for this thesis. Related to that effort, it became necessary to reach an understanding about the main challenge posed in the road construction sector and how solution could be proffered. Thence, to proffer solution to this main challenge, a central question was proposed i.e. **"How can an improved/high performance and eco-friendly asphalt mix be produced considering, sustainability and durability"**?. This central question was split into sub questions, which provided working steps or method to the production of sustainable asphalt mixes. Once these fundamental steps were outlined, the research was able to commence .

To aid the production of sustainable mixes, five mix variants were developed to compare the relative characteristics of the mixes. The new asphalt mixes consisted of 80% "RAP" and 20% virgin materials according to the client specifications. To enable the production of mixes with 80% RAP, rejuvenators were introduced due to their ability to restore the properties of the aged bitumen present in the "RAP". The method involved the production and testing procedure of 5 new asphalt mixes i.e. 1 Reference mix and 4 other mixes containing rejuvenators in accordance to the Standard NEN norm.

The choice of the most suitable mix was dependent on three main factors namely ; the Type Test result, sustainability (Eco Chain) and cost of the mix. The Type test result considered the relative characteristics of the asphalt mixes in regards to stiffness, fatigue and permanent deformation, while the mix sustainability was analyzed using EcoChain software considering the Life Cycle Analysis (LCA) data of materials and products used in the mix production. More so, the cost analysis of the 5 variants of the asphalt mixes were compared to determine the mix with the least cost in terms of production in the asphalt plant. With the results obtained from these factors, a Multi Criteria Analysis (MCA) was set up to make a conclusion on the most sustainable mix.

In addition, it was realized that the ability to produce asphalt mixes with high "RAP" percentage is possible (80%) but there are technical challenges involved, which is as a result of the inability of the mineral aggregates in the mix to properly bind together. More so, producing a mix with 80% "RAP" in the asphalt plant is challenging because the capacity of production in tons/hour decreases as a result of heating and drying of a high "RAP" percentage, thence taking more time in the current facilities.

Furthermore, it was concluded that the undesired test results, was obtained because the bitumen content (%) derived from the "RAP" at the beginning of the research was incorrect. This is due to the fact that, the obtained bitumen content (%) at the beginning of the research was higher than the amount obtained at the end of the research, which was as a result of variation in the "RAP".

Conclusively, it was recommended that the "RAP" to be used in the production of the new mixes should be more consistent and under control in order to have more homogeneity in the asphalt mixes and also to avoid obtaining distinctive bitumen content. More so, it was concluded that to obtain better test results, more bitumen properties need to be known, which implies that only the R & B and Penetration Test is insufficient to determine the accurate bitumen content (%) in the "RAP". Thence, an advanced DSR (Dynamic Shear Rheometer) test should be introduced to determine the additional properties of the aged bitumen from the "RAP". This is because when considering the black rock behavior of aged bitumen, the AC "RAP" with highly aged bitumen acts like a rock and it is uncertain if the aged and virgin bitumen mix properly.

Abstract

Asphalt is a material composed of mineral aggregates namely sand, stone and filler binded with a viscous fluid (bitumen) to pave roads, parking lots, airports etc. About 63% of CO₂ emissions result from asphalt constructions according to the Gelderse CO₂-footprint. The target of Rijkswaterstaat and Provinces towards sustainability is reducing CO₂ emissions on road traffic by -40% in 2030 based on the European Union regulations and climatic accordance. As years go by, clients have requested for asphalt mixes which fit into the policy of sustainability, hereby allowing Rijkswaterstaat to place a priority on the reduction of direct and indirect CO₂ emissions coming from suppliers and material use. Over the past decades, research has been made by contractors concerning the need to produce sustainable mixes which addresses the challenges of asphalt mix durability and increased CO₂ emissions from asphalt production.

The aim of the thesis, is to develop or innovate new design concepts for improved and sustainable asphalt mix, hence proffering a solution to the sustainability challenge posed in the road construction sector by using rejuvenators to increase process optimization of asphalt granulates. More so, some objectives of the thesis include the production of a cost efficient & sustainable asphalt mix with the same/improved mechanical properties, asphalt mix with 80% recycled asphalt granulate "RAP" etc. Thence, to aid the production of sustainable mixes, rejuvenators were introduced. The rejuvenators were applied during the research process, because it increases the percentage of "RAP" recyclability in the asphalt mix and simultaneously restores the properties of the aged bitumen present in the "RAP".

In order to achieve these goals, a central research question was proposed. The essence of this question is to proffer solution to the challenge of sustainability i.e. **"How can an improved/high performance and eco-friendly asphalt mix be produced considering sustainability and durability"?**

Within the thesis scope, various alternatives were considered, but only five variants were chosen, which are namely ; one reference mix without rejuvenator and four other mixes with various rejuvenators. These mixes were produced in order to compare their relative properties based on sustainability which is the main focus of the research.

The selection of a sustainable asphalt mix was dependent on three main factors namely ; the type test result, sustainability and cost which implies that any mix which was regarded sustainable within the thesis scope needs to comply with all these factors. For the type test, the mixes were tested based on resistance to stiffness, fatigue and permanent deformation in accordance to the Standard NEN norms. With the test results, the selection of the asphalt mix with the most suitable relative test property was made. Secondly, the sustainability of the asphalt mix was determined by the use of EcoChain considering three main aspects namely ; Climate change (CO₂ emissions), Environmental Cost Indicator (MKI) and Energy use. The mixes were analyzed according to these aspects, and the most suitable mix according to EcoChain analysis was determined. Thirdly, the cost of the produced mixes were compared to make a selection of the mix with the least cost in regards to the production in the asphalt plant.

Conclusively, with the computed result, the Multi Criteria Analysis (MCA) was set up to analyze the mix which fully complies with all the factors in order to make the choice of the most sustainable mix.

Acknowledgement

This Advisory Report is written in the scope of a final thesis research, within the International study (Civil Engineering) by a student of HZ University of Applied Sciences in Vlissingen, The Netherlands. The final graduation thesis, was performed at DIBEC Materiaalkunde, a subsidiary of Ballast Nedam during the 4th year of the study programme. The research thesis was based on the development and improvement of sustainable asphalt mixes, under the supervision of two in-company mentors ; drs. ir. M. (Mahesh) Moenielal and A. Arjan Slotboom and the supervisory teacher Giuliana Scuderi (PhD), a lecturer at HZ University of Applied Sciences. The mobility period lasted from 2nd February 2017 till 30th June 2017.

The main purpose of the research thesis, is to innovate new design concepts for improved and sustainable asphalt mixes, which proffers solution to the challenge of sustainability posed in the road construction sector. The development of the new design concept involved the use of rejuvenators in the process optimization of asphalt granulates i.e. the production of efficient and sustainable asphalt mixes with the same/improved mechanical properties, considering asphalt mix with 80% recycled asphalt pavement "RAP". Furthermore, the sustainability of the produced asphalt mixes in terms of CO2 emissions was analyzed by considering its Life cycle Analysis (LCA).

The first weeks of the research execution was quite challenging, due to the fact that there was limited literature and information concerning the relation of asphalt mix production to sustainability, the quantity and types of rejuvenators to be used etc. More so, as a result of the high bitumen content (%) present in the "RAP", it was a quest of necessity whether or not to add virgin bitumen to the new asphalt mixes. Furthermore, the ability to source for more relevant and useful information relating to the quantification of rejuvenators was quite a task because limited and insufficient information was provided by the suppliers. During progress meetings, this challenge was discussed with my in-company mentors and the solution proffered was quite helpful.

Profound gratitude goes to my in company-mentors drs.ir. M. Mahesh Moenielal who enlightened my knowledge broadly and deeply about asphalt mix production, and also provided me with useful information sources. More so, Arjan Slotboom who provided guidelines during the execution of the tests in the laboratory. I am also grateful to my supervisory teacher, Giuliana Scuderi(PhD) who gave guidelines for the preliminary draft of the report during the progress meetings, to ensure a professional final product was delivered.

Prior to this thesis, I had little knowledge on asphalt mixes & its various production processes. These past months, has been an incredible personal and professional experience to me because it has deeply enlightened my knowledge about asphalt and the elements needed to be considered for asphalt sustainability and durability.

Abidemi Olosunde,
Nieuwegein, The Netherlands.
July 21, 2017.

Keywords and Abbreviations

AC	Asphalt Concrete.
AC Bind/Base	Asphalt Concrete applied in the binder or base layer.
Aged bitumen	Bitumen extracted from "RAP".
Aggregate	Granular material of natural, manufactured or recycled origin used in construction.
APA	Asphalt Plant Amsterdam.
APRR	Asphalt Plant Rotterdam Rijnmond.
Asphalt aggregate	Stone ,sand, filler in an asphalt mix.
Asphalt granulate	Recycling of asphalt.
Axle Spectrum	Spread of axle loads over the Asphalt Pavement Construction.
Bitumen	A viscous liquid or solid substance consisting essentially of hydrocarbons or their derivatives, which is substantially soluble in sulfur carbon.
Coarse aggregate	Designation given to larger aggregates greater with $D > 4\text{mm}$ or $d \geq 1\text{mm}$.
Deionized/Demineralized water	Water used in the laboratory to carry out tests which is free of ions and minerals.
DuboCalc	This is a sustainable construction calculator developed by Rijkswaterstaat to calculate the sustainability and environmental costs in civil engineering practices.
Durability	Technical lifespan of asphalt mix.
DSR	Dynamic Shear Rheometer.
Filler	Aggregate of mineral origin, added to asphalt mixes.
Flashpoint	Temperature at which bitumen or rejuvenator will ignite with an open flame.
Grading	Grain size in a particular composition.
Gyrator	Compactor for cylindrical samples.
Gyrator test samples	Test samples made from Gyrator.
GWW	Books used in the road construction sector for Cost Calculation .
kN	Kilo Newton.
LCA	Life Cycle Analysis
Mineral aggregate	Aggregate of mineral origin resulting from an Industrial process involving thermal or other modification.
MKI	Environmental Cost Indicator based on Dutch Standards accepted by road authorities.
Mpa	Mega Pascal ($1 \text{ Mpa} = 1\text{N/mm}^2 = 1\text{MN/m}^2$)
Natural aggregate	Aggregate from mineral sources which has been subjected to nothing more than mechanical processing.
NEN	Dutch Norms used during Asphalt Mix Test.
NMD	National Environmental Database
PA	Porous Asphalt.
PI	Penetration Index.
RAP	Reclaimed Asphalt Pavement.
RAW	Standard RAW Regulations used in Road Construction Sector in the Netherlands.
RJ	Rejuvenator

Rejuvenator	Agents used for restoring the properties of aged bitumen, improving mix flexibility and reducing the consumption of virgin materials.
Rejuvenated bitumen	Revitalized and Renewed aged bitumen through the addition rejuvenators.
Rubble	Coarse fraction of stones (diameter >2mm)
RON	Rijksdienst voor Ondernemende Nederland.
RWS	Rijkswaterstaat
R & B	Ring and Ball
SD	Standard Deviation
SBK	Foundation of Building Quality
Softening point	Temperature at which bitumen under standardized test conditions attains a specific consistency.
Sustainable	The contribution to a mix in terms of CO2 reduction.
Tyre Spectrum	Spreading of the particular classes of tyre on the asphalt pavement construction.
Virgin bitumen	Fresh bitumen which is added to an asphalt mix.
Viscosity	The behavior of bitumen depending on temperature.
VBW	Department of Bituminous Work

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1. Introduction

The aim of this thesis is to develop new design concepts for improved and sustainable asphalt mixes. The need to design or innovate improved and sustainable asphalt mix has been the main challenge posed daily in road construction sector. Over the past years, research has been made by clients and contractors concerning the need to produce sustainable mixes which addresses the challenges of asphalt mix durability and increased CO₂ emissions from asphalt production thence proffering solution to the challenge by increasing the mix technical life span, recyclability of mix, maintenance and application techniques of mix. The steps which were considered are namely the research background, description of available knowledge in theoretical framework, a step by step guide of working methods that included the selection of different mix variants taking into consideration the technical aspects, functional aspects, environmental aspects and cost. More so, the asphalt mix variants were produced, including calculations, test methodology to choose the mix which complies with all sustainability requirements.

1.1 Background

Asphalt is a material composed of mineral aggregates binded with a viscous fluid to pave roads, parking lots, airports etc. Asphalt mix consists of a binder (bitumen) and mineral aggregates namely sand, stone and filler. In the Netherlands, the first laid asphalt was used on a highway in Wassenaar in the form of a penetrated rubble layer (C.R.O.W, 2010). Ever since, there has been a question with its development in construction and expansion of the road network in the seventies of the twentieth century (C.R.O.W, 2010).

Asphalt mix production is more or less a continuous process, starting from the mixing of old asphalt granulate with other virgin materials to produce a new mix in the asphalt plant. Asphalt production is done in asphalt plants which can either be a fixed or mobile mixing plant producing up to 800 tons of asphalt per hour (EAPA, 2017). Thereafter, the produced asphalt mix is transported in specially insulated trucks to prevent the asphalt from forming a cool thin crust around a much hotter core which can alter or affect its characteristics when laid by the paver or during compaction (Asfalt Centrale Over Betuwe, 2017), the transported asphalt mix is laid on the roads for traffic use.

After a period of time, maintenance activities occur, hereby leading to the removal of the asphalt layer on roads also known as asphalt milling technique. The old or broken asphalt granulate also known as “Reclaimed Asphalt pavement” (RAP) is transported back to the asphalt processing plant for the production of new asphalt mix. The figure on the next page show details on the continuous process of asphalt recycling (figure 1).



Figure 1 : Asphalt Recycling (Source : (Kringloop van Asfalt, 2013))

1.2 Problem Formulation

Over the past decades, the population of traffic users has grown enormously, causing more damages on roads networks, thus leading to high or frequent maintenance cost. As a result of this, there has been need to produce improved and durable asphalt mixes which will last for a longer period and also reduce maintenance cost. The longer life span/duration of asphalt solely depends on the type of asphalt mix. Therefore, as years go by the need to produce a more sustainable and durable asphalt mix has been on high demand in the road construction sector.

Asphalt is used for the construction of various categories of roads, but what differs is the different types of asphalt used for the various categories. The expansion of the road network has strongly increased, leading to a drastic change in travel time over the years. Statistics show that road traffic grows in a period of ten years faster than other forms of transportation, hence having a negative effect on the environment and safety (C.R.O.W, 2010). The top layer applied on national roads differ from the type used for provincial roads, which is due to the fact that the maximum speed, traffic volume and axle loads allowed on these roads differ from one another. Thus, different asphalt mixes are designed to suite the various categories of roads. For example Porous Asphalt (PA) is applied on highways instead of Dense Asphalt Concrete (DAB) because of its functional properties which includes reduced noise effect, water drainage capacity etc. These properties prevent splash and spray effect, ensuring a suitable road for users. Figure 2 on the next page shows the highway network in the Netherlands and the various types of asphalt applied.



Figure 2 : Highway network in the Netherlands, 2010 (Source : (C.R.O.W, 2010))

Over the past decades, about 63% of CO₂ emissions result from asphalt constructions according to the Gelderse CO₂-footprint, which is quite a high percentage. The target of Rijkswaterstaat and Provinces towards sustainability is reducing CO₂ emissions on road traffic by -40% in 2030 based on the European Union regulations and climatic accordance. As years go by, clients have requested for asphalt mixes which fit into the policy of sustainability, hereby allowing Rijkswaterstaat to place a priority to reduce direct and indirect CO₂ emissions coming from suppliers and material use.

1.3 Research Description

The need to design sustainable asphalt mixes is proposed by road authorities like Rijkswaterstaat and the Province of Gelderland to contractors. Therefore, this thesis is focused on improving the asphalt mixes by using a higher “RAP” percentage through the addition of rejuvenators.

The possible asphalt mixes are produced and tested considering different alternatives/variants. With the obtained test results, the selection of the most suitable mix was narrowed down considering certain criteria. In the research process, the production of improved asphalt mixes was based on the production of a mix with >50% asphalt granulate i.e. the use of a higher percentage of “RAP”. Nevertheless, within the thesis scope, options were evaluated and discussed to determine the most efficient way of producing sustainable and durable asphalt mixes. Asphalt mix performance can be assessed uniformly since the introduction of the CE marking by means of stiffness, fatigue, and resistance to permanent deformation. The mechanical properties of these mixes were set out in Type Test Reports which contractors or construction agencies used to differentiate between asphalt pavement constructions.

For the innovation of improved and sustainable asphalt mixes, some factors put into consideration are namely energy reduction, more recycling of “RAP”, reduction of CO₂ emissions etc. These processes were used to innovate the sustainable asphalt mixes, thus directly linking them to process optimization in construction. More so, during the innovation process of the improved asphalt mix, it was very important/crucial that the mechanical properties of the mix were unaltered. The target of Rijkswaterstaat towards sustainability is based on the European Union regulations, climatic accordance and reduced CO₂ emissions. Hence, Rijkswaterstaat places a priority to reduce direct and indirect CO₂ emissions coming from suppliers and material use. On the basis of the CO₂ performance ladder, CO₂ emissions was reduced from 157.6 KN (2009) to 143.1 KN (2015) giving a reduction of -9% and aiming for future attainments in the year 2020 by a significant reduction of -20% (Rijkswaterstaat, 2017).

1.4 Objectives of the Research

The main goal of the thesis is to develop or innovate, improved and durable asphalt mixes which proffers a solution to the challenge of sustainability posed in the road construction sector by using rejuvenators in process optimization of asphalt granulates. In order to construct roads which can cope with the transportation growth in years to come, sustainability is optimal. This hereby brings about the question of constructing sustainable roads. In regards to this, the materials used for the road construction need to be improved. Therefore, to offer a solution to the challenge of sustainability which arises in the road construction sector, the material used for construction purposes need to be improved, hence leading to the examination of asphalt technical and functional properties. Over the years, there has been research or studies going on concerning the recyclability and sustainability of asphalt. These new developments in the field of asphalt mixes and application help to ensure the necessary balance between traffic, living and transportation.

The research objectives are also described as aim of the thesis generally categorized into the environmental and technical objectives. The environmental objectives include aspects ensuring the research is environmentally beneficial i.e. environmentally friendly namely sustainable use of renewable virgin materials, optimal recyclability, saving of virgin materials and fuel, reduction of CO₂ emissions etc., while the technical objectives

include aspects which makes the research technically favorable namely higher strength and quality of the asphalt mix, increased lifespan of mix etc. The other research objectives are further discussed in the following sub chapters.

1.4.1 Efficient and sustainable asphalt mix with the same/improved mechanical properties.

One of thesis objectives is to design an efficient and sustainable asphalt mix with the same or improved mechanical properties i.e. the asphalt mix is designed to offer a solution to the challenge of unsustainable mixes. While designing this mix, it is also important to take into account that the material properties remain the same without being unaltered , to obtain desired results.

1.4.2 Asphalt mix with >50% recycled asphalt.

Designing an asphalt mix with >50% “RAP” is another objective of the thesis research. This objective is in conformation with the client’s requirement to produce mixes with less virgin materials & more recycled asphalt granulates. More so, it is also part of the research methods to analyze the outcome of producing asphalt mixes with higher “RAP” percentages.

1.4.3 Efficient use of virgin materials and asphalt granulates.

The efficient use of virgin materials and asphalt granulate help to ensure that asphalt retrieved from milling technique is recycled and re-used in the production of the new mix, hereby reactivating the aged binder. More so, the research also ensures that virgin materials such as sand, stones, fillers etc. are effectively used in the production of the new mix.

1.4.4 Technical Improvement and Customization solution for asphalt constructions

This objective is important because, it increases the lifespan (durability) and quality of the asphalt mix, thus optimizing the mix by supporting its resistance/strength when paved on the road. Therefore, allowing to fully enjoy the advantages of the application of the new asphalt mix in several construction projects.

1.4.5 Improved mix performance by reduction of fuel and CO2 emissions.

The mixes produced are environmentally friendly i.e. a mix which reduces the percentage of CO₂ emissions and fuel. This implies the mix has a positive effect on the environment by decreasing environmental pollution. More so, as a result of decrease in environmental pollution, the mix performance is improved i.e. increased mix lifespan, sustainability etc.

1.5 Research Questions

To ensure the main challenge posed to road construction sector is solved, it is necessary to improve the asphalt mixes, therefore the main question is set as follows :

"How can an improved/high performance and eco-friendly asphalt mix be produced considering, sustainability and durability"?

The assignment is divided into smaller sub-questions that serve as step-by-step guide to answer the main question. The set sub-questions are as follows:

- What factors need to be considered in order to produce asphalt mix with >50% "RAP"?
- How can a higher percentage of "RAP" be recycled in a new mix?
- How can the efficient use of raw materials and "RAP" be combined to produce sustainable asphalt mixes?
- How can the molecules of the aged bitumen present in the "RAP" become modified?
- How can the composition of "RAP" be obtained i.e. the bitumen content and the coarseness of mineral aggregates ?
- How can the properties of the aged bitumen be determined?
- What experiments will be considered within the research scope to test Asphalt Concrete mixes and what Standard norms will be used ?
- How can the base layer thickness of the produced asphalt mixes be determined ?
- What factors need to be taken into consideration in order to produce a mix with decreased CO₂ emissions ?
- What factors will be considered to analyze the sustainability of the produced asphalt mixes ?
- How can the most cost efficient mix be determined considering the produced asphalt mixes?
- How the choice of the most sustainable asphalt mix be determined ?

In the preceding chapters, a brief background and introduction was made concerning the main challenge of asphalt sustainability posed to the road construction sector. More so, sub questions were formulated to provide an answer to the main research question **"How can an improved/high performance and eco-friendly asphalt mix be produced considering, sustainability and durability"?**. With these research questions, the research activities are outlined and described in detail in chapter 3.1 .

Reading guide.

Chapter 2 : This chapter contains the theoretical framework, which is a description of selected and investigated information sources relevant to the research topic. It critically analyses the definitions and theories from previously conducted research based on various information sources which provides a working basis for the research. The topics included in the theoretical framework, are mainly related to the thesis which includes the main components of a road network, type of asphalt mix to be produced and it's relative layer of application, binder and virgin materials to be used for the asphalt mix production and also information concerning the software's to be used during the thesis.

Chapter 3 : This chapter analyzes the way in which the research was carried out, taking into consideration various aspects of the work process, hence justifying the choice of variant using the design process flow chart. More so, it describes the method of the research process by critically analyzing the research and test activities. The research activities are tasks carried out to provide answers to the research questions and the outcome of these activities serve as an end product to the production of sustainable mixes. On the other hand, the test activities involves the tasks executed during the laboratory test, and the results from these tests determine if the produced mixes complies with the various test requirements.

Secondly, a schedule of requirements was developed to outline the functional and technical requirements of the mix which is in accordance to the client's specifications. The functional requirements describes the functional characteristics of the produced asphalt mixes while the technical requirements considers technical aspects, the mix needs to comply with according to the clients specifications. In addition to the schedule of requirements, the safety and boundary conditions considered during the mix production is also explained in detail. Furthermore, the alternatives considered for the production of sustainable asphalt mixes is described considering the most important aspects of the thesis. These alternatives are narrowed down into variants to give an overview or the selected type of asphalt mixes which were produced. Having chosen the variants, the asphalt mixes were produced and tested according to the Standard NEN norm. These laboratory tests procedure is described in full detail namely ; bitumen extraction process from "RAP", mix composition, bitumen property test, stiffness, fatigue and permanent deformation test.

Additionally, the OIA software used to calculate the base layer thickness is described, giving an overview of the parameters taken into consideration which are namely stiffness, fatigue, etc. With the OIA calculation, the base layer thickness of each asphalt mix is compared based on various traffic intensities. The EcoChain used to check the mix sustainability is also described, stating the important factors considered namely Climate change, MKI and Energy Use. The influence of these factors on the asphalt mixes are analyzed to compare and contrast the mix which is most sustainable. More so, the cost analysis of the each asphalt mix is made in regards to production in the asphalt plant in order to select the mix with the least production cost.

Conclusively, the Multi Criteria Analysis (MCA) is described in detail, considering various aspects within the thesis scope taken into consideration in order to make a choice of the most sustainable asphalt mix. The important aspects considered within the thesis scope namely ; rejuvenator property, laboratory testing, OIA calculation, EcoChain and Cost. These aspects are further sub divided into criteria, with which a weight score is given depending on its relative level of importance.

Chapter 4 : This chapter gives an interpretation to the result obtained from the previous chapter i.e. the method. In this chapter, the result from the tests i.e. mix composition test, stiffness, fatigue and permanent deformation are interpreted in order to distinguish the mixes which comply to the test requirement. More so, the result

obtained from the OIA calculation, EcoChain and Cost Analysis is also analysed to determine the asphalt mix which complies to these requirements.

Chapter 5 : This chapter gives an overview of the 5 Multi Criteria Analysis (MCAs), carried out within the thesis scope considering the 5 aspects i.e. rejuvenator property, laboratory tests, OIA calculation, EcoChain and Cost earlier stated in the method by describing their relative relevance to the research and highlighting the most important or relevant criteria. More so, the MCA results from each aspect is compared and contrasted to obtain result of the most suitable mix in regards to that particular aspect. With the results from the 5 aspects, a general MCA is carried out to make a choice of the most sustainable mix which complies to the 5 aspects.

Chapter 6 : This chapter is a discussion concerning the bottlenecks encountered during the test and possible solutions which can be preferred. It also discusses the reasons for the variation in the “RAP” used during the research and the possibilities of avoiding this variation for the research continuation.

Chapter 7 : This chapter gives a conclusion of the research i.e. the final result obtained at the end of the research, highlighting the most important aspects and the challenges encountered. More so, the recommendation describes the process in which the bottlenecks or challenges encountered can be solved for further research purposes using newly introduced methods and techniques .

2. Theoretical Framework

In this chapter, a brief description on the literature study related to the thesis is made. The theoretical background of the research related topics are described, taking into consideration the important aspects namely ; asphalt concrete, bitumen, classes of bitumen, rejuvenator, rejuvenator products, virgin materials etc. A brief description of these aspects are made, highlighting their relevance to production of the new asphalt mixes.

2.1 Literature on Components of a Road Construction

A road is made up of two main components namely the earth works and the pavement construction. The earthworks is made up of the sand bed, ground surface and soil improvement while the pavement is made up of the asphalt layers and base granular (figure 3). Within the thesis scope, emphasis is laid more on the asphalt pavement construction i.e. precisely the base layer. This is due to the fact that, the type of asphalt mix produced during the research is mostly applied to the base layer.

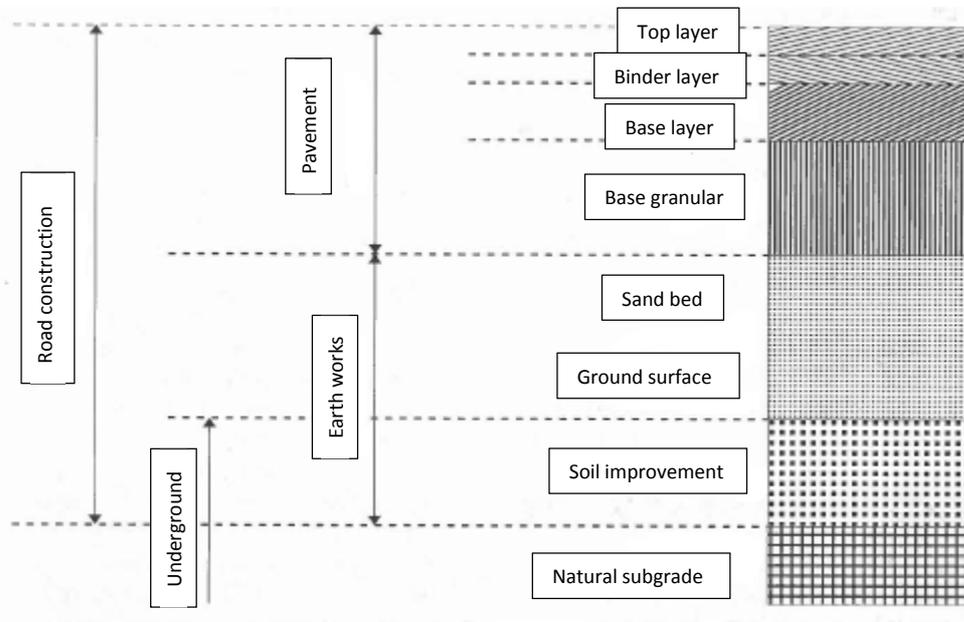


Figure 3 : Components of a road construction (Source : (C.R.O.W, 2010)).

As earlier stated, asphalt laid on roads consists of three layers namely the top layer, binder layer and the base layer. The different asphalt layers have different lifespans, most especially according to the type of mix applied to a specific layer (Asphalt Centrale Over Betuwe, 2017). The top layer needs the most maintenance and must fulfill high requirements, because this is where most of traffic load occurs coupled with other environmental conditions namely precipitation, splash and spray etc., hence relatively the most expensive layer.

More so, the top layer should compile with requirements in terms of wear resistance, resistance to deformation, resistance to atmospheric and chemical influences, skid resistance, flatness, water retention, noise reduction,

color, light reflection and texture (C.R.O.W, 2010). On the other hand, the binder layer is between the top and base layer, the application of the binder must be made to the highest degree of flatness, as corrections are undesirable in the thickness of the top layer. The binder layer serves as an anchor for the top layer and must achieve a good shear stress from the top to base layer (C.R.O.W, 2010).

The base layer acts as an application surface, for the top and binder layer and withstands the load capacity of the other two layers. Thus, enabling it to accommodate the tensile stress which may occur as a result of the traffic load, hereby placing requirements on the fatigue resistance of the material (C.R.O.W, 2010). The base layer's resistance to fatigue has to be highly sufficient in order to absorb the tensile stress which emanate without altering its structural strength (Asfalt Theorie, 1994). In addition, this layer must have a sufficiently high resistance to permanent deformation in order to be able to follow uneven moderate settlements without cracking (Asfalt Theorie, 1994). An example of an asphalt mix applied in the base layer is Asphalt Concrete (AC). A detailed illustration of mix application can be found in appendix 1.

As earlier stated, the buildup of the road construction is made up of two main elements namely the earth works and pavement construction. The pavement construction consists of the three asphalt layers and base granular, while the earth works is made up of the sand bed, ground surface and soil improvement layer. A schematization of the asphalt layer pavement is shown in figure 4. Based on the design principles, conditions and different levels of requirements constructive solutions are designed to meet these conditions (C.R.O.W, 2010).

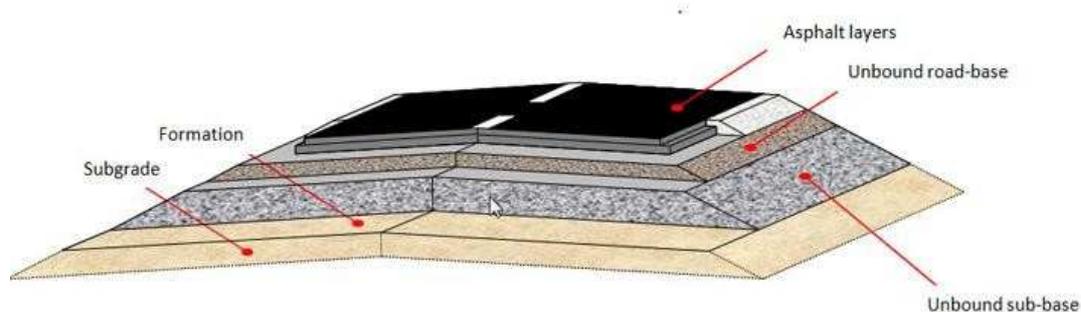


Figure 4 : Asphalt layer Pavement (Source : (EAPA, 2017)).

2.2 Literature on Asphalt Concrete

Asphalt concrete is made up of stone, sand, filler, and bitumen. It is one of the 17 asphalt mixes produced in the asphalt plant, which is also used in the road construction sector in the Netherlands. AC can be applied in the top, binder and base layer depending on their relative mix composition and particle size distribution. (Hergebruik van asfaltgranulaat in het kader van een optimale bouwcyclus, 1994).

In addition, asphalt concrete is a mix based on the concrete principle, which means that the buildup of the grain skeleton is sought to a close possible grain packing, thus causing the lowest possible hollow space in the mineral aggregate (C.R.O.W, 2010). As a result of the dense packing, the number of contact points between the skeleton grains is very high, which improves the stability of the mix, while on the other hand the contact pressure per

contact point remains low, so that crushing is reported (C.R.O.W, 2010). The particle size distribution of asphalt concrete, depends solely on the diameter of mineral aggregate. The maximum density theoretically obtained as particle size distribution is as a result of the Fuller curve (C.R.O.W, 2010) which is represented as ;

$$P = \left(\frac{d}{D}\right)^{0,45}$$

where

- P : distribution through sieve with diameter d
- d : grain size (mm)
- D : maximum grain size in mix (mm)

Figure 5, shows the particle size distribution of AC mixes used in the road construction sector. From the graph, it is seen that the particle size distribution of AC 11 lies very close to the Fuller curve, which is due to the coarse sand fraction in this mix. The AC 11 is unlike AC 22, which lies far away from the Fuller curve making it more applicable in practice. The parameter mostly influenced when the grading near the Fuller curve is density.

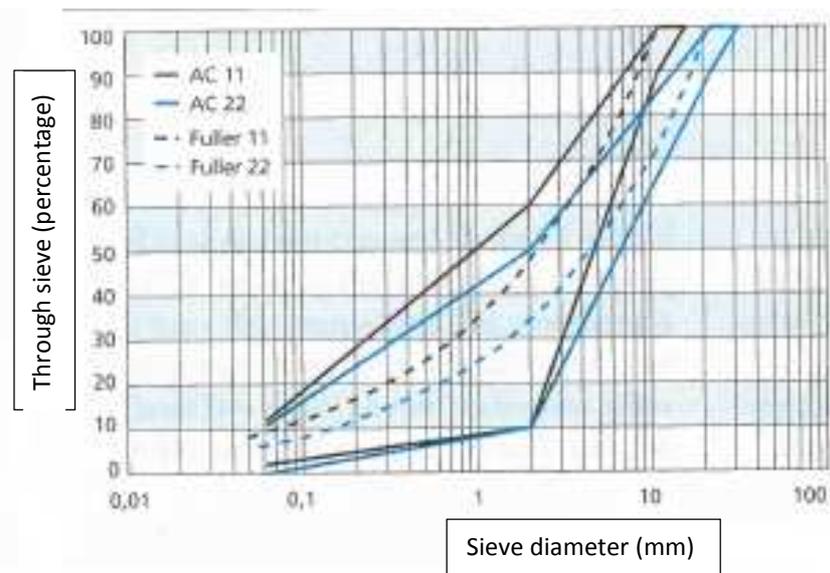


Figure 5 : Characteristic particle size distribution of asphalt concrete (Source : (C.R.O.W, 2010)).

Asphalt concrete can be applied in any of the three asphalt layers namely AC base, AC Surf and AC bind depending on their relative grain size. Within the thesis scope, more emphasis is laid on the AC base, because for pavement design, the base layer is the most important when considering fatigue resistance.

2.2.1 Asphalt Concrete for Base layer

Asphalt concrete used in the base layer is indicated with AC base, with bitumen content generally between 4.5% and 5.0% (m/m). Depending on the layer thickness, several classes of AC base which are used are namely ; AC 32 base, AC 22 base or AC 16 base (C.R.O.W, 2010). For asphalt pavement with a low-traffic intensity, gravel (unbroken aggregate) can be used as a supplementary material, which implies that the internal friction and the resistance to permanent deformation is relatively low. In order words, for heavy loaded pavement, broken aggregate (stone layer) is applied, which means that resistance to permanent deformation is significantly higher than when using gravel. Within the thesis scope, more emphasis is laid on AC 22 base because, the grading of the “RAP” used for the mix production is 22mm.

2.2.2 Literature on Mineral Aggregates

Asphalt mixes consist of stones, sand, and filler which are called the mineral aggregates. In addition to the mineral aggregates, a binder is also added i.e. bitumen. The mix composition has a major influence on the mechanical-physical behavior of the road surface. Soft rock or improper grain shape can lead to crushing of the road surface when loaded by heavy traffic. More so, when the amount of bituminous binder is relatively low in an asphalt mix, it largely determines the behavior of the bituminous structure. The requirements for which the asphalt mix must comply are laid down in the Standard RAW Norms, 2015 .

2.2.2.1 Mineral Aggregate

The mineral aggregates are categorized into three namely :

- Stone fraction (grain diameter >2mm)
- Sand fraction (grain diameter 63µm -2mm)
- Filler fraction (grain diameter <63µm)

The origin, particle size distribution and the properties of the mineral aggregates is briefly highlighted in the following paragraphs.

2.2.2.1.1 Stone fraction

Origin

The importation of stones from outside the Netherlands have increased in recent years, as a result of decrease of stones in the northern parts of the country. Nowadays, a lot of use is made of coarse material such as granite from Scotland and Norway (C.R.O.W, 2010).

Grading

The stone fraction is made up of little and broken materials and the maximum grain size depends on the layer thickness in which the grain is processed. In the Standard NEN norms, there are requirements for which the particle size distributions must be met. The nominal particle size distribution are 2/6, 4/8, 8/11, 11/16, 16/22 and 22/32 which are based on the minimum and maximum grain size in millimeters (C.R.O.W, 2010).

Property

The grain properties of the stone layer should be as cube-shaped as possible. With this, the grain then offers the greatest possible resistance to crushing and gives better internal friction to the mix (C.R.O.W, 2010). In addition, there are requirements made for rough surface and flat pieces .

2.2.2.1.2 Sand fraction

Origin

The sand fraction may consist of one or more sand types. Practically everywhere in the Netherlands there is sand in the soil that can be used for the preparation of asphalt mixes. The particle size distribution is different throughout the country depending on the location (C.R.O.W, 2010). Sand from the same pit can also have a different particle size distribution. Sand is divided into different classes by means of grain size, the geological mode of construction. The types of sand used in the road construction sector are namely :

- Breker sand derived from rock breaker broken river gravel or grove material
- River sand

Distribution

The distribution of the sand fraction must be according to the Standard RAW Norms 2015 with 4 different sieves namely 2mm, 500 μ m, 180 μ m and 63 μ m (C.R.O.W, 2010).

Property

The particle size distribution plays a major role in the stability, the voids and the binder needs of the asphalt mix. The desired properties of adhesion, crushing and internal friction correspond to the previously treated properties of the stone fraction (C.R.O.W, 2010).

2.2.2.1.3 Filler

Origin

The filler used in the Netherlands with a (grain diameter <63 μ m) comprises of mixtures of fly ashes with limestone flour and mineral silicates. The limestone is derived from quarries in Winterswijk, Germany and Belgium while the fly ashes are mainly from power plants in the Netherlands, Germany and Belgium (C.R.O.W, 2010).

Distribution

In the particle size distribution of the filler, the grain diameter is not greater than 2mm. During the mix composition, it should be noted that the amount of added factory filler is not equal to the voids in the filler fraction. This is due to the fact that, the filler fraction is added with the amount of 63 μm from sand, stone and "RAP" (C.R.O.W, 2010). According to the Standard RAW norm 2015, for every mix the virgin filler is decreased by 1%, this is because filler is already present in the other virgin materials which will be used for production of the new mix.

Property

The main properties of the filler in an asphalt mix are as follows :

Mainly that together with the bitumen, the filler forms the mortar (adhesive). With a proper filler / bitumen, the bonding appears to be three times as high.

The filler has a stiffening effect on the binder, thereby improving the viscous behavior of the binder.

2.3 Literature on Bitumen

Bitumen according to the NEN norms, is defined as a very viscous liquid or solid substance consisting essentially of hydrocarbons or their derivatives, which is substantially soluble in sulfur carbon (C.R.O.W, 2010). It is used as a binder in asphalt mixes and is categorized by its penetration index (PI), a single number that is extracted from two tests namely: the ring & ball test and the penetration test. These two tests, therefore establish the temperature dependent visco-elastic properties of bitumen, hence testing the bitumen only on its rheology (Z. Su, W. Giezen, F. Zandvoort, 2012).



Figure 6 : Bitumen
(Source : (Sunny
Paints & Tar
Products, 2017)

The tests are mainly carried out by the supplier, while additional (optional) testing may be done in the asphalt plant. In additional testing, the bitumen fatigue and the stone bitumen affinity are shown to correlate only loosely with the PI-index. More so, when additional testing is done, it is not uncommon to find the PI-index to be incorrect, though the scale and implications of this is quite broad.

2.3.1 Origin of bitumen

Bitumen is a black sticky or dark colored (solid, semi- solid, viscous) amorphous cementitious material that can be found in different forms which occurs naturally and is produced as a result of petroleum processing from crude oil (BITUMINA HI-TECH PAVEMENT BINDERS, 2017). Presently, approximately 80% of bitumen is on demand for road construction (figure 7), which makes it a very important virgin material in the road construction sector.

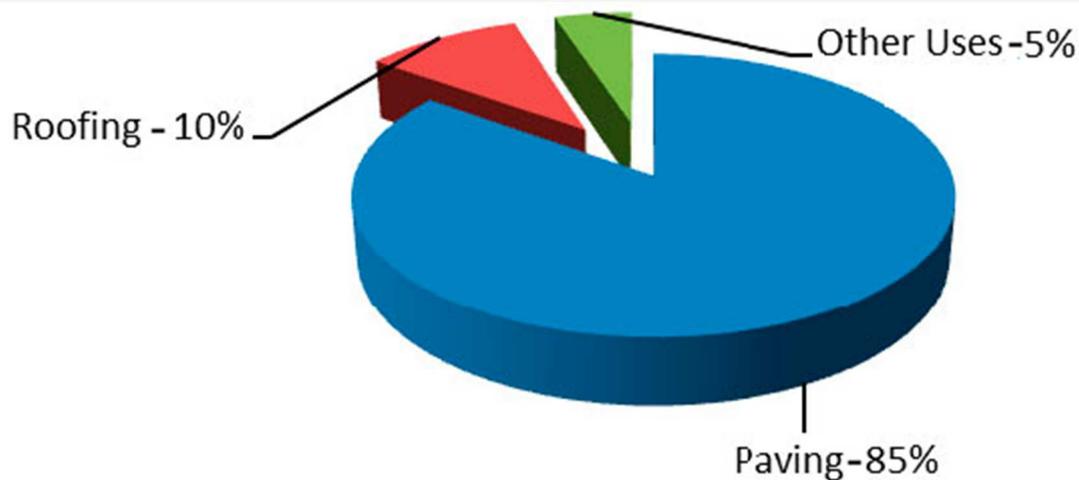


Figure 7 : Use of bitumen in the Road Construction Sector (Source : (BITUMINA HI-TECH PAVEMENT BINDERS, 2017)).

Furthermore, there are several compositions of bitumen, but an exact composition of bitumen does not exist. As a result of this, bitumen is mostly confined to a division in known groups of hydrocarbons. The first division is in asphaltenes and maltenes. Asphaltenes are large unsaturated hydrocarbons in a net like structure (figure 8), while maltenes are divided in three groups namely : saturated aromatics, unsaturated aromatics, and polar aromatics (VBW Asfaltkunde, 2006). A short description of these groups is given in the following paragraphs:

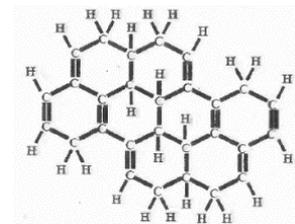


Figure 8 : Asphaltenes

Saturated aromatics

These bind badly to other materials because all “open “ covalent bonds are filled in an energy-favorable way with hydrogen.

Unsaturated aromatics

These are similar to saturated aromatics, but these include double bonds between carbon, which are energetically unfavorable. These aromatics can easily form chemical bonds with other hydrocarbons.

Polar aromatics

These are aromatics which have oxides mixed in occasionally, these oxides can be electrically charged ions or filled with hydrogen. The ion give the possibility for Van der Waals forces. The polar aromatics and asphaltenes are due to their polarity mainly responsible for the mechanical behavior of the bitumen, while the unsaturated hydrocarbons in the aromatics may interlock enhancing the network structure, especially at low temperatures. An increased network structure however, decreases the self-diffusion coefficient which creates healing, while not stopping the diffusion of oxygen , which causes aging and water sensitivity, which may cause stresses upon freezing in the bitumen-stone interface.

Besides this phenomenon, (S. Nahar., A. Schmets., A. Scarpas, 2016) described the difference in trace metals per source, and how to find them. The trace metals in bitumen vary enough that the source can be identified from the analysis of trace metals found in the bitumen alone. These metals also affect the properties of the bitumen, for example the concentrations of especially vanadium and nickel are good indicators for the aging propensity.

Bitumen with a similar rheology may age differently or have a different affinity with other materials, yet this is all the bitumen is tested for. Other properties vary with a variation coefficient of at least 30%, which is close enough in properties for global calculations but a big factor when creating an optimized design which is raveling-sensitive. Especially because these vary per bitumen batch. It's probable that the AC-mix type test is tested with one batch of bitumen, while in the five years that the type test is viable a couple of other batches are used. This effect can be safeguarded against by testing each batch of bitumen which on a voluntary basis is being done for at least some of the batches.

2.3.1 Properties of Bitumen

Bitumen possesses properties which aids the proper binding of the mineral aggregates in the mix. These include penetration, softening point (Ring and Ball), penetration index (PI), property after aging, flashpoint, solubility, dynamic viscosity by 60°C, kinematic viscosity by 60°C etc. The properties are all important because, it determines the degree to which the aggregates are binded. Nevertheless, within the thesis scope emphasis is laid mainly on only three properties namely Penetration, Softening point (Ring and Ball) and Penetration index (PI), due to the fact that the property of the aged bitumen present in the "RAP" is determined in this way. More so, the percentage of bitumen present in the aged bitumen can be determined, in order to know the amount of virgin bitumen needed to be added to the new asphalt mix.

2.3.2 Classes of bitumen

There are three main classes of bitumen used in the road construction sector, but the classification is dependent on their relative level of penetration. The bitumen classes often used are namely ; 35/50, 40/60 and 70/100. These classes are classified further into the soft and hard bitumen class, depending on their various characteristics. The hard bitumen class has a higher melting temperature and lower penetration, while the soft bitumen has a lower melting temperature and higher penetration (table 1). The class 70/100 is mostly added to

“RAP” mixes because it is softer and more viscous, thus blends properly with asphalt mixes as a result of its lower melting temperature and higher penetration level unlike the other two classes.

More so, AC “RAP” mixes have high stiffness as a result of the ageing bitumen. On the scale of comparing the blending properties of mixes, the aged bitumen present in “RAP” has a low penetration and high melting temperature. Therefore, considering the black rock behavior of aged bitumen, the AC “RAP” with highly aged bitumen acts like a rock and it is uncertain if the aged bitumen mixes properly with the virgin bitumen. The “RAP” is composed of a stone skeleton which is fixed with a binder, mortar (mix of sand, filler and bitumen). With the low penetration and high softening point of the aged bitumen, it is uncertain that there is a bonding effect between the aged bitumen and the virgin bitumen. Thence, to ensure a better bonding effect and mixing, a softer class bitumen is applied. With the properties of the bitumen class 70/100, it is most suitable to be applied in the AC Base layer mixes, because when mixed with virgin bitumen it produces a bitumen class of 35/50 with very stiff mixes. More details of bitumen class properties can be found in appendix 2.

Table 1 : Basic Differences Between Soft and Hard Bitumen

The table below shows the main difference between the properties of hard and soft bitumen on basis of their relative properties.

Soft Bitumen	Hard Bitumen
Lower melting temperature	Higher melting temperature
More sensitive for raveling on roads (as a result of splitting of mineral aggregates)	More sensitive for cracks on roads
A higher penetration	Lower penetration
Softens faster when applied on roads during summer period.	Softens slowly when applied on roads during summer period.
Reduced stiffness and a higher fatigue in mix	Increased stiffness and lower fatigue of asphalt mix.
Examples are 70/100, 160/210 and 250/330	Examples are 20/30, 35/50 and 40/60

2.4 Literature on Rejuvenators

In this chapter, one of the methods considered to produce sustainable asphalt mix is discussed. Rejuvenators are agents used for restoring the properties of aged bitumen, improving mix flexibility and reducing the consumption of virgin materials (Holmes, 2017). These agents have the potential to reduce and reverse the aging of asphalt mixes by reducing cracking, raveling etc. (Prapaitrakul N., 2005). The increasing incorporation of highly oxidized bitumen material into pavements has emphasized the need to establish long term durability via effective rejuvenation (Tabatabaee H.A., 2016).

Rejuvenators consist of three mechanisms for treating aged bitumen namely solvators, compatibilizers and softeners. Solvators helps to reduce the viscosity of the continuous solvent phase and the modulus of the overall bitumen, thus having a little effect on the intermolecular agglomeration and self-assembly of the polar micelles. Compatibilizers on the other hand, have an affinity for multiple fractions in the bitumen, hence disrupt/ break-up asphaltene associations. Lastly, the softeners contain low viscosity additions which saturate fractions in the viscous liquid (Cargill, 2017).

Solvents and compatibilizers which simultaneously exhibit properties are known as reactivators. The main aim of the reactivation process is not the reversal of aging but rather the impact of aging on bitumen's mechanical and rheological properties, damage resistance and overall durability and resistance (Tabatabaee H.A., 2016). To buttress the point earlier stated, (Holmes, 2017) emphasized that rejuvenation does not mean reversing the oxidation, rather it means a return of the visco-elastic properties of the binder. More so, rejuvenators are used to restore properties of an asphalt by providing a better and long lasting mix. These emulsions contain oils that reduces the viscosity of an existing asphalt, thus decreasing the cohesive failure of the asphalt as the flexibility of binder is improved (Prapaitrakul N., 2005).

2.4.1 Properties of Rejuvenator

Some properties of a rejuvenator are namely :

- Aids the proper blending of aged and virgin bitumen.
- Equal (or better) aging behavior than original binder.
- Restores balance of Bitumen fractions.
- Restores phase / colloidal stability.
- Reduces brittleness / improve damage resistance.
- Restores "healing" ability.

2.4.1.1 Rejuvenative agents in Recycled Asphalt Mixes

It is summarized that the effects of rejuvenative agents on recycled asphalt mixes and on laboratory-compacted mixes with aging are significant. In a study according to (Prapaitrakul N., 2005), four types of agents were analyzed to show their effect on recycled asphalt mixes. These agents are namely: flux oil, reclamite, dutrex and dust oil. Some limiting parameters encountered as a result of rejuvenators added to recycled asphalt mixes as suggested are described below. These parameters show the effectiveness/ineffectiveness of the rejuvenative agents in relation to the binder properties.

- Results showed that dutrex and dust oil were very effective at softening the aged binder while reclamite was not as effective as the first two agents . The flux oil was relatively ineffective due to its high quantity required to restore original binder properties.
- Marshall Stability of the recycled mix was reduced due to effects of the softening agent.
- Resilient modulus of the recycled mix also decreased to within the range of the newly constructed pavement.
- The relation between stiffness of mixes and binder hardening was also observed in the laboratory, due to the fact that heavily aged mixes should consist of stiffer binder as a result of binder oxidation. It was discovered that reclamite mix stiffened more than others while its binder stiffened less than others.

With these results, conclusions cannot be really made concerning the action of the rejuvenators added to the new asphalt mixes. This is due to the fact that, the rejuvenators used for the research process are different from

the ones used in previously conducted research. Nevertheless, there is a possibility that the results will be similar because all rejuvenators act analogously. In the following chapter, the impact of rejuvenator on aged bitumen will be evaluated to examine the effects or the reaction of rejuvenators on the bitumen extracted from “RAP”.

2.4.2 Impact of Rejuvenator on Aged bitumen

In the following sub chapters, the impact of rejuvenator on aged bitumen is analyzed considering three aspects namely the behavior of virgin bitumen, behavior of aged bitumen and the behavior of rejuvenated bitumen.

2.4.2.1 Virgin bitumen

The molecules of a virgin bitumen are loosed & unconstrained i.e. not tightly packed to each other. A phenomenon responsible for the flexibility of the bitumen. With the free state of the particles, the bitumen is more flexible when heated, thence reducing the fatigue effect of the asphalt mix. Figure 9, shows the behavior of the virgin bitumen with the free state of molecules.

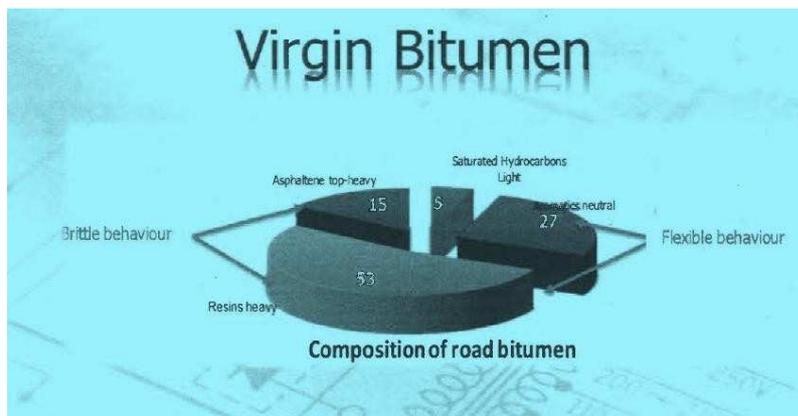


Figure 9 : Virgin bitumen (Source : (Van Weezenbeek Specialties, 2016)

2.4.2.2 Aged Bitumen

The molecules of aged bitumen are tightly packed to each other. A phenomenon responsible for the hardness of the bitumen from the Reclaimed Asphalt Pavement "RAP". The tightly packed molecules of the bitumen makes it inflexible, therefore increasing the fatigue, cracking of the asphalt mix. Figure 10, shows the behavior of the aged bitumen with the molecules.

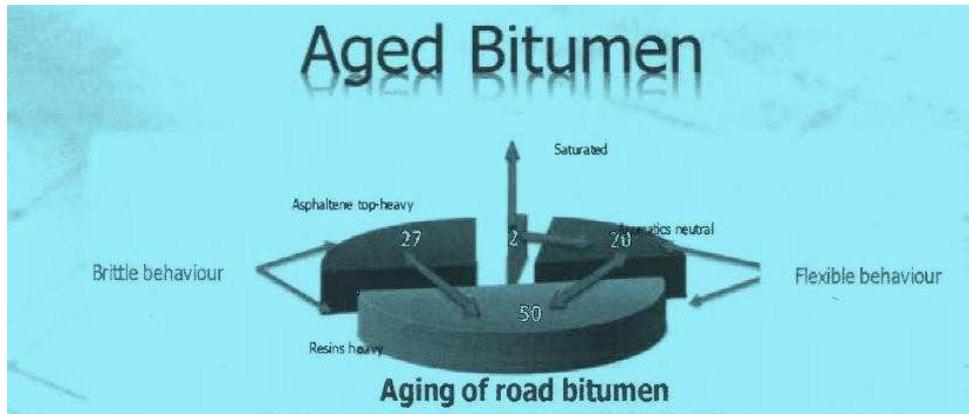


Figure 10 : Aged bitumen (Source : (Van Weezenbeek Specialties, 2016))

2.4.2.3 Rejuvenated Bitumen

The molecules of aged bitumen are tightly packed, therefore the addition of a rejuvenator enables the splitting and flexibility of the bitumen molecules present in the Reclaimed Asphalt Pavement "RAP", hence causing the viscous liquid to become renewed. The rejuvenator works by revitalizing the aged bitumen i.e. reducing the modulus and splitting up the hard molecules, by softening and making it more flexible to enable the proper binding of the mineral aggregates and binder in the asphalt mix (Cargill, 2017). In addition, the rejuvenator increases the bitumen fluidity in the old asphalt, thus reducing effects of stiffness and cracking in the new mix. Figure 11, gives a comparison of different states of bitumen considering the same temperature.

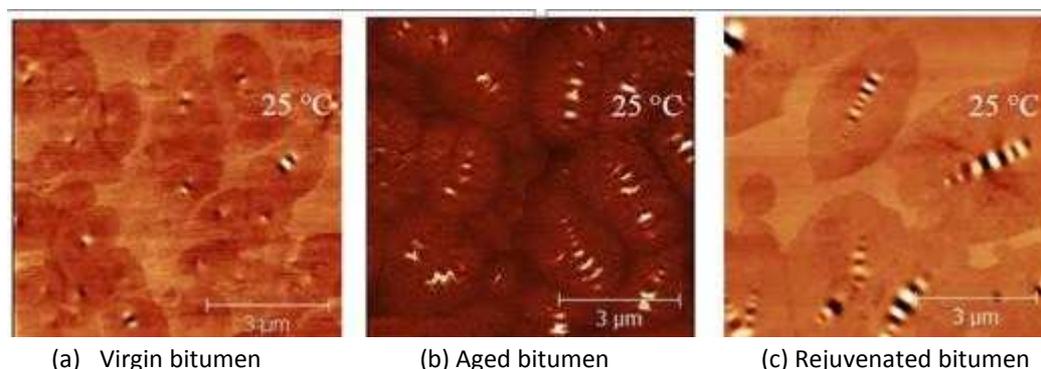


Figure 11 : Effect of rejuvenator on aged bitumen (Source : (Cargill, 2017))

Many rejuvenators can be used to reduce the impact of aging in bitumen, but the selection of rejuvenator depends solely on its effectiveness. According to experiments carried out by (Tabatabaee H.A., 2016) , comparisons were performed on the 40hr PAV aged PG 64-22 (Pen 50-70) base binder using an equal 5% by weight dosage of recycling agent to the 40hr PAV aged bitumen. More so, fractionation was performed on aged and rejuvenated binders comparing Modified Vegetable Based Oil Rejuvenator (Anova 1817) and the Aromatic Petroleum-Based Recycling Agent, SARA (Saturates , Aromatics, Resins, Asphaltenes) to comprehend the possible effects on their mechanism. (Tabatabaee H.A., 2016), hereby concluded that the rejuvenators increased the maltene phase of the aged bitumen and as a result reduced the asphaltene to maltene ratio. In addition, it was indicated that the addition of the aromatic oil-based rejuvenator had the highest contribution to the aromatic fraction of the aged bitumen while the other maltene fractions remained relatively unchanged (figure 12a), but the addition of Modified Vegetable Oil-based Rejuvenator (Anova 1817) increased both the aromatic and resin content of the maltene phase thus serving as a “reactivator” (figure 12b) . The graphical interpretation of the result is shown below (figure 12).

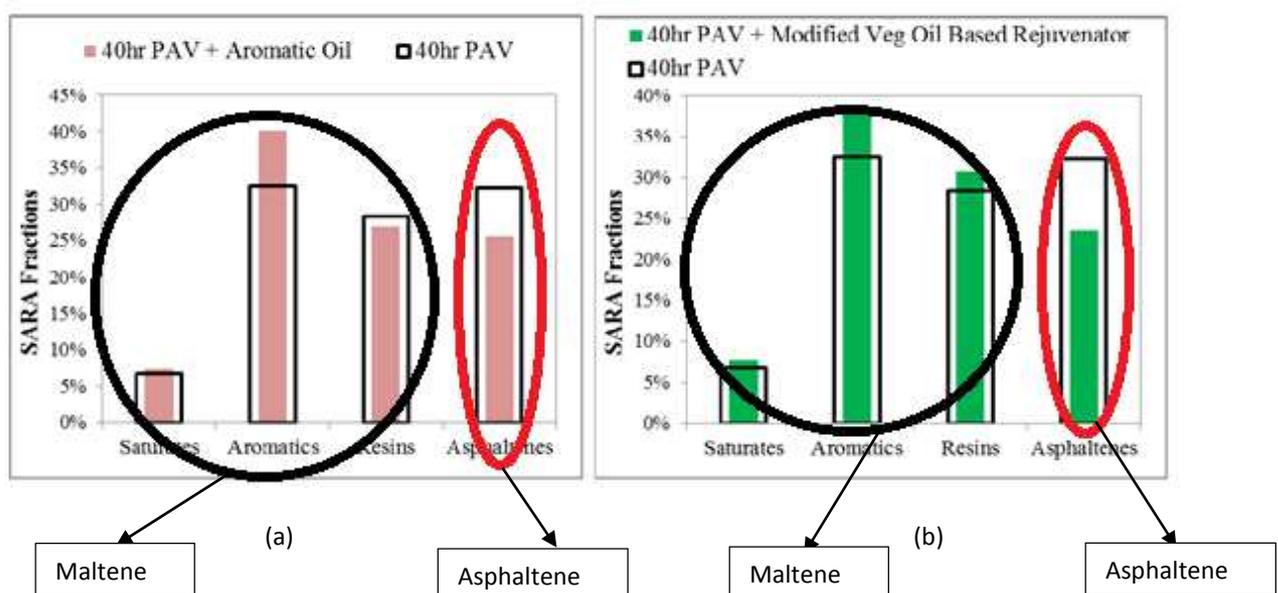


Figure 12 : Effect of rejuvenation on SARA fractions of 40hr PAV-aged bitumen using (a) an aromatic oil based-rejuvenator, and (b) a Modified Oil Base Rejuvenator (Anova 1817) (Source : (Tabatabaee H.A., 2016)).

2.4.2.4 Characteristics of an effective rejuvenator.

In order to ensure that a rejuvenative agent is effective, it needs to exhibit some characteristics which includes its ability to break the tightly packed molecules present in aged binder. More so, a rejuvenating agent reduces the overall viscosity through a decrease in the effective particle size of the asphaltenes by peptizing the asphaltenes (Holmes, 2017). A rejuvenator has to play crucial roles before it is classified effective. Therefore, some crucial roles of a rejuvenator classified by (Holmes, 2017) are highlighted below :

- Restoration of maltene characteristics.
- Activate aged binder and not just soften or plasticize the binder.
- Eliminate/reduce cracking and maintain/improve rut resistance.

- High flash point for use in HMA Plant.
- Disperse readily and maintain miscibility with asphalt blender.
- Must be uniform from batch to batch.

2.5 Rejuvenator Products

There are various types of rejuvenators used in the Road construction sector, but few applied within the thesis scope are namely PrePhalt FBK , AR 830-6, Rheofalt HP-AM and Anova 1817. These rejuvenators were selected to compare and contrast their effects when added to asphalt mixes. In the following paragraphs, a short description of these rejuvenators are given.

2.5.1 PrePhalt FBK

This is one of the rejuvenators used in the road construction sector to reduce the impact of aging in bitumen. This rejuvenator shows asphaltene stabilizing behavior by dynamically upgrading the aged bitumen back to its original properties which slows down the physical hardening of the bitumen, thus slowing the aging process (Van Weezenbeek Specialties, 2016). PrePhalt FBK was used during the research because, it aids the use fewer virgin materials and higher percentages of recycled asphalt granulates which is an objective of the research.



Figure 13 : PrePhalt FBK (Source : (Van Weezenbeek Specialties, 2016))

2.5.2 AR 830-6

This rejuvenator is optimized to enhance the workability of paving mixes with high “RAP” content by mobilizing and rejuvenating the aged bituminous binder (Kraton Corporation, 2016). This rejuvenator was chosen within the research scope because, it restores the flexibility of the aged material giving improved crack resistance workability of the reclaimed asphalt for easier application and improved surface appearances. AR 830-6 was used during the research because it suites the objective of the research.



Figure 14 : AR 830-6

2.5.3 Rheofalt HP-AM

This is a biopolymer vegetable resin additive used for 100% recycling of asphalt. It is a 100% natural liquid rejuvenator made from cashew nut oil, which does not contain any flux oils or light volatile components (Ventraco Innovation Centre, 2017).

Rheofalt HP-AM rejuvenates asphalt back to its original properties without compromising its quality, by simultaneously reducing the cost and use of virgin materials. In addition, the Rheofalt HP-AM possesses a penetration corrector which is a natural modification to soften hard bitumen hence making it possible to modify every type of bitumen to the required penetration and properties. Rheofalt was used during the research because it aids the use fewer virgin materials and higher percentages of recycled asphalt granulates which is an objective of the research.



Figure 15 :
Rheofalt HP-AM

2.5.4 Anova 1817

This is a bio-based solution (asphalt mix rejuvenator) developed to extend the life cycle of asphalt roads. More so, this solution reverses and reduces the impact of aging on asphalt performance, properties, and durability by taking into consideration the three mechanisms of treating aged bitumen. The solvators helps to reduce the viscosity and modulus of the mix and hardly effect agglomerations (Cargill, 2017).

In addition, this rejuvenator modifies the rheology of the bitumen, thus increasing the useful temperature interval of bitumen from many different crude sources through higher softening at lower temperatures without sacrificing the high end temperature while limiting temperature grade loss (Cargill, 2017). Anova 1817 was chosen as one of the rejuvenators within the thesis because, it acts as an excellent polymer compatibilizer. The presence of compatibilizer in Anova 1817 reduces the viscosity of the bitumen and also reduces high MW agglomerations while the softeners in the fluid causes reduction modulus, colloidal instability and also precipitation of asphaltenes (Cargill, 2017).



Figure 16 : Anova 1817

Conclusively, Anova 1817 possesses some unique properties because it enables the addition of high percentage “RAP” to the mix by simultaneously reducing its production temperature. More so, the rejuvenator restores aged bitumen rheology and compatibilizers, thus enhancing cracking resistance.

2.5.5 Rejuvenator Product Comparison

Rejuvenators used in the road construction sector, have various properties which include physical and chemical properties. These properties are mainly divided based on the purpose of the rejuvenator application in an asphalt mixing. Within the thesis scope, the compared rejuvenator properties are mainly based on the main aim of the research which is the allowance of a high percentage of “RAP” recycling. Table 2, gives an overview of the selected rejuvenator properties.

The rejuvenators products earlier stated in chapter 2.5, enable the use of a high “RAP” percentage. Nevertheless, these rejuvenators also vary in different aspects, but the level of variation cannot really be emphasized as a result of the source of production. In order to determine their level of variation relative physical and chemical properties of the rejuvenators are compared (table 2), to have a prior insight on the type of rejuvenator which will produce a better result i.e. an improved mix after testing. The most important features considered are namely ; the recyclable “RAP” content, design aspects, rate of energy consumption etc. A brief explanation of these features or properties are as follows :

2.5.5.1 Recyclable RAP Content.

This involves the ability of the rejuvenator to aid the use of a higher “RAP” percentage because this property is one of the research requirements. More so, it is also important that each rejuvenator aids the recycling of “RAP” with a minimum percentage of 60 %.

2.5.5.2 Durability & Sustainability

This means that the rejuvenator needs to exhibit durable characteristics in its applications with all design aspects of an asphalt. With the application of the rejuvenator, the produced mix should be durable i.e. have an increased technical life span than other asphalt mixes . In addition to durability, the addition of rejuvenator should make the asphalt mix more sustainable i.e. have more improved properties and characteristics.

2.5.5.3 Energy Consumption.

This involves the ability of the rejuvenator to reduce the energy consumption i.e. allow a lower energy consumption during mix production and workability. Therefore, the rejuvenator should have the ability to enhance the workability of recycled asphalt.

2.5.5.4 Prosperity (CO₂ emissions).

This implies that, it is paramount for the rejuvenator when added to the mix to decrease the percentage CO₂ emissions in the environment during production. This is due to the fact that, sustainability within the thesis scope means contribution to a mix in terms of CO₂ reduction.

2.5.5.5 Flashpoint

Flashpoint is temperature at which bitumen/rejuvenator will ignite with an open flame. This property is important during the research process and especially during the production of the mixes in the Asphalt Plant because, the degree of the flashpoint of a rejuvenator determines if it will cause an ignition or not during production. More so, it is preferable that rejuvenator products have a higher flashpoint, due to the fact that during production in the Asphalt Plant the temperature in mixing drum can go up to 300 °C and the rejuvenators with a lower flashpoint can ignite. Therefore, it is preferable within the thesis scope that, the rejuvenator products have a minimum flashpoint of 230°C in order to avoid the risk of explosion. Another benefit of having a product with a higher flashpoint is because it can directly be applied on “RAP” without the need of extra precautions in the Asphalt Plant.

2.5.5.6 Production in the Asphalt Plant

This regards the production of the mix in the asphalt plant. It considers if extra precaution needs to be taken during production, when applying a particular type of rejuvenator to the new asphalt mix. This property is partially dependent on the flash point of the product, due to the fact that a mix with lower flashpoint requires extra precaution.

2.5.5.7 Cost

This implies that the rejuvenator should be least expensive, due to the fact that the cost of the rejuvenator has directly or indirectly an effect on the total cost of the mix production in the Asphalt plant. More so, the relative cost of the rejuvenator contributes to the mix sustainability, which is due to the fact that a sustainable mix with a high cost is not quite appealing to the client.

2.5.5.8 Type of mix.

This considers the ability of the rejuvenators to be applied to any pavement layer mix. Hence, it is important that the selected rejuvenator products can be applied to all mixes especially base layer mixes. This is due to the fact that, only based layer mixes are produced during the thesis scope.

Table 2 : Comparison of Selected Rejuvenator Products and Properties

Product Criteria	AR 830-6 (Rejuvenator)	Anova 1817 (Rejuvenator)	PrePhalt FBK (Rejuvenator)	Rheofalt HP-AM (Rejuvenator)
• Supplier	• Arizona.	• Cargill	• Van Weezenbeek Specialties	• Ventraco
• Recyclable “RAP” content	<ul style="list-style-type: none"> Aids the use of a higher percentage of “RAP” (i.e. allows the recycling of up to 80% “RAP”). 	<ul style="list-style-type: none"> Aids the use of a higher percentage of “RAP” (i.e. allows the recycling of 70%-100% RAP in the base layer). 	<ul style="list-style-type: none"> Aids the use of a higher percentage of “RAP” 60-100% (i.e. allows 95% RAP in the base layer). 	<ul style="list-style-type: none"> Aids the use of a higher percentage of “RAP”.
• Design aspect : Sustainability and Durability	• It is sustainable and durable.	• It is sustainable and durable.	• It is sustainable and durable.	• It is sustainable and durable.
• Energy consumption	• It reduces the energy consumption by simultaneously decreasing the production temperature of the mix.	<ul style="list-style-type: none"> It allows a lower energy consumption i.e. lower mix temperature at the same workability. 	• It causes a higher energy consumption as a result of heating the “RAP”.	• It allows a lower energy consumption by enhancing the workability of recycled asphalt.
• Prosperity (CO2 emissions,)	• The LCA of the product is unavailable due to the fact that it is an experimental product.	• The LCA of the product can probably be combined with Eco chain.	• The LCA of the product can probably be combined with Eco chain. The product is fully recyclable by saving of 1,5million tons of CO2 for every truckload).	<ul style="list-style-type: none"> The LCA of the product can probably be combined with Eco chain. The product reduces the amount of CO2 emissions to the environment. The product is fully recyclable with the combination of bitumen.
• Flashpoint	• It has a flashpoint of >200°C.	• It has a flashpoint >290°C.	• It has a flashpoint of >200°C.	• It has a flashpoint of 201°C.
• Production in Asphalt Plant	<ul style="list-style-type: none"> It requires extra precaution during mix production in the asphalt plant as a result of the low flash point. The contact of flame and the rejuvenator needs to be avoided to prevent risk of explosion. 	• It can be applied during mix production the asphalt plant and does not require extra precaution.	• It requires extra precaution during mix production in the asphalt plant as a result of the low flash point.	<ul style="list-style-type: none"> It requires extra precaution during mix production in the asphalt plant as a result of the low flash point. It also requires early dosage in nearly all asphalt plants.
• Cost	• It is cost friendly because it enables the use of less virgin aggregates, virgin bitumen with a higher percentage of “RAP” content.	• It is cost friendly because it enables the use of less virgin aggregates, virgin bitumen with a higher percentage of “RAP” content.	<ul style="list-style-type: none"> It is cost friendly because it enables the use of less virgin aggregates, virgin bitumen with a higher percentage of “RAP” content. It is 2x cheaper than other rejuvenator products. 	• It is cost friendly because it enables the use of less virgin aggregates, virgin bitumen with a higher percentage of “RAP” content.
• Type of mix	<ul style="list-style-type: none"> It can be applied to any pavement layer, because the effect of the product is on the binder. 	• Its application is mainly restricted to the base layer.	• Its application is mainly restricted to the base layer.	• It can be applied to any pavement base layer.

The comparison of the rejuvenator property, is a general information obtained from the suppliers depending on each product performance. Nevertheless, the properties will be used as a basis to set up criteria and sub-criteria for the Multi Criteria Analysis which will be further used during the research process as one of the requirements to determine the most sustainable mix. For the MCA, the rejuvenator property will be divided into groups in order to provide a better overview of each product characteristics.

2.6 Virgin Materials

Apart from the 80% “RAP” used in the production of the new asphalt mixes. The mix contains other virgin materials namely the mineral aggregates, filler and binder. The binder used are namely ; bitumen, PrePhalt FBK, AR 830-6, Rheofalt HP-AM, Anova 1817 which are stated earlier in chapter 2.3 and chapter 2.5 respectively. The mineral aggregates are namely:

- River sand
- Scottish granite 8/16
- Scottish granite 16/22
- Bestone 4/8

The mineral aggregates were selected based on the choice of DIBEC for the production of base layer mixes, which is as a result of the bitumen properties and coarseness of mineral aggregates present in the RAP (appendix 3). Secondly, these particular mineral aggregates were chosen as a result of their availability at the Storage Depot in the Asphalt Plant. In the following paragraphs, a brief explanation of the filler and mineral aggregates is given, with a description of the relative percentages added to the asphalt mixes. Within the thesis scope, there is limited information available from the suppliers of the virgin mineral aggregates used in the production of the asphalt mixes. This is due to the fact that, the materials were not obtained directly from the suppliers, but rather were obtained from the Storage depot at Asphalt Plant Amsterdam (APA), according to the DIBEC’s instructions.

2.6.1 Filler from Mineral Aggregates

The filler is one of the virgin materials used in the production of the new asphalt mixes. In the road construction sector, there are different fillers which are applied to asphalt mixes ranging from very weak to middle type fillers. Within the thesis scope, the filler used production of the asphalt mixes was obtained during the separation of mineral aggregates in the Asphalt Plant and only a little percentage, i.e. 1% was used, which is as a result of the use of less virgin materials. Figure 17, shows an example of the filler used during the research.



Figure 17 : Filler

2.6.2 River sand

This is another mineral aggregate used in the production of the new asphalt mixes. The river sand is obtained during the decrease in velocity of the rivers, whereby the larger grains remain and only the small ones are taken (Zand, 2017). The grains of river sand are angular and are obtained from some rivers in the Netherlands namely ; Scheldt, Maas, Rhine, East German rivers (Zand, 2017) etc. Moreso, the percentage of the river sand used in the production of the new asphalt mix is quite minimal i.e. 1 % which is as a result of the use of more RAP and less mineral aggregates.



Figure 18 : River sand

2.6.3 Scottish granite 8/16

The Scottish granite 8/16 is one of the mineral aggregates used within the thesis scope for the production of the new asphalt mixes. The colour of the Scottish granite 8/16 is either Pinkish or reddish (figure 19). It is a coarse aggregate in the category Gc 90/10 with $D > 4\text{mm}$ and $d \geq 1\text{mm}$. Some properties of the Scottish granite 8/16 are namely the flakiness index, percentage of totally crushed particles and the Los Angeles coefficient. According to norm (code :NEN-13043) (appendix 4), it falls within the category F/30 i.e. has a flakiness index of ≤ 30 . For the percentage of crushed stones, it is classified as C100/0 i.e. the percentage of totally crushed or broken particles by mass is between 90-100. For resistance to fragmentation, the stone falls within the category LA25 i.e. the Los Angeles coefficient is ≤ 25 . The percentage of Scottish granite 8/16 used in the production of the new asphalt mix is 10,2 % which is quite a higher percentage than the other mineral aggregates. More information on the properties of Scottish granite 8/16 can be found in (appendix 5).



Figure 19 : Scottish granite 8/16

2.6.4 Scottish granite 16/22

The Scottish granite 16/22 is another mineral aggregates used within the thesis scope for the production of the new asphalt mixes. The Scottish granite 16/22 is also a coarse aggregate in the category Gc 90/15 with $D > 4\text{mm}$ and $d \geq 1\text{mm}$. The properties are similar to 8/16 because they are from the same origin, and the only difference is their relative particle size. The percentage of Scottish granite 16/22 used in the production of the new asphalt mix is 6,7 %. Figure 20, shows an example of Scottish granite 16/22. More information on the properties of Scottish granite 16/22 can be found in appendix 5.



Figure 20 : Scottish granite 16/22

2.6.5 Bestone 4/8

The Bestone 4/8 is one of the mineral aggregates, used within the thesis scope for the production of the new asphalt mixes. The colour of the Bestone 4/8 is grey (figure 21). It is also a coarse aggregate in the category GC85/15 with $D > 4\text{mm}$ and $d \geq 1\text{mm}$. Some properties of the Bestone 4/8 are namely the flakiness index, percentage of totally crushed particles and the Los Angeles coefficient. According to norm (code : NEN-13043) (appendix 4), it falls within the category *F125* i.e. has a flakiness index of ≤ 25 . For the percentage of crushed stones, it is classified as *C100/0* i.e. the percentage of totally crushed or broken particles by mass is between 90-100. For resistance to fragmentation, the stone falls within the category *LA15* i.e. the Los Angeles coefficient is ≤ 15 . The percentage of Bestone 4/8 used in the production of the new asphalt mix is 1 % which is quite a small percentage, compared to other mineral aggregates. More information on the properties of Bestone 4/8 can be found in appendix 5.



Figure 21 : Bestone 4/8

2.7 Sustainability

Within the research scope, the sustainability of the asphalt mixes will be determined using EcoChain software. In order to do this, other tools namely Environmental Cost Indicator (MKI) and Life Cycle Analysis (LCA) are incorporated into the EcoChain to analyze the sustainability of the asphalt mixes.

2.7.1 MKI (Environmental Cost Indicator)

MKI represents Environmental Cost Indicator and the number that is calculated indicates the environmental costs (€) for a project. These are the costs that are incurred if all negative environmental impacts for construction and maintenance of the project have to be offset against current measures (MKI score van wegen aanleg en onderhoud, 2017). The negative environmental impacts of materials and virgin materials and their processing in construction and maintenance work are calculated in a standard manner using a standardized LCA (Life Cycle Analysis). This data is managed by the SBK (Foundation of Building Quality) in a database that allows DuboCalc to make the calculations. This also implies that, DuboCalc can only count on materials and virgin materials included in the database. In addition, a more durable design and execution is sent to:

- Minimizing transport distances of (secondary) commodities;
- The pursuit of sustainable materials and virgin materials.
- Recycling of (released) materials and virgin materials.

Furthermore, the MKI is a tool used to determine the environmental cost of an asphalt mix . Therefore, the lower the environmental cost the more sustainable a mix becomes. For this purpose, the sustainable use of virgin materials used in the production of an asphalt mix are grouped into two sub aspects namely :

- Selection of virgin materials
- Sustainable mix.

2.7.1.1 Selection of virgin materials and commodities

This plays a vital role in the environmental cost indication in terms of the acquisition of virgin materials i.e. where and how are the virgin materials retrieved. Apart from the acquisition of virgin materials, the production methods (energy consumption, climate impacts), recycle percentages etc. also have an effect on the MKI score which can either be positive or negative. Therefore, the standard method used in the determination of sustainability is the preparation of a Life Cycle Analysis (LCA). The SBK, thence collects this data from many materials and virgin materials used in the GWW.

2.7.1.2 Sustainable mix

This deals with aspects such as transportation distance i.e. how far do the materials have to travel. This considers the transport distance i.e. how far the materials and mineral aggregates are transported to the asphalt plant. Nevertheless, this problem can be solved by decreasing supply using locally available materials.

The aspects of the environmental cost, are both analyzed in DuboCalc and are further expressed in a DuboCalc calculation in an MKI score. Thus the lower the MKI score, the higher the sustainability application of the chosen virgin materials. However, not all materials and virgin materials are available in DuboCalc.

The MKI score of an asphalt mix for road a construction, is mainly determined by the bulk and virgin materials. Some findings of DuboCalc calculations for road projects (MKI score van wegen aanleg en onderhoud, 2017) are as follows ;

- For the virgin materials i.e. sand, gravel, stone etc. applied in the foundation, the transport distance counts and the use of (secondary) virgin materials from the immediate environment and the closing of the ground balance are favorable measures ;
- For materials used for paving namely asphalt, concrete and paving blocks. The mode of production (use of virgin materials, material recycling, energy consumption and transport to asphalt plant in the Netherlands is important.

Therefore, it requires an integral standardized LCA approach to qualify the material as sustainable and also to compare the materials. The focus may therefore be on the MKI score of the applied bulk materials for a construction. During the production of mixes, it is a little difficult as a contractor, to freely optimize the mix design because there is more focus on the MKI score of the applied bulk materials. Nevertheless, the location of the virgin materials can also be decided by the mix designer. Thence, within the research scope, the MKI score of all the asphalt mixes will be analyzed to determine the mix with the lowest MKI score.

2.7.2 Life Cycle Analysis

LCA represents Life Cycle Analysis, which is a tool used in determining the total environmental impact of a (construction) product during its entire lifecycle, i.e. extraction of virgin materials, production, transport, construction and maintenance (EcoChain Technologies B.V., 2017).

Rijkswaterstaat, provinces and municipalities have the necessities, to examine the LCA of a product so that sustainable asphalt variants can be purchased in the context of sustainable procurement. In addition, asphalt plants have the need to analyze the production circuit, because reduction in major energy consumption and CO₂ emissions can be realized in the production chain (EcoChain Technologies B.V., 2017). In 2010, Rijkswaterstaat, in connection to the pilot project A3 in DuboCalc, made available a DuboCalc product database. This product data base contains 10 asphalt product LCAs which are still registered in the National Environmental Database (NMD) of the SBK. A fast analysis from the Department of Bituminous Work (VBW) of Bouwend Nederland and EcoChain Technologies in an Intron-analysis from 2013 showed that, there were internal inconsistencies with the old LCA figures, such as the ratio between CO₂ and MKI, and the effect of the Partial Recycling (EcoChain Technologies B.V., 2017).

For this reason, the (Rijksdienst voor Ondernemende Nederland) and the asphalt sector (represented by the VBW of Bouwend Nederland) were urged need to be to generate LCAs and other environmental data in a simple, user-friendly and transparent way of existing and new asphalt mixes (EcoChain Technologies B.V., 2017).

Therefore, with the new LCA :

- Reliable and accurate quantitative environmental data of 17 branch representative mixes from the asphalt sector can be calculated. The 17 branch representative mixes can be found appendix 6.
- The asphalt sector, with VBW as a representative, can deliver key figures and LCAs from the 17 most common asphalt mixes used in the Netherlands as input for the NMD and DuboCalc.
- A basis for construction calculations can be made and also realization of works that cause less or no environmental impact (sustainable purchasing).

In addition, the new LCA data provides Asphalt Plant an opportunity to gain insight into the environmental impacts of the 17 branch representative mixes and compare this to their own performance in EcoChain. With the environmental calculations of the various asphalt mixes, a targeted decision can be made in the context of sustainable procurement. The ability to consult the database for new asphalt products i.e. branch representative mixes from the asphalt sector. The key figures in the LCA, thence provides entrepreneurs within the asphalt sector immediate insight into the impact of environmental measures in products and processes.

The basis for implementing LCA is the reference unit. The reference unit is formulated in two forms:

- product unit
- functional unit.

Within the research scope, focus is made on the production unit because it involves the production of asphalt mixes. The production unit is described as the production, demolition and waste processing phase of 1 ton of asphalt. The LCA analysis is made for the asphalt mixes considering its production in the asphalt plant by comparing the LCA data of all the materials used in production using the process tree of LCA.

2.7.2.1 Process Tree of LCA

The process tree of LCA includes all economic flows (both materials, products and energy) required for the product unit. Figure 22, shows the process tree for the production of the asphalt, in accordance with the determination method which include ; virgin materials /energy extraction, production phase, demolition and waste phase, and reuse and recycling. The construction phase and the maintenance phase are excluded for this research, due to the fact that they are irrelevant for the thesis purpose. Nevertheless, the LCA of the produced asphalt mixes is determined by combining the LCA of virgin materials and products used during the production process.

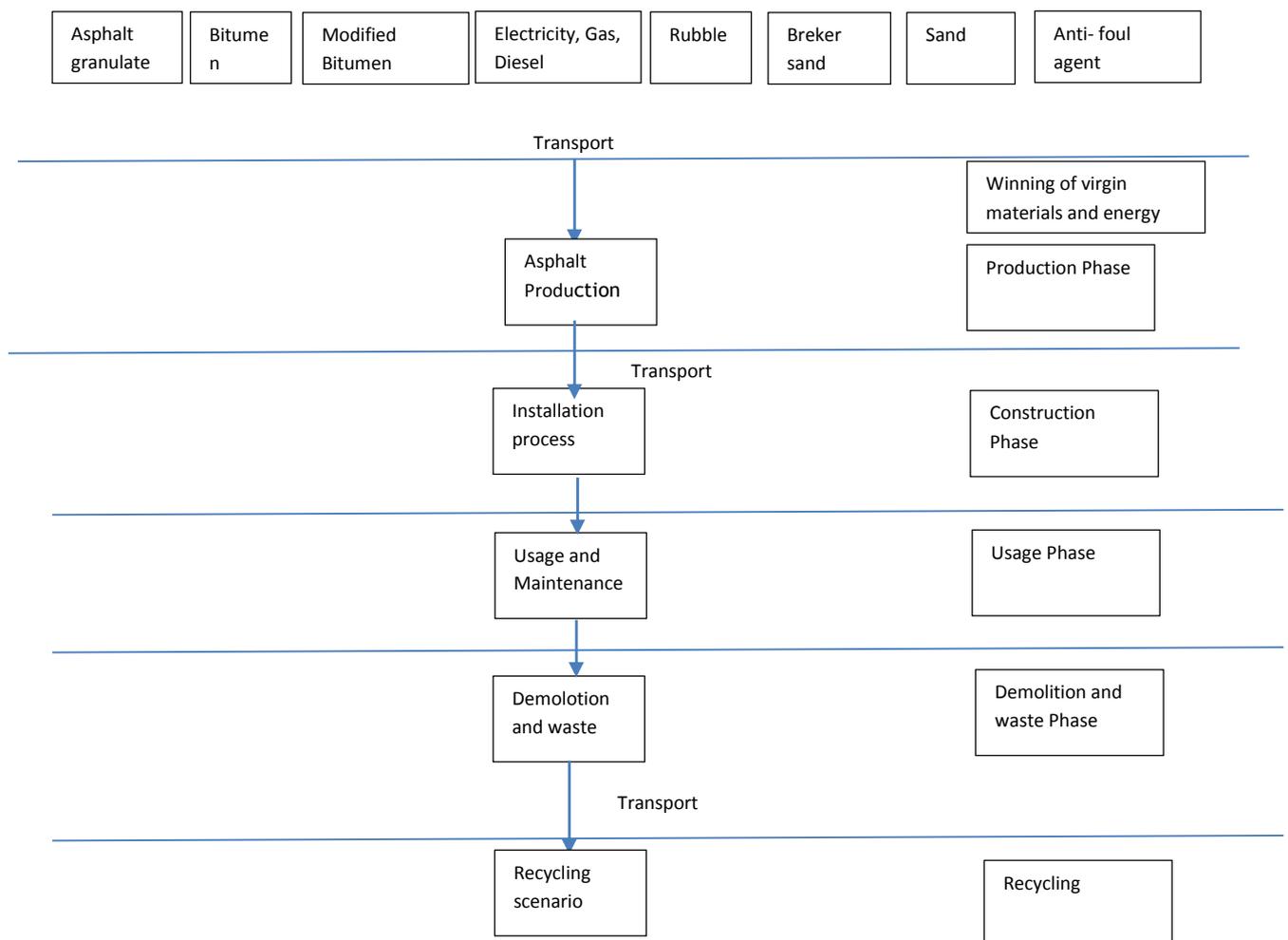


Figure 22 : LCA Process Tree (Source : (EcoChain Technologies B.V., 2017))

2.7.3 EcoChain

With the analysis of the MKI and LCA, the data from these tools will be input into the EcoChain to determine the mix sustainability. EcoChain is an environmental management software which works by creating awareness for the asphalt manufacturer concerning the type of the virgin materials required during production and the energy flow in the production plant, process and product by examining the mix relative level of sustainability. The input data allows the manufacturer to know where production efficiency can be optimized in order to achieve the most environmental results by saving energy and materials, thus significantly reducing cost (EcoChain Technologies B.V., 2017).



At the beginning of the thesis, it was stated that the sustainability and durability of the produced asphalt mixes is of great importance, due to the fact that clients and contractors within the road construction sector want to invest and focus more on the use of sustainable materials. The sustainability of asphalt mixes cannot be effectively determined in the asphalt plants (Asphalt Plant Amsterdam (APA) or Asphalt Plant Rotterdam Rijnmond (APRR)), due to the lack of inadequate programs in the plant. EcoChain was therefore incorporated during the thesis to check the sustainability of the produced asphalt mixes by determining the MKI (Environmental Cost Indicator), the percentage of CO₂ emissions and energy usage during the asphalt production process. In addition, the software is used within the thesis scope to analyze the durability and sustainability of the produced asphalt mixes by comparing the LCA (Life Cycle Analysis) data of all products used during the production namely the virgin materials, "RAP", rejuvenators, environmental costs and supply chain transparency.

Therefore, the sustainability of the produced mixes in EcoChain is determined based on the MKI score, LCA of the products/virgin materials, CO₂ emissions and Energy Usage.

3. Method

In this chapter, details of the tasks executed during the research process are described giving an overview of the various activities carried out, which are namely the research activities, test activities, schedule of requirements, process of tests execution, OIA calculation, EcoChain, Cost and MCA. These activities are highlighted stating their requirement for the research process and how they are executed in order to obtain the end product which is the production of an improved and sustainable asphalt mix.

More so, the method involves the production process of the new asphalt mixes. The mixes produced are AC base mixes, and the rejuvenator products earlier stated in chapter 2.5 were added to the mixes. A total of 5 mixes were produced i.e. 1 Reference mix and 4 other mixes containing rejuvenators. More so, the description of test procedure for AC base mixes according to the Standard NEN norm is described. In this chapter, the names of rejuvenators used during the research process is not mentioned but are rather represented with numbers for confidential purposes (appendix 7). The produced asphalt mixes are as follows :

- Mix 0 : Reference mix : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100)+ No rejuvenator.
- Mix 1 : AC 22 Base/Bind (80% RAP) + Rejuvenator 1.
- Mix 2 : AC 22 Base/Bind (80% RAP) + Rejuvenator 2.
- Mix 3 : AC 22 Base/Bind (80% RAP) + Rejuvenator 3.
- Mix 4 : AC 22 Base/Bind (80% RAP) + Rejuvenator 4.

3.1 Research Activities

The research activities are mainly related to the sub questions i.e. generally considering the research process, while the test activities mainly outline the tasks carried out during the test. The purpose of these activities are to arrive at the end product which is the production of sustainable asphalt mixes. The research activities includes the tasks carried out to provide answers to the sub questions earlier outlined in chapter 1.5. With these activities, result is provided which serves as a working method to the production of sustainable asphalt mixes. More so, it is important to note that some of the research activities are already executed in the theoretical framework and their results are further incorporated in the Method. An overview of the research activities are given on the next page in table 3.

Table 3 : Research Activities

Research question	Task/ Activities	Result
<ul style="list-style-type: none"> What factors need to be considered in order to produce an asphalt mix with >50% ‘RAP’? 	<ul style="list-style-type: none"> Research on the highest ‘RAP’ percentage recycled in the road construction sector till date. Research on the requirements of recycling ‘RAP’. 	<ul style="list-style-type: none"> Production of mix with more than 50% ‘RAP’.
<ul style="list-style-type: none"> How can a higher percentage of ‘RAP’ be recycled in a new mix? 	<ul style="list-style-type: none"> Research on the use of high ‘RAP’ percentage in asphalt mixes. Research on the factors which need to be considered to produce mix with higher ‘RAP’ percentages. 	<ul style="list-style-type: none"> Addition of rejuvenators to the new mix.
<ul style="list-style-type: none"> How can the efficient use of raw materials and ‘RAP’ be combined to produce sustainable asphalt mixes ? 	<ul style="list-style-type: none"> Research on types of rejuvenators available in the road sector which fits into the research scope. Research on types of rejuvenator which decrease the use of virgin materials. 	<ul style="list-style-type: none"> Comparison of rejuvenators.
<ul style="list-style-type: none"> How can the molecules of the aged bitumen present in the ‘RAP’ become modified? 	<ul style="list-style-type: none"> Research on the process modification of aged bitumen into rejuvenated bitumen. 	<ul style="list-style-type: none"> Rejuvenated bitumen
<ul style="list-style-type: none"> How can the composition of ‘RAP’ be obtained i.e. the bitumen content and the coarseness of mineral aggregates ? 	<ul style="list-style-type: none"> Bitumen Extraction Procedure. Extraction of aged bitumen. Particle size distribution of ‘RAP’. 	<ul style="list-style-type: none"> Extracted aged bitumen. Mix Composition and Bitumen Property Test. Sieve Analysis.
<ul style="list-style-type: none"> How can the properties of the aged bitumen be determined? 	<ul style="list-style-type: none"> Research on the how the properties of the aged bitumen is determined. Research on the factors which need to be taken into consideration. 	<ul style="list-style-type: none"> Penetration Test (code : NEN-EN 1426). R & B Test (code : NEN-EN 1427) Penetration Index (code : NEN-EN 12591).
<ul style="list-style-type: none"> What experiments will be considered within the research scope to test Asphalt Concrete mixes and what Standard norms will be used ? 	<ul style="list-style-type: none"> Research on the Type test carried out for AC base mixes. Research on the Type Test which fits within the research scope. 	<ul style="list-style-type: none"> Stiffness Test (code : NEN-EN 12697-26) Fatigue Test (code : NEN-EN 12697-24+A1) Permanent deformation (code : NEN-EN 12697-25)
<ul style="list-style-type: none"> How can the base layer thickness of the produced asphalt mixes be determined ? 	<ul style="list-style-type: none"> Research on how to calculate the base layer thickness . Calculation of base layer thickness of the 5 produced asphalt mixes. 	<ul style="list-style-type: none"> OIA Calculation
<ul style="list-style-type: none"> What factors need to be taken into consideration in order to produce a mix with decreased CO2 emissions ? 	<ul style="list-style-type: none"> Drawing up a schedule of requirements. Research on the functional and technical requirements of the mix considering the clients specifications. The use of EcoChain software to check the durability of the mix. 	<ul style="list-style-type: none"> EcoChain
<ul style="list-style-type: none"> What factors will be considered to analyze the sustainability of the produced asphalt mixes ? 	<ul style="list-style-type: none"> Research on factors which need to be considered to check the mix sustainability. Research on criteria to be considered within the research scope in terms of sustainability. Research on the effect of environmental cost indicator (MKI) on the mix sustainability. Research on the life cycle analysis (LCA) of the bitumen, rejuvenators and mineral aggregates used in the production of the new mix. Research on the amount of energy usage required for the production of a mix. Research on how the MKI and LCA can be incorporated into EcoChain to determine the mix sustainability. 	<ul style="list-style-type: none"> Analysis of Environmental Cost Indicator (MKI) Analysis of the Life Cycle Analysis of the mix (LCA) EcoChain
<ul style="list-style-type: none"> How can the most cost efficient mix be determined considering the produced asphalt mixes? 	<ul style="list-style-type: none"> Research on the binder cost i.e. bitumen and rejuvenator. 	<ul style="list-style-type: none"> Cost analysis of the 5 asphalt mixes.

	<ul style="list-style-type: none"> • Research on the cost of asphalt mixes without binder. • Research on the cost of asphalt mixes with binder. 	<ul style="list-style-type: none"> • Cost comparison of the 5 asphalt mixes.
<ul style="list-style-type: none"> • How the choice of the most sustainable asphalt mix be determined ? 	<ul style="list-style-type: none"> • Research on factors to be considered to make a choice of the most sustainable mix i.e. rejuvenator property, laboratory testing, OIA Calculation, EcoChain and Cost. • The MCA analysis of these 5 factors. 	<ul style="list-style-type: none"> • MCA result of Rejuvenator Property. • MCA result of Laboratory Testing. • MCA result of OIA Calculation. • MCA result of EcoChain. • MCA result of Cost • Overall Comparison of the 5 MCA"s.

3.1.1 Test Activities

The test activities, unlike the research activities involves mainly the laboratory activities, this includes tasks carried during the bitumen extraction procedure and also after the production of the tests samples. An overview of the test activities is shown in the table below (table 4), stating the aim of test, result and the required value according to Standard NEN-EN norm.

Table 4 : Test Activities

Test/Experiment	Task/Activities	Aim of Test	Result	Required value according to Standard NEN norm
<ul style="list-style-type: none"> • Bitumen Property Test 	<ul style="list-style-type: none"> • Bitumen Extraction Procedure 	<ul style="list-style-type: none"> • Obtaining the composition of the "RAP" i.e. bitumen content (%) and coarseness of mineral aggregates. 	<ul style="list-style-type: none"> • Extracted aged bitumen. • Mix Composition and Bitumen Property Test. • Sieve Analysis. 	<ul style="list-style-type: none"> • There is no standard value for the bitumen content (%), The result can vary depending on the type of "RAP" used.
<ul style="list-style-type: none"> • Penetration Test 	Penetration Test (code : NEN-EN 1426). <ul style="list-style-type: none"> • Sample 1 aged bitumen. • Sample 2 aged bitumen. • Sample 3 aged bitumen. 	<ul style="list-style-type: none"> • The aim of the test is to determine a measure of bitumen hardness extracted from the "RAP" under the following conditions i.e. measuring the penetration at 25°C in 0.1mm of a standard needle, for 5 seconds under a load of 100g. 	<ul style="list-style-type: none"> • Result from three aged bitumen sample • Average result obtained from three aged bitumen samples 	<ul style="list-style-type: none"> • Penetration at 25°C of bitumen class 35/50 should be between 35-50 (unit 0,1mm).
<ul style="list-style-type: none"> • Ring and Ball Test 	Ring and Ball Test (code : NEN-EN 1427). <ul style="list-style-type: none"> • Sample 1 aged bitumen • Sample 2 aged bitumen. 	<ul style="list-style-type: none"> • The aim of the test is to determine the temperature, at which the aged bitumen softens or becomes viscous. 	<ul style="list-style-type: none"> • Result from two aged bitumen sample. • Average result from two aged bitumen samples. 	<ul style="list-style-type: none"> • The difference between the two temperatures obtained during the test should not exceed 1 °C for softening points below 80 °C. • For softening points below or equal to 80 °C, the result should be expressed as to the nearest 0,2 °C

				the mean of the temperatures.
<ul style="list-style-type: none"> Penetration Index 	Penetration Index (code : NEN-EN 12591) <ul style="list-style-type: none"> Calculation of penetration index of the extracted bitumen. 	<ul style="list-style-type: none"> The aim of the penetration index is to determine of a measure of the temperature dependence of the bitumen penetration 	<ul style="list-style-type: none"> Result of Penetration Index. 	<ul style="list-style-type: none"> Penetration index of bitumen class, 35/50 should be between -1,5 to +0,7
<ul style="list-style-type: none"> Stiffness 	Stiffness (code : NEN-EN 12697-26) <ul style="list-style-type: none"> Reference mix : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100)+ No rejuvenator. Mix 1 : AC 22 Base/Bind (80% RAP) + Rejuvenator 1. Mix 2 : AC 22 Base/Bind (80% RAP) + Rejuvenator 2. Mix 3 : AC 22 Base/Bind (80% RAP) + Rejuvenator 3. Mix 4 : AC 22 Base/Bind (80% RAP) + Rejuvenator 4. 	<ul style="list-style-type: none"> The main aim of the test is to determine the resistance to stiffness of the produced asphalt mixes 	<ul style="list-style-type: none"> Comparison of results from 5 mixes. Comparison of mixes in relation to stiffness. 	<ul style="list-style-type: none"> For OL-C Traffic Category, the minimum required value S_{min} and maximum S_{max} are 7000 MPa and 14000 MPa respectively, i.e. $7000 \leq x \leq 14000$ MPa.
<ul style="list-style-type: none"> Fatigue 	Fatigue (code : NEN-EN 12697-24+A1) <ul style="list-style-type: none"> Reference mix : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100)+ No rejuvenator. Mix 1 : AC 22 Base/Bind (80% RAP) + Rejuvenator 1. Mix 2 : AC 22 Base/Bind (80% RAP) + Rejuvenator 2. Mix 3 : AC 22 Base/Bind (80% RAP) + Rejuvenator 3. Mix 4 : AC 22 Base/Bind (80% RAP) + Rejuvenator 4. 	<ul style="list-style-type: none"> The main aim of the test is to determine the resistance to fatigue of the produced asphalt mixes. 	<ul style="list-style-type: none"> Comparison of results from 5 mixes. Comparison of mixes in relation to fatigue. For OL-C Traffic Category, $\epsilon_6 \geq 90$. 	<ul style="list-style-type: none"> For OL-C Traffic Category, $\epsilon_6 \geq 90$.
<ul style="list-style-type: none"> Permanent deformation 	Permanent deformation (code : NEN-EN 12697-25) <ul style="list-style-type: none"> Reference mix : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100)+ No rejuvenator. Mix 1 : AC 22 Base/Bind (80% RAP) + Rejuvenator 1. Mix 2 : AC 22 Base/Bind (80% RAP) + Rejuvenator 2. Mix 3 : AC 22 Base/Bind (80% RAP) + Rejuvenator 3. Mix 4 : AC 22 Base/Bind (80% RAP) + Rejuvenator 4. 	<ul style="list-style-type: none"> The main aim of the test is to determine the resistance to permanent deformation of the produced asphalt mixes 	<ul style="list-style-type: none"> Comparison of results from 5 mixes. Comparison of mixes in relation to permanent deformation. 	<ul style="list-style-type: none"> For OL-C Traffic Category, $f_c \leq 1,4$.

3.2 Method Description

The selection of the most suitable mix is dependent on three main factors namely ; Type test result, Sustainability (EcoChain) and Cost of the mix. The Type test result depends on the relative characteristics of the mix in regards to stiffness, fatigue and permanent deformation, while the level of the mix sustainability is analyzed using EcoChain and the Cost is comparison of the asphalt mixes in regards to production in the asphalt plant. In addition, as earlier stated the names of rejuvenators used during the research process is not mentioned but are rather represented with numbers for confidential purposes (appendix 7).

Sustainable Asphalt Mix		
Type Test Result	Sustainability : EcoChain	Cost

This chapter describes the execution process of the research by taking into consideration various steps which leads to the achievement of the final product. More so, a detailed explanation of the thesis is described by structuring the research work process. The process is structured in a different manner than usual, because the determination of the most suitable mix is dependent on the obtained test results, which are further narrowed down using the Multi-Criteria Analysis (MCA). The chart on the next page, shows the work flow process (figure 23), created based on the final product which need to be delivered :

- Program of Requirements (Technical/Functional Requirements).
- Alternatives/Variants.
- Experiment/Test.
- Test Results.
- Cost.
- EcoChain.
- OIA Calculation.
- Evaluation of Multi Criteria Analysis (MCA).
- Advisory/Technical report.
- Technical Drawings.
- Portfolio proving acquired competencies.

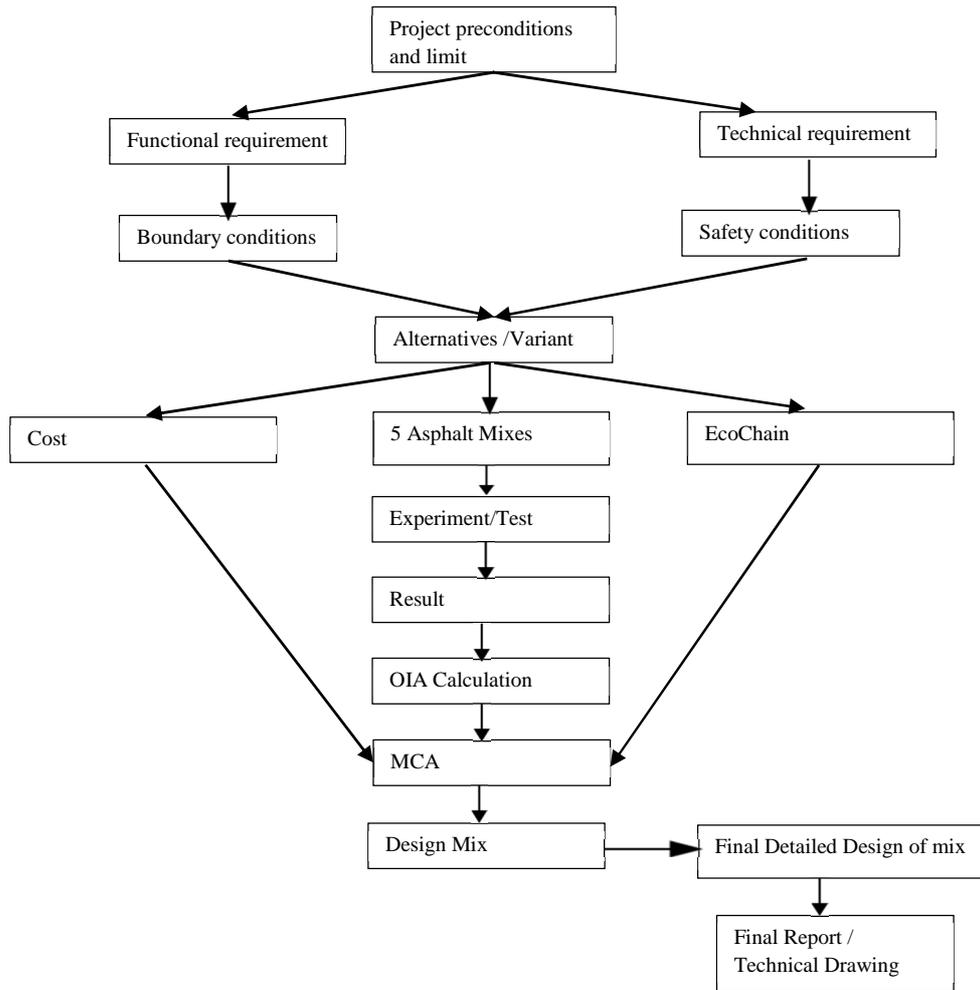


Figure 23 :Design Process Flow Chart

3.3 Schedule of Requirements

Apart from the design method, there are other applied research method based on a design approach, which is used in the production of new asphalt mixes within the thesis scope. This research method gives an overview of all the fulfilled demands and specifications required by the client and other relative parties involved in the research.

The schedule of requirements have been set up based on the client's specifications. This schedule of requirements are set up based on meetings and verbal communications with the client. It gives an overview of all the demands or specifications, which has to be compliant to the mix design. The objective is to outline all wishes and requirements of the client and all other relevant parties involved so that the exact function of the produced mix is fully clear and established. The schedule of requirements is divided into two aspects namely the functional and technical requirements. The former is set up to identify the functions of the produced mixes while the latter is more detailed and specific. The functional and technical requirements are described in the next sub chapters.

3.3.1 Functional Requirements

3.3.1.1 *More than 50% "RAP" recycling*

The recycling of more than 50% RAP is a very important functional requirement. This is due to the fact that, in the road construction sector, the ability to recycle a higher "RAP" percentage in the Asphalt Plant is quite a challenge because the capacity of production in tons/hour decreases as a result of the heating and drying of the "RAP". Therefore, it was one of the client's demand to produce asphalt mixes up to 80% "RAP" and simultaneously proffer a solution to its production challenge in the asphalt plant.

3.3.1.2 *Durability of Base layer Mixes*

The durability of the mixes refers to the technical lifespan of the mixes. This is a functional requirement of the client, due to the fact that the new asphalt mixes, need to have a similar or longer technical lifespan, in addition to its sustainability. The essence of durability, is to produce a mix which can perform its technical obligations over a longer period of time. According to the calculation made by Rijkswaterstaat in DuboCalc, the life span of base layer mixes should have a minimum and maximum lifespan of 20 and 60 years respectively. Therefore, it implies that the lifespan of the produced asphalt mixes should be in accordance to the requirement of Rijkswaterstaat i.e. a minimum and maximum lifespan of 20 and 60 years respectively.

3.3.1.3 Flashpoint of Rejuvenators

According to the client's specification, the flashpoint of rejuvenators added to the new asphalt mixes should have a minimum value of 230°C, in order to avoid ignition while mixing in the Asphalt Plant and also to avoid the risk of explosion.

3.3.1.4 Thickness of the AC Base Layer

According to the client's specification, the thickness of base layer mixes should comply with the specifications given by Rijkswaterstaat, according to OIA calculation for innovated base layer mixes for OIA calculation. Thus, the minimum and maximum base layer thickness of the produced mixes should be within 50 and 90 mm respectively.

3.3.1.5 Density of Asphalt Samples

According to the client's specification, the density of the produced prismatic samples, to be used to test for stiffness and fatigue should not exceed 2380kg/m³. More so, the density of the produced cylindrical samples, to be used for the permanent deformation test should not exceed 2380kg/m³.

3.3.1.6 Dimensions of Asphalt Samples

According to the client's specification, the produced prismatic samples should have a width of 50mm ± 1mm, height of 50mm ± 1mm and length of 450mm ± 1mm respectively. In addition, the produced cylindrical samples should have a diameter of 99,8mm and height of 60mm.

3.3.1.7 Mass of "RAP" for extraction

The mass of "RAP" required for extraction is according to the Standard RAW Norm 2015, which is dependent on the largest sieve size of the "RAP" to be used in the production of the new asphalt mix. This implies that Mass of "RAP" = 100g * Large sieve size of "RAP". Thus for the thesis, the largest sieve size is 22,4 as a result of the AC "RAP" was used. Thence, it means that the mass of "RAP" to be used for the bitumen extraction should be 2240g.

3.3.2 Technical Requirements

3.3.2.1 Type of bitumen

The type of bitumen to be used in the production of new asphalt mixes should be in the soft class bitumen, and also have a high penetration and low melting temperature because of the aged bitumen present in the “RAP”. More so, the 70/100 class was specifically chosen by the client because, it is mostly used in the road construction sector to produce asphalt mixes and can be applied to any asphalt layer.

3.3.2.2 Type of rejuvenators

The type of rejuvenators, to be used within the research scope was specified by the client. This is as a result of the fact that, since a high percentage of “RAP” is used in the production of new asphalt mixes, the client demanded that, the type of rejuvenators to be added to the mixes need to aid the use of a higher “RAP” percentage.

3.3.2.3 Type of asphalt mix

The type of asphalt mix, to be produced was specified by the client i.e. whether the mix to be produced should be applied in the top, binder or base layer. According to the client’s demand, Asphalt Concrete mixes applied in the base layer should be produced, due to the fact that the challenge of mix sustainability is most prone to the highways as a result of the daily traffic intensity. Thus, the AC base mixes will be applied to the base layer to bear the load capacity of the other two types of layers while simultaneously solving the challenge of sustainability.

3.3.2.4 Production of Technical mixes

One of the technical requirements of the clients, is the production of mixes which are technically improved. This implies that the produced asphalt mixes, should be in accordance to the Standard RAW Norm 2015. This requirement was specified by the client, to ensure that all mixes produced comply with the regulation used in the road construction sector in the Netherlands.

3.3.2.5 Technical Test

One of the clients technical specifications, is that calculations for the bitumen property test and Type Test should be in accordance to the NEN norms of asphalt testing (appendix 8). This is to ensure that the produced asphalt mixes are tested in conformity to the Dutch regulations.

3.3.2.6 Classification of the mixes according to Standard RAW Regulations

This technical specification made by the client, is to assure that the produced mixes are classified or categorized based on the traffic intensity category which is in accordance to the Standard RAW Regulation. This technical demand was made, due to the fact that the asphalt mixes applied in the base layer are grouped into four classes respectively ; OL-IB, OL-A, OL-B and OL-C. These classes represent their relative truck intensity and the indicator area of application with road type classification according to Dutch Standard. Nevertheless, only the OL-C category is analyzed within the thesis scope because it considers the highest traffic intensity.

- OL- C : truck intensity > 2500 .

Therefore, it is important that the produced base layer mixes is classified under the OL-C which is the base layer mix applied for highways or provincial roads which can accommodate a traffic intensity of > 2500 trucks. The detail of the classification according to traffic intensity can be found in appendix 9 table 31.19.

3.3.2.7 Stiffness, Fatigue and Permanent Deformation Value

This demand was specified by the client to ensure that relevant values of stiffness, fatigue and permanent deformation are divided in the corresponding category class of asphalt concrete mixes for base layer. More so, this technical requirement is to ensure that the relative values of Stiffness (S_{min} & S_{max}), fatigue (ϵ_6) and permanent deformation (f_c) comply with the Standard RAW Norm for OL-C traffic category, which is due to the fact that the produced base layer mixes are mainly to be applied on highways and Provincial roads. More information on AC mixes applied to base layers can be found in appendix 9.

3.3.3 Alternatives

After the summation of desires and demands of the client from the schedule of requirements, the alternatives were developed i.e. the alternatives considered to produce a sustainable asphalt mix. At the beginning of the research, the alternatives put into consideration are listed, but as a result of the limited time frame a lot of alternatives were not executed. The alternatives which are listed below were considered for the production of sustainable asphalt mixes. The names of rejuvenators used during the research process is not mentioned, but are represented with numbers for confidential purposes (appendix 7).

- Mix 0 : Reference mix : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100)+ No rejuvenator.
- Mix 1 : AC 22 Base/Bind (80% RAP) + Rejuvenator 1.
- Mix 2 : AC 22 Base/Bind (80% RAP) + Rejuvenator 2.
- Mix 3 : AC 22 Base/Bind (80% RAP) + Rejuvenator 3.
- Mix 4 : AC 22 Base/Bind (80% RAP) + Rejuvenator 4.
- Mix 5 : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100) + Rejuvenator 1.
- Mix 6 : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100) + Rejuvenator 2.
- Mix 7 : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100) + Rejuvenator 3.
- Mix 8 : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100) + Rejuvenator 4.

3.3.3.1 Reliability of Variants

The alternatives are narrowed down into variants. These variants were chosen in accordance to the objective of the thesis i.e. the production of mixes with 80% “RAP” by the addition of rejuvenators. These variants were set up based on the Standard mix produced in the asphalt plants i.e. (AC 22 Base/Bind 60% “ RAP ” 35/50). With the reference mix as a variant, the characteristics or properties of the other asphalt mixes containing rejuvenators can be compared, and it can be determined if the mix which contains rejuvenator is sustainable or not. The variants chosen are outstanding compared to others. With the variants, the effect of the rejuvenators in the asphalt mix can be seen unlike the other mixes which contain the rejuvenators and bitumen. This is because as a result of the bitumen present in the Mix 5, 6, 7 and 8, the chemical properties of rejuvenators can be altered, thence giving undesired result during tests.

3.3.4 Variants

The variants are chosen based on the Standard mix produced in most asphalt plants and also on the rejuvenators which will be added to the mixes. During the research, five variants were selected out of the previously stated alternatives, considered for the production of sustainable asphalt mixes. The five variants comprises of 80% “RAP” which includes a reference mix without rejuvenator and four other mixes with 4 rejuvenators. The four other variants comprise of different rejuvenators and the purpose of this is to compare its characteristics depending on their relative properties. The chosen variants are namely ;

- Mix 0 : Reference mix : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100)+ No rejuvenator.
- Mix 1 : AC 22 Base/Bind (80% RAP) + Rejuvenator 1.

- Mix 2 : AC 22 Base/Bind (80% RAP) + Rejuvenator 2.
- Mix 3 : AC 22 Base/Bind (80% RAP) + Rejuvenator 3.
- Mix 4 : AC 22 Base/Bind (80% RAP) + Rejuvenator 4.

The rejuvenators are encrypted for confidentiality to protect the interest of the contractors and the product suppliers (appendix 7). The coding of the asphalt concrete mixes covered by (code : NEN-EN 13108) (appendix 8g) CE is authorized by reference to AC 22 Base/Bind 70/100 where ;

AC : Asphalt Concrete .
 22 : maximum grain size (in mm).
 Base/Bind : indication of the asphalt layer.
 70/100 : penetration of bitumen (in 0,1mm).

3.3.4.1 Variant Description

The variants earlier stated are briefly described in the following paragraphs.

Mix 0 : Reference mix : AC 22 Base/Bind (80% RAP) + Virgin Bitumen (70/100)+ No rejuvenator

This variant is produced as one of the asphalt mixes and is used as a reference mix, to compare the other variants. The mix 0 contains asphalt concrete applied mostly in the base layer , with a maximum grain size of 22mm and a bitumen class of 70/100 without rejuvenator.

Mix 1 : AC 22 Base/Bind (80% RAP) + Rejuvenator 1

This variant is produced as one of the asphalt mixes. The mix 1 contains asphalt concrete applied mostly in the base layer , with a maximum grain size of 22mm and rejuvenator 1 i.e. one of the products earlier mentioned in chapter 2.5.

Mix 2 : AC 22 Base/Bind (80% RAP) + Rejuvenator 2

The mix 2 is also asphalt concrete applied in the base layer which contains the same proportion of mineral aggregates as mix 1, but the only difference is the binder i.e. rejuvenator 2, another type of rejuvenator randomly chosen from chapter 2.5.

Mix 3 : AC 22 Base/Bind (80% RAP) + Rejuvenator 3

The mix 3 is asphalt concrete applied in the base layer which contains the same proportion of mineral aggregates as mix 1, but the only difference is the binder i.e. rejuvenator 3, i.e. another type of rejuvenator randomly chosen from chapter 2.5.

Mix 4 : AC 22 Base/Bind (80% RAP) + Rejuvenator 4

The mix 4 is asphalt concrete applied in the base layer which contains the same proportion of mineral aggregates as mix 1, but the only difference is the binder i.e. rejuvenator 4, i.e. another type of rejuvenator randomly chosen from chapter 2.5.

3.4 Bitumen Property Test

The experiment to test the asphalt mixes, is dependent on the variant selection made in the previous chapter, (chapter 3.3.4). Within the thesis scope, AC 22 base/bind is chosen as the reference mix because the base mix allows the use of more than >50% “RAP”. More so, the production of the new asphalt mix (AC 22 base/bind + 80% “RAP”) is based on the standard mix used by DIBEC for innovative base layer mixes (AC 22 base/bind 35/50 + 60% “RAP”) because almost the same factors are put into consideration, during production in the asphalt plant. The test was executed, according to the NEN-EN norms of asphalt testing considering all important parameters. As earlier stated, the class of bitumen added to a mix is determinant on the mix flexibility (chapter 2.3.2). Therefore, the bitumen class 70/100 was added to the reference mix because, it exhibits better properties than other bitumen classes i.e. higher penetration and low melting temperature which is suitable for the test. For the research ; Mix composition, Bitumen property test, Stiffness, Fatigue and Permanent deformation tests were carried out. Nevertheless, before the commencement of the test, the bitumen content (%) of the “RAP” was determined. The following chapters describe the test procedure and the amount of bitumen content (%) obtained from the “RAP”.

3.4.1 Mix Composition and Bitumen Property Test

At the beginning of the test in the laboratory, samples of “RAP” were taken to extract the aged bitumen and determine the percentage present in the “RAP” by carrying out the penetration and R & B test.

3.4.1.1 Bitumen Extraction Procedure

The bitumen was extracted from the “RAP” to determine the bitumen properties present in the “RAP”. For this experiment, three samples of “RAP” weighing 2240g each i.e. a total of 6720g was taken. The aim of the bitumen extraction procedure is to obtain the composition of “RAP” i.e. bitumen content (%) and coarseness of the mineral aggregates. This was therefore, carried out using the extraction machine (figure 27a), to extract the aged bitumen. The weight of extracted bitumen was not determined because, it was irrelevant and also because the amount of extracted bitumen varied for each “RAP” sample. Nevertheless, the average bitumen content obtained from the RAP was determined, the result can be found in chapter 4.1. The extracted bitumen was further tested, to determine the hardness and softening temperature using the Penetration and R & B Test explained in the following paragraphs.



(a) Extraction machine



Collection tap

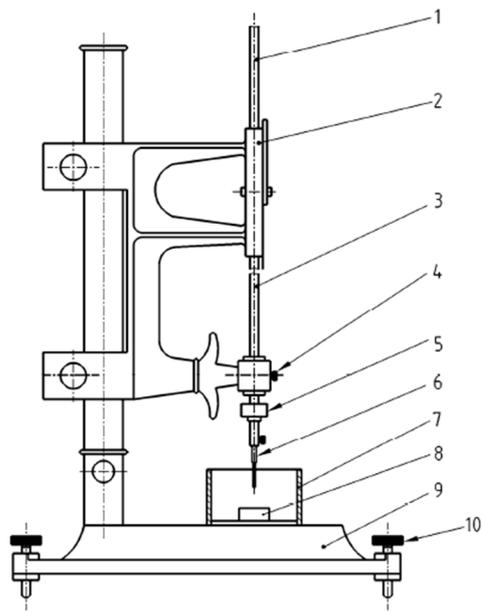
(b) Bitumen collection compartment

Figure 24 : Bitumen extraction Process

3.4.4.2 Penetration Test

The penetration test was carried out according to the norm (code :NEN-EN 1426) (appendix 8a). The aim of the test was to determine a measure of bitumen hardness extracted from the "RAP" under the following conditions i.e. measuring the penetration at 25°C in 0.1mm of a standard needle, for 5 seconds under a load of 100g. As earlier stated, aged bitumen was extracted from three samples of "RAP" in order to obtain average result of the bitumen hardness. The range of values for the penetration test according to the Standard NEN norms is as follows :

- Penetration at 25°C of bitumen class 35/50 should be between 35-50 (unit 0,1mm).



- Key
1. Spindle.
 2. Dial assembly.
 3. Needle holder.
 4. Release assembly.
 5. 50g mass.
 6. Needle and ferule.
 7. Transfer dish with flat bottom.
 8. Test sample container.
 9. Base plate (stand).
 10. Level adjustment screw.

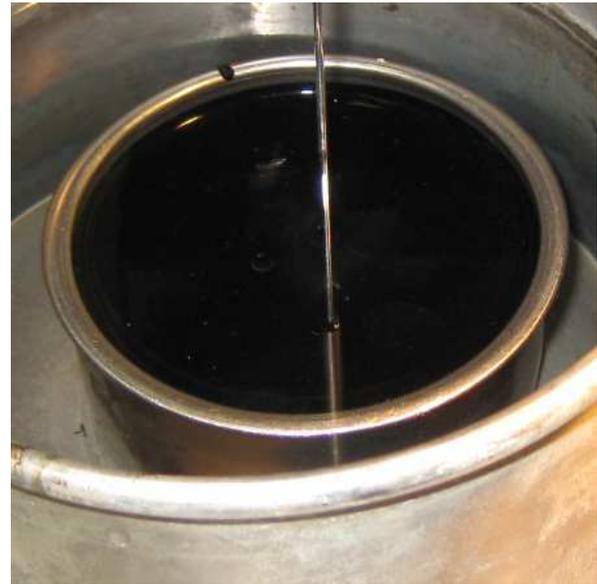
Figure 25 : Penetrometer

3.4.4.2.1 Penetration Test Procedure

The test was carried using the Penetrometer (figure 28). The test was carried out thrice, using the three extracted samples of the aged bitumen. The sample of the bitumen was placed in the test sample container. With the 50g mass, the needle and ferule was released for 5seconds into the sample of aged bitumen. After 5 seconds, the level of penetration was determined and noted. Thereafter, the level adjustment screw was used before carrying out the test on the other two samples. Figure 29d, on the next page shows an overview of the test procedure i.e. the needle penetrating the aged bitumen. The results obtained from the three samples were registered in order to calculate the average result. The test results can be found chapter 4.2.



(c) Penetrometer



(d) Surface of aged bitumen

Figure 26 : Bitumen penetration test

3.4.4.3 Ring and Ball Test (R & B)

The bitumen Ring and Ball test was carried out according to the norm (code : NEN-EN 1427) (appendix 8b). The aim of the test was to determine the temperature, at which the aged bitumen softens or becomes viscous. The R & B test was carried out under required laboratory conditions using a demineralized water at a temperature of 15°C. The demineralized or deionized water is free of ions and minerals and is used in the laboratory to carry out the R & B test for accuracy purposes by ensuring the same result is obtained even if the test is conducted in another laboratory within the Netherlands. The test was executed by placing the extracted aged bitumen on the ball and then in the demineralized water, and heating until the aged bitumen softens. The softening point of R & B was obtained by taking the average of two observations rounded to 0,2. The range of values for the R & B test according to the Standard NEN norms is as follows :

- The difference between the two temperatures obtained during the test should not exceed 1 °C for softening points below 80 °C.
- For softening points below or equal to 80 °C, the result should be expressed as to the nearest 0,2 °C the mean of the temperatures.

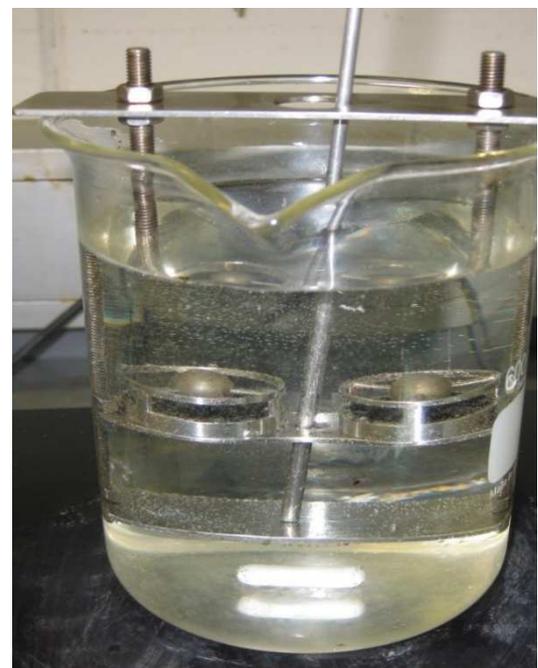
3.4.4.3.1 Ring & Ball Test Procedure

Demi water (demineralized or deionized water) is one of the essentials required for the experiment. The use of the water is essential during the test to avoid trapping air bubbles, on the surface of the test sample which can affect test result. More so, the demi water is used to ensure the same test results are obtained even if tests are carried out in different laboratories within or outside the Netherlands. Two horizontal discs of bituminous binder, cast in shouldered brass rings were heated at a controlled rate in a liquid bath while each supports a steel ball.

A thermometer was placed in the demi water, before it was further placed on an electric plate. Thereafter, the water was warmed up to soften the extracted bitumen. Conclusively, the softening point i.e. temperature at which the bitumen softens is registered as the mean of the temperatures at which the two discs soften enough to allow each ball, enveloped in bituminous binder, to fall a distance of $(25,0 \pm 0,4)$ mm. For the second sample, the same procedure was followed and the melting temperature which was registered. The average of these two observations were taken rounded to 0,2, thus providing the result to be used further in the experiment. The test results can be found chapter 4.3.



(e) Heating of demi water



(f) Softening of aged bitumen

Figure 27 : R & B Test

3.4.4.4 Penetration Index (P.I.)

The aim of the penetration index is to determine of a measure of the temperature dependence of the bitumen penetration. This was carried out according to the norm (code : NEN-EN 12591) (appendix 8c). The important parameters taken into consideration are namely ; the softening temperature, the average penetration value of the three samples of the aged bitumen. According to the Standard norm, the penetration index of bitumen class, 35/50 should be between -1,5 to +0,7

The P.I was calculated using :

$$P.I = \frac{20. Tv + 500.logpen - 1952}{Tv - 50.log pen + 120}$$

where

Tv is the softening point R & B ,in °C.
pen is the penetration of the bitumen in
0,1mm

3.4.4.4.1 Penetration Index Procedure

The Penetration Index is calculated from the values of penetration at 25°C, 100g, 5s determined in accordance to the norm (code : NEN-EN-1426) (appendix 8a) and the softening point determined in accordance to the norm (code : NEN-EN-1427 (appendix 8b). The calculation of the P.I was based on the following hypothesis of Pfeiffer and Van Doormael:

- At the temperature of the softening point, the penetration of a bitumen is (800 × 0,1) mm.
- When the logarithm (base 10) of penetration is plotted against temperature, a straight line is obtained, the slope A of which is defined as :

$$A = \frac{(20 - Ip) * 1}{(10 + Ip) 50}$$

The calculation of the P.I was made in an excel sheet (appendix 18) and the result can be found in chapter 4.4.

3.4.2 Test Analysis

The results obtained, from the extraction procedure of the aged bitumen, Penetration and R & B test will be used as a basis to determine the class and amount of virgin bitumen content (%) which will be added to the new asphalt mix. This is because, the mix to be produced is the AC Base/Bind 35/50 and the values from the penetration and softening point of the aged bitumen will determine percentage and soft class bitumen required.

3.4.2.1 Sieve Analysis

The sieve analysis was done in order to determine coarseness of mineral aggregates and particle size distribution of the “RAP”. The result can be found in (chapter 4.1) and detailed excel calculation in (appendix 12).

3.4.2.1.1 Calculation of Mineral aggregate composition

With the “RAP” particle size distribution, and the result of the bitumen percentage. It was necessary to calculate the amount virgin bitumen, filler and mineral aggregates required for the production of the new asphalt mix.

3.4.2.1.2 Procedure for Mix Calculation

The amount or percentage of mineral aggregates required for the production of the new asphalt mix was determined based on the percentage of the “RAP” and the properties of the aged bitumen. A standard calculation procedure was taken into consideration to get the right proportions of the mineral aggregates (figure 31). The detailed calculation of the particle size distribution can be found in (appendix 11).

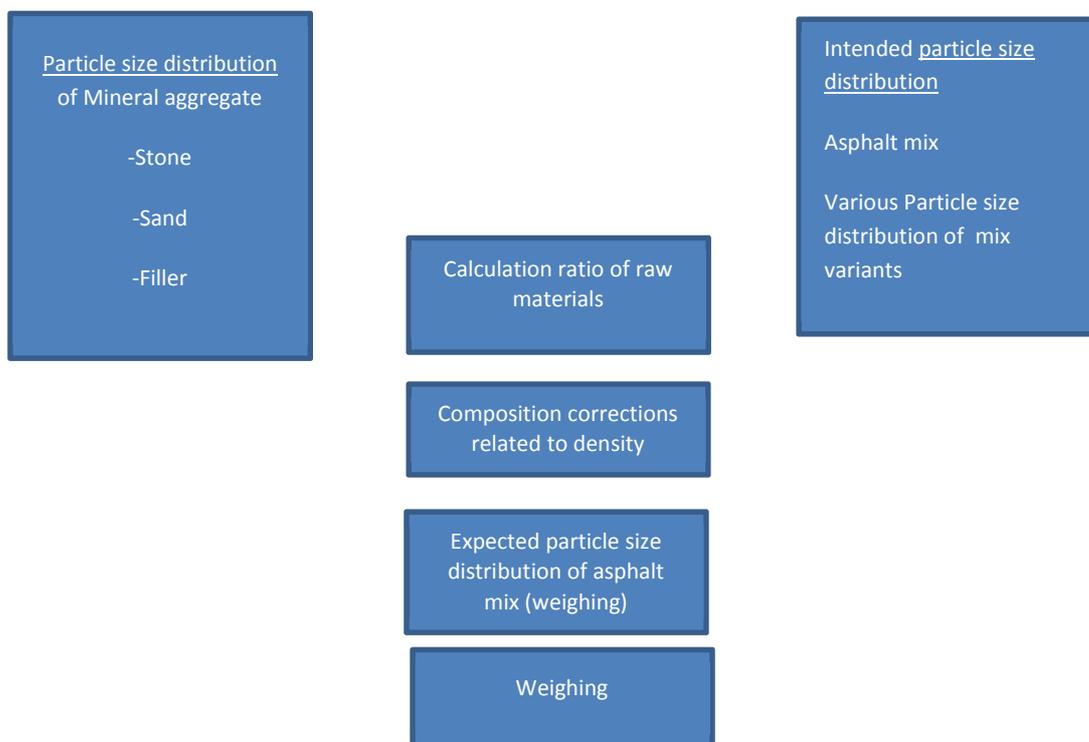


Figure 28 : Schematization of Asphalt Mix Calculation (Source : (VBW Asphalt, 1995))

3.5 Production of Asphalt Samples

This chapter describes, the method of production of the asphalt samples used for the tests. The asphalt samples produced, are based on the 5 variants stated in chapter 3.3.4 i.e. Reference mix and 4 other mixes with different types of rejuvenators. Within the thesis scope, prismatic and cylindrical asphalt samples were produced, which is as a result of the tests carried out. The prismatic asphalt samples were produced to test for resistance to stiffness and fatigue test, while the cylindrical samples were produced to test for resistance to permanent deformation. The production of the prismatic asphalt sample and cylindrical asphalt sample was executed according to the norm, code : NEN-EN 12697- 35 (appendix 10a).

3.5.1 Mixing Procedure of Asphalt Samples

The mixing procedure of the asphalt samples comprises of the production and compaction procedure of the prismatic samples and the cylindrical samples which are explained in the following paragraphs.

3.5.1.1. Mixing Procedure of Prismatic Samples

The production of the prismatic asphalt samples was executed according to the norm of asphalt mix production, (code : NEN-EN 12697-35) (appendix 10a). Prismatic samples were produced for the 5 asphalt variants. The virgin materials used for the production are namely, filler from aggregate, Riversand, bestone 4/8, Scottish granite 8/16, Scottish granite 16/22 and Binder which was based on the material percentage earlier calculated (appendix 11). The only virgin material altered was the binder which is as a result of the various binders in the mixes. An overview of each mix composition is given below :

Prismatic Samples : Mix 0 : 80 % "RAP" + Virgin materials + Bitumen
Mix 1 : 80 % "RAP" + Virgin materials + RJ 1
Mix 2 : 80 % "RAP" + Virgin materials + RJ 2
Mix 3 : 80 % "RAP" + Virgin materials + RJ 3
Mix 4 : 80 % "RAP" + Virgin materials + RJ 4

To produce the prismatic samples, the mixing drum was heated to a temperature of about 150° C - 155° C. The required amount of "RAP" was poured into the mixing drum and mixed for 2 minutes. Thereafter, the measured amount of binder i.e bitumen or rejuvenator was added to the RAP and mixed for another 30 seconds. Finally, the virgin materials were added to the "RAP" and binder in the mixer and was mixed for another 2minutes 30 seconds inorder to obtain an homogenous asphalt mix, and also to ensure that all the materials were properly coated with the binder. The same production procedure was repeated for the production of all the 5 asphalt mix variants. The figure on the next page (figure 24), shows the asphalt mix in the mixing drum.



Figure 29 : Asphalt Mix in the mixing drum

After production, the asphalt mix was compacted . The details of the compaction procedure, is outlined in the following paragraphs.

3.5.1.2 Production/Compaction Procedure

The produced mix needed to be compacted in order to achieve the density specification provided by the client i.e. 2380kg/m³. The asphalt mix was compacted according to the norm, code : NEN-EN 12697-33 (appendix 10b).

Since the essence of producing the prismatic sample, is to test the resistance to stiffness and fatigue. According to the Standard RAW norm 2015, it is required that for the stiffness and fatigue test, the prismatic samples should have a minimum thickness of 70mm and a height of + 20mm which is in accordance to the norm, code : NEN-EN 12697-24 (appendix 10c).

After the compaction process, the slab was allowed to cool for 1 day inorder to ensure that the mineral aggregates and binder were properly binded. Thereafter, the samples were sawed and polished to the desired thickness and height i.e 50 mm x 50mmx 450mm according to the regulations for sawing and polishing, code : NEN-EN 12697-24 (appendix 10c). The polished asphalt samples were kept in the Climate control storage at a temperature of 15°C for a period of two weeks inorder to allow the settling of the samples before testing. Figure 25a, on the next page, shows an example of the compacted asphalt sample, while 25b shows a sawed and polished prismatic sample.

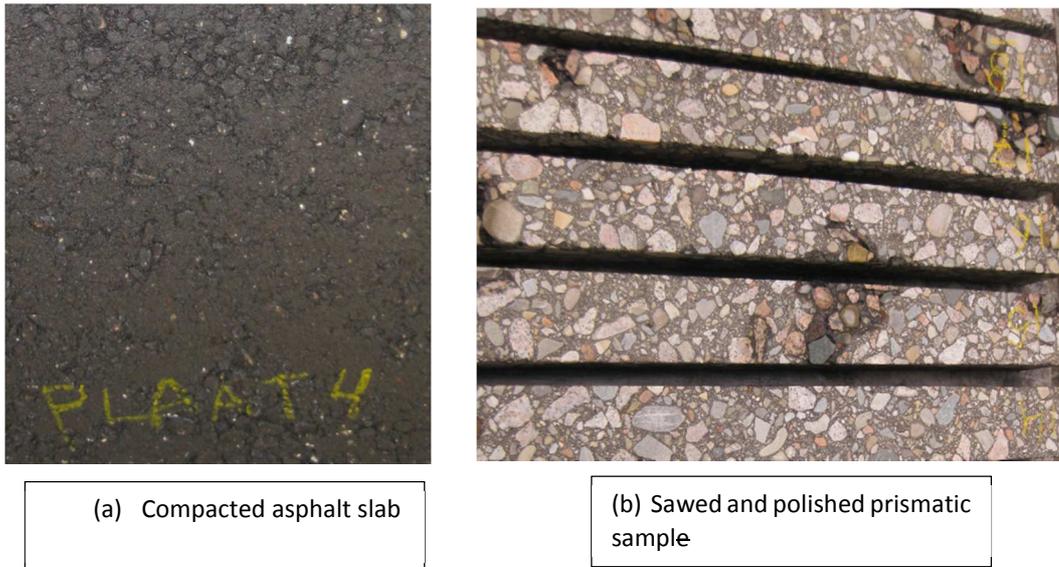


Figure 30 : Asphalt Samples

3.5.1.3 Mixing Procedure of Cylindrical Samples

The production of the cylindrical asphalt samples or gyrator samples was executed according to the norm of asphalt mix production, (code: NEN-EN 12697-35) (appendix 10a). The cylindrical samples were produced for the 5 asphalt variants and 4 samples were produced for each variant, giving a total of 20 cylindrical samples. The virgin materials used for the production are namely, filler from aggregate, Riversand, bestone 4/8, Scottish granite 8/16, Scottish granite 16/22 and Binder which was based on the material percentage earlier calculated (appendix 11). The only thing which differs in the cylindrical samples is the binder. An overview is shown below :

- Cylindrical samples :
- Mix 0 : 80 % "RAP" + Virgin materials + Bitumen
 - Mix 1 : 80 % "RAP" + Virgin materials + RJ 1
 - Mix 2 : 80 % "RAP" + Virgin materials + RJ 2
 - Mix 3 : 80 % "RAP" + Virgin materials + RJ 3
 - Mix 4 : 80 % "RAP" + Virgin materials + RJ 4

To produce the cylindrical samples, the mixer was heated to a temperature of amount of 150° C - 155° C. The required amount of "RAP" was added into the mixer and mixed for 2 minutes. Thereafter, the measured amount of binder i.e bitumen or rejuvenator was added to the "RAP" and mixed for another 30 seconds. Finally, the virgin materials were added to the "RAP" and binder in the mixer and was mixed for another 2minutes 30 seconds inorder to obtain an homogenous asphalt mix, and also to ensure that all the materials were properly coated with the binder. The same procedure was repeated for the production of the 5 asphalt mix variants. After production, the samples were compacted . The details of the compaction procedure is outlined in the following paragraph.

3.5.1.4. Production/Compaction Procedure

The produced gyrator samples, needed to be compacted in order to achieve the density specification provided by the client i.e. 2380kg/m³. The samples were compacted according to the norm, code : NEN-EN 12697-31 (appendix 10d). The gyratory compactor was calibrated according the standard as follows :

A vertical compaction pressure of 600 ± 10 kPa,
Number of revolutions per minute : 30 ± 2 ,
Internal gyrator angle : $0,82 \pm 0,02^\circ$,
Internal diameter : 100 ± 1 mm, respectively $150 \text{ mm} \pm 1$ mm

Since the essence of producing the gyrator sample, is to test the resistance to permanent deformation, According to the Standard RAW norm 2015, it is required that for triaxial test, the cylindrical samples should have a diameter of $100\text{mm} \pm 1\text{mm}$ and a height of $77\text{mm} \pm 3 \text{ mm}$.

Therefore, the produced samples were compacted to a diameter of $100\text{mm} \pm 1\text{mm}$ and height of $77\text{mm} \pm 3 \text{ mm}$. After the compaction process, the gyrator samples were allowed to cool for 2 days in order to ensure that the mineral aggregates and binder were properly binded. Thereafter, the top and bottom of the samples were sawed and polished to the desired diameter and thickness i.e $99,8\text{mm} \times 60\text{mm}$ according to the regulations of sawing and polishing, code : NEN-EN 12697-25 (appendix 10e).

The polished gyrator samples were kept in the Climate control storage at a temperature of 15°C for a period of two weeks in order to allow the settling of the samples before testing. Figure 26a, shows compacted gyrator samples, while 26b shows the sawed polished cylindrical samples.

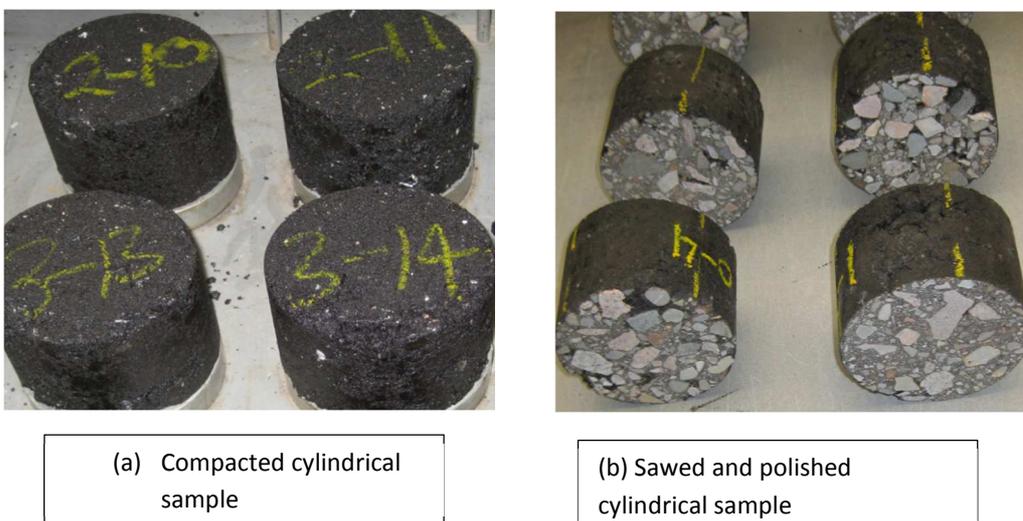


Figure 31 : Cylindrical Samples

3.5.2 Asphalt Concrete Test

The experiments for testing the properties of asphalt concrete were carried out using the norm (code : NEN-EN 13108-1) in conformity with (code : NEN-EN 13108-20) (C.R.O.W, 2010). The properties needed to be tested are:

- Stiffness test in accordance with (code : NEN-EN 12697-26) (appendix 8d).
- Fatigue resistance (four-point bending test) in accordance with (code : NEN-EN 12697-24) (appendix 8e)
- Resistance against permanent deformation test in accordance with (code: NEN-EN 12697-25) (appendix 8f).

3.5.2.1 Stiffness Test

The stiffness test is one of the functional test carried out within the Type Test for Asphalt Concrete mixes. The test was carried out according to the norm (code :NEN-EN-12697-26) (appendix 8d). The main aim of the test, is to determine the resistance to stiffness of the produced asphalt mixes. For this test, prismatic asphalt samples were required. The test was carried out by testing nine samples per asphalt mix, thus giving a total of 45 asphalt samples. Figure 32 shows an example of the produced asphalt samples.



Figure 32: Prismatic asphalt sample

3.5.2.1.1 Stiffness Test Procedure

The test was implemented by placing each prismatic test sample with a length of 450mm, width of 50mm and a height of 50mm into the four point bending machine under a room temperature of 20°C (figure 33). A fixed strain was placed on the test sample under frequency sweep between 0,1Hz - 30 Hz under a strain of 50µm/m. which is supposed to be a non-destructive strain. The stiffness modulus gotten at 8Hz at 20°C was registered which is in accordance to the norm (code : NEN-EN 13108-20) (appendix 8g).

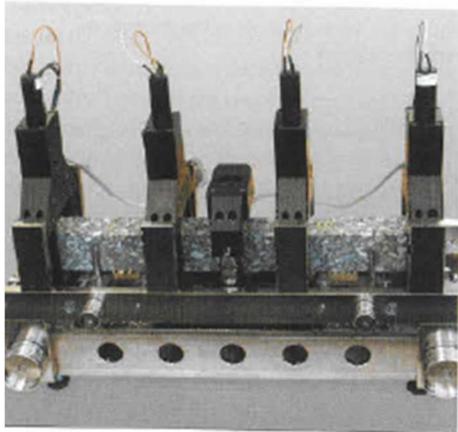


Figure 33: Prismatic asphalt sample in a four point bending machine

3.5.2.2 Fatigue Test

The fatigue test is quite similar to the stiffness test, because the stiffness modulus is taken into consideration. The test was carried out according to the norm, (code : NEN-EN-12697-24 +A1) (appendix 8e). The main aim of the test, is to determine the resistance to fatigue of the produced asphalt mixes. For this test, the same prismatic asphalt samples used during the stiffness test were required .

3.5.2.2.1 Fatigue Test Procedure

The test was implemented, by placing each prismatic test sample into the four point bending machine under a room temperature of 20°C . A constant strain level was placed on the test sample under a frequency of 30Hz under one of the three different repetitions ; 10 000, 100 000, 1 000 000. These repetitions were done to determine the end of the technical life span of the test sample. More so, only one repetition was tested per prismatic sample due to the fact that fatigue test is a destructive test.

The figure on the next page, (figure 34), shows the characteristic progression of stiffness during the fatigue test. In addition, the technical life span N_{fat} of the relevant test sample was defined as the number of repetitions whereby the half value of the initial stiffness is taken (E_{ini}).

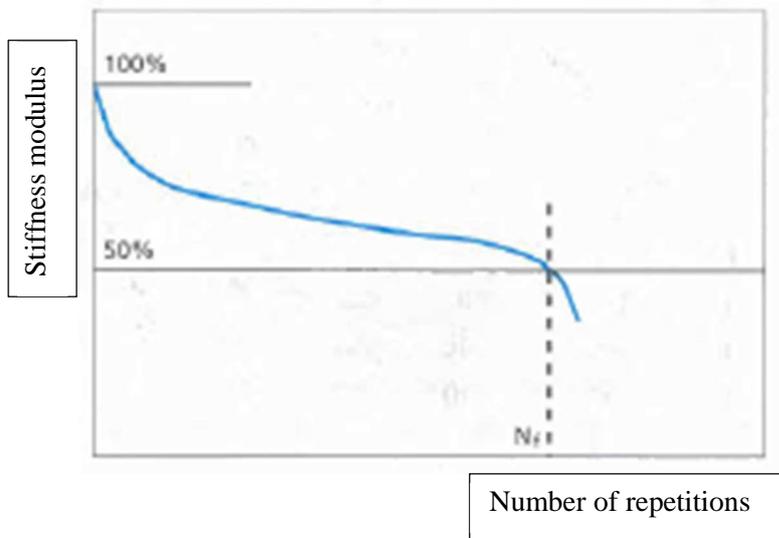


Figure 34 : Progression of Stiffness during fatigue test (Source : (C.R.O.W, 2010))

For the thesis, by three strain levels, 3 different repetitions were done, giving a total of 9 fatigue test samples per mix. The logarithmic value from the test sample strain and N_{fat} were inputted in a graph (figure 35).

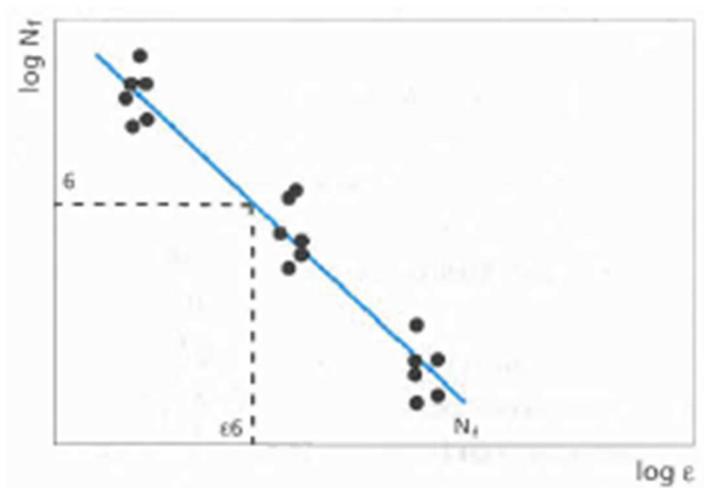


Figure 35 : Fatigue test of an asphalt mix (Source : (C.R.O.W, 2010))

Thereafter, with the use of linear regression a straight line was fitted through the 9 measurement points known as the fatigue line. The strain level was determined where the number of repetitions 1 000 000 was predicted, the strain level was represented with ϵ_6 . More so, the fatigue line is represented with Wohler curve and is represented as follows :

$$\log(N_{fat}) = \log(k_1) + k_2 \cdot \log(\epsilon)$$

where :

N_{fat} = fatigue technical lifespan in number of repetitions.

k_1 = material parameter.

k_2 = material parameter .

ϵ = strain (μm).

3.5.2.3 Permanent Deformation test

The permanent deformation test is one of the functional test carried out within the Type Test for Asphalt Concrete mixes. The test was carried out according to the norm (code : NEN-EN-12697-25) (appendix 8f). The main aim of the test is to determine the resistance to permanent deformation of the produced asphalt mixes. A schematization of the test principle is shown below (figure 36).

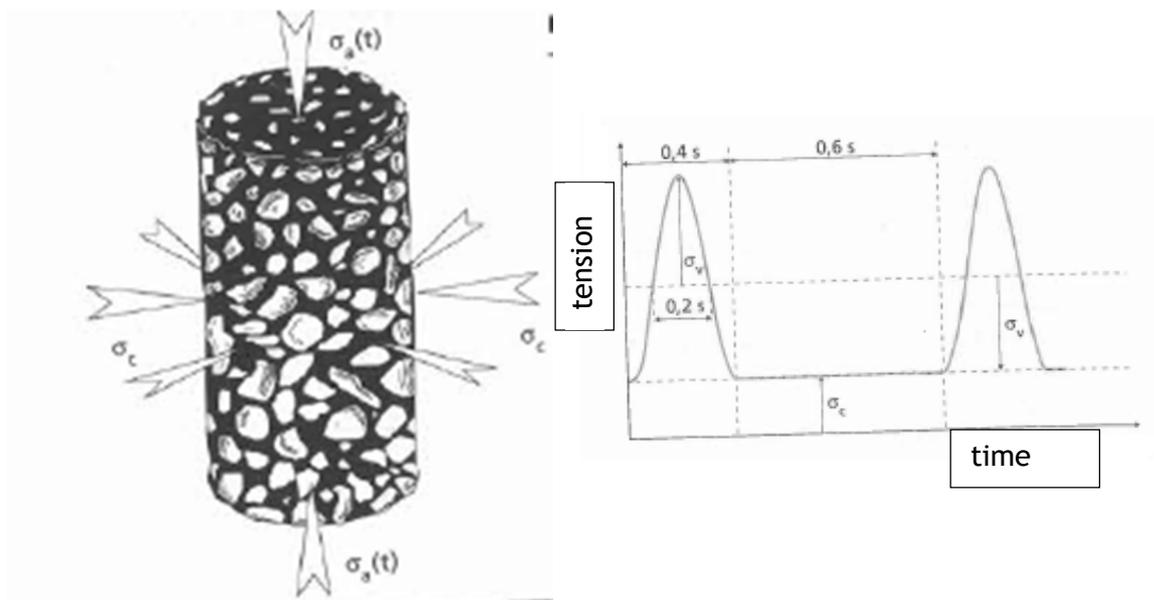


Figure 36 : Cyclical pressure test for asphalt mixes

The permanent deformation test layer for base mixes was executed according to Standard RAW norm using :

Temperature = 40°C

$\sigma_c = 0,05\text{MPa}$ (support pressure)

$\sigma_v = 0,20\text{MPa}$ (haversine axial tension)

$\sigma_{a,max} = \sigma_c + 2\sigma_v = 0,45\text{MPa}$ (total axial tension)

3.5.2.3.1 Permanent Deformation Test Procedure

For this test, cylindrical test samples were required. The test was carried out by testing three samples per asphalt mix, thus giving a total of 15 cylindrical samples. An example of the cylindrical asphalt samples is shown below (figure 37).



Figure 37: Cylindrical samples

The test was implemented by placing each cylindrical sample with a diameter of 100mm and a height of 60mm in the test machine under a room temperature of 40°C (figure 38).



Figure 38 : Permanent Deformation test

The sample was placed in a rubber socket placed in a cell. This produced a double pressure i.e. the vertical pressure and the static horizontal pressure, whereby the static component became even as the static horizontal pressure (figure 38). The dynamic component has a frequency of 1Hz per second a haversine shaped impulse, placed on the sample with an impulse time of 0,4s at 0,45MPa, having a resting time interval of 0,6s at 0,05MPa. With this impulse, the resulting height change was measured. The tests lasted for 10 000 repetitions per cylindrical sample.

After the completion of test for the five asphalt mixes, the results were cumulated using the graph (figure 39). The result were derived by taking into consideration a number of stages during the tests, the stage 1 is the initial part of the creep curve. At this stage, the slope of the curve decreases with the increasing number of cycles, stage 2, represents the middle part of the creep curve, whereby the slope of the curve is quasi constant and expressed by the creep rate f_c . The data for the test was inputted into the calculation sheets which produced the average result per mix.

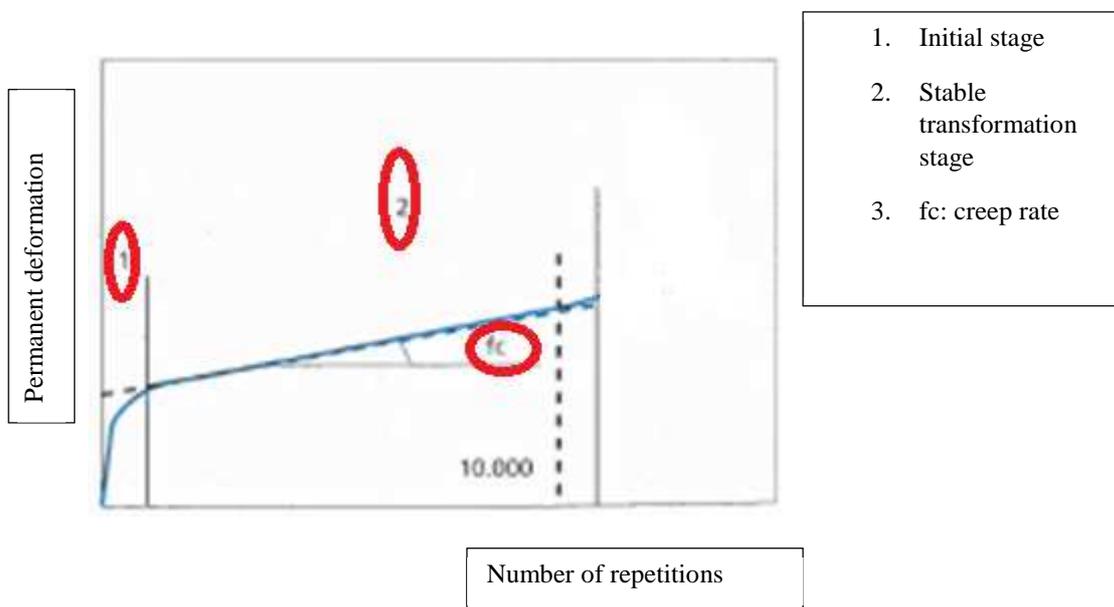


Figure 39 :Deformation curve for asphalt in practice ((C.R.O.W, 2010))

3.6 OIA Calculation

The OIA calculation is used in the asphalt sector, to calculate the thickness of asphalt layers ranging from the top layer, binder layer and base layer. Within the thesis scope, calculations are made to determine the base layer thickness only for the base layer, due to the fact mixes produced is AC Base/Bind “80% RAP” which is mostly applied in the base layer. For every mix, the values derived from the test samples are noted. With these results, the coefficients of both fatigue and stiffness are calculated.

The OIA calculation, is used to determine the required thickness for asphalt layers i.e. top, binder and base layer and also determine the truck load intensity/working day, a layer can bear. The required base layer thickness for each mix was calculated, taking into consideration the value of stiffness , fatigue (appendix 13). The base layer thickness of seven variants were calculated in comparison to the Variant G (Standard Mix : AC 22 Base/Bind 60% “RAP” 35/50). The variant G is the mix used by DIBEC to compare their innovated base layers.

- Variant G : The standard mix used by DIBEC to compare innovative base layers.
- Variant 0 : AC Base/Bind “80% RAP” + Virgin Bitumen (70/100) + No rejuvenator.
- Variant 1 plus : AC Base/Bind “80% RAP” + RJ1
- Variant 1 : AC Base/Bind “80% RAP” + RJ 1
- Variant 2 : AC Base/Bind “80% RAP” + RJ 2
- Variant 3 plus : AC Base/Bind “80% RAP” + RJ 3
- Variant 3 : AC Base/Bind “80% RAP” + RJ 3
- Variant 4 : AC Base/Bind “80% RAP” + RJ 4

Within the thesis scope, the OIA calculation is used to calculate the base layer thickness of each asphalt variant depending on various truck load intensities per working day. The truck load intensities are 1000 , 5000, 10 000 and 20 000 trucks which are specifications given by the client. In order to calculate the truck load intensity/working day, each asphalt mix can bear, a truck load of various categories were analyzed namely ; 1000 , 5000, 10 000 and 20 000 trucks. The calculation was based on a Standard construction for the AC Base mix, by using data obtained from the data base of the design construction mode of Rijkswaterstaat.

The OIA calculation for the asphalt pavement was made in accordance to the specifications given by Rijkswaterstaat. For this specifications, certain factors were considered which are namely the asphalt pavement, design life span, structural damage etc. The asphalt pavement considers the number of layers the asphalt construction is made up of, hence providing a substantial contribution to the bearing capacity. The design lifespan of the asphalt pavement is the period in years within which no greater structural damage occurs than the maximum permitted structural damage, and no exceedance in the resistance to permanent deformation occurs with the required reliability.

It is represented as the design period in OIA because, it considers the period whereby the asphalt pavement needs to be strengthened. Structural damage is defined as crack formation or disintegration of asphalt layers. This damage can as a result of fatigue of the asphalt layers under traffic etc. Within the thesis scope, the calculation of the base layer thickness is divided into two major aspects namely :

- Design Load
- Calculation of the Asphalt Pavement

These aspects are further sub-divided into the following :

Design Load

- Total number of trucks with axle load greater than 20 kN during the design period.
- Characteristic number of truck axles during the design period.
- Axle spectrum.
- Tyre Spectrum
- Category of Truck Intensity.
- Speed of traffic.

Calculation of the Asphalt Pavement

- Hydraulic bound base.
- Subgrade.
- Calculation of Base Layer Thickness.

In the following paragraphs, the method of calculation of these aspects is described in detail.

3.6.1 Design Load

The design load of the asphalt pavement in OIA was calculated according to the following specifications given by Rijkswaterstaat :

- The expected number of trucks during the design period.
- An axle spectrum that describes the percentage distribution of the expected trucks over a number of axle load classes.
- A tyre spectrum that describes the percentage distribution of the truck tyre within one axle load class to four distinct tyre spectrums (i.e. single air, double air, broadband, super Broadband). Nevertheless, the same tyre spectrum is assumed for each axle load class in OIA).

3.6.1.1 Total number of trucks with axle load greater than 20 kN during the design period :

The total number of trucks with axle load greater than 20kN during the design period is calculated using the formula follows :

$$n_{total} = V \cdot a_{vw} \cdot W \cdot F_r \cdot G \cdot t \cdot F_v$$

where ;

ntotal : Total number of trucks with axle load greater than 20 kN during the design period.

V : Number of trucks per working day by direction of traffic /lane.

aww : Average number of axles with load greater than 20 kN per truck.

W : Number of working days per year.

Fr : Correction factor for the number of lanes per direction of traffic (flow).

G : Growth factor of truck traffic.

T : Design period or design lifespan (years).

Fv : Correction factor of speed of truck traffic.

3.6.1.1.1 Parameters

V : The number of trucks per working day by direction of traffic/lane is chosen as a variable i.e. 1000trucks, 5000trucks, 10 000trucks, 20 000trucks, which is a specification given by the client to compare the influence of the traffic load on the pavement construction.

aww : The average number of axles with load greater than 20 kN per truck is given as 4,0 which is according to the client specifications.

W : The number of working days is chosen as 270 working days/ year which is according to the client specifications.

Fr : The correction factor (Fr) is 0,95, which is chosen according to the RWS specification in the case of a permanent overtaking prohibition for trucks. Attached to (appendix 14, table 4.1) are the correction factor (Fr) specified by RWS.

G : The value of growth factor for the truck traffic is calculated using the formula :

$$G = \frac{\left(1 + \frac{g}{100}\right)^t - 1}{\frac{g}{100} \cdot t}$$

whereby :

G : traffic growth
g : Annual growth of heavy traffic as indicated in the demand specification (%/year)
t : Design period required for the asphalt pavement construction

Nevertheless, the traffic growth (G) is represented as 1,5 % which is a specification given from the client.

T : The design period of the asphalt pavement construction is represented as 20 years according to client specifications, thus T is 20 years.

Fv : This is chosen in relation to the truck speed given by the client i.e. 80km/hr. The Fv value is chosen in accordance to the RWS specification for correction factor of speed of truck traffic (appendix 14, table 4.6)

3.6.1.1.2 Calculation Values

The following values were used to make further calculations in OIA to obtain the result of *ntotal*. The parameters used in the calculation are shown below. The value of V is variable for the different traffic intensities, while the values of the other parameters remain constant.

- V = Variable (1000trucks, 5000trucks, 10 000trucks, 20 000trucks)
- avw = 4,0
- W = 270 working days/ year
- Fr = 0,95
- G = 1,5%
- T =20 years
- Fv = 1,0

Table 5, shows the calculation to the number of trucks with axle load greater than 20kN considering the variable traffic intensities.

Table 5 : Calculation of *ntotal* for Various Traffic Intensities

Traffic intensity	<i>ntotal</i>
<i>ntotal</i> 1000 trucks	$ntotal = \sqrt{1000 \text{ trucks} * avw * W * Fr * G * T * Fv}$
<i>ntotal</i> 5000 trucks	$ntotal = \sqrt{5000 \text{ trucks} * avw * W * Fr * G * T * Fv}$
<i>ntotal</i> 10 000 trucks	$ntotal = \sqrt{10\ 000 \text{ trucks} * avw * W * Fr * G * T * Fv}$
<i>ntotal</i> 20 000 trucks	$ntotal = \sqrt{20\ 000 \text{ trucks} * avw * W * Fr * G * T * Fv}$

With the calculation, number of truck axles greater than 20kN during the design period was calculated. The details to the calculation can be found in appendix 15.

3.6.1.2 Characteristic number of truck axles during the design period

The traffic load is determined by multiple parameters namely truck intensity, average growth axes, lane distribution, axle spectrum, Tyre spectrum. These parameters have some degree of uncertainty, depending on the way they are determined. If the parameters are predominantly estimated, the uncertainty of the traffic load is high. However, it is cumbersome to have the corresponding uncertainty applied per parameter. In case of axle and tyre spectra, the uncertainty is quite difficult because they are not single parameters.

For simplicity, the uncertainty in traffic data is discounted in a single uncertainty factor *F_{origin}*, with which the total number of truck axes is multiplied over the Design period.

To calculate the characteristic number of axles during the design period, the uncertainty factor and the expected number of trucks during the design period is required. The uncertainty factor used for the calculation is chosen as 1,8 due to the fact that, a high uncertainty factor was required because a comparison calculations was made. Attached to appendix 14, table 4.2 is an overview of the uncertainty traffic factor (*F_{origin}*) used in the road construction sector.

The characteristic number of truck asses is calculated as :

$$N_{char.total} = n_{total} \cdot F_{origin}$$

where ;

n_{total} : total number of trucks with axle load greater than 20 kN during the design period.

F_{origin} : the uncertainty factor of traffic load

Table 6, shows the calculation to the characteristic number of truck axles during the design period considering the variable traffic intensities. The value of *n_{total}* vary for each traffic intensity but the value of *F_{origin}* i.e 1,8 remains constant.

Table 6 : Calculation of *N_{char}*, for Various Traffic Intensities

Traffic intensity	<i>N_{char}</i> .
1000 trucks	<i>n_{total}</i> 1000 trucks* <i>F_{origin}</i>
5000 trucks	<i>n_{total}</i> 5000 trucks* <i>F_{origin}</i>
10 000 trucks	<i>n_{total}</i> 10 000 trucks* <i>F_{origin}</i>
20 000 trucks	<i>n_{total}</i> 20 000 trucks* <i>F_{origin}</i>

With the calculation, the characteristic number of truck axles during the design period was calculated. The details to the calculation can be found in appendix 15.

3.6.1.3 Axle spectrum

The percentage distribution of the number of expected truck axles over a number of axle classes is described in OIA as axle spectrum. The axle spectrum was chosen according to the RWS specifications for heavy loaded axle class. In the table 7, an illustration of the input axle spectrum in OIA is shown. Attached to appendix 14, table 4.4, is the details of the axle spectrum according to RWS specifications.

Table 7 : Axle Spectrum

Axle class (kN)	Heavy loaded (Axle Spectrum (%))
20 - 40	15,6
40 - 60	27,1
60 - 80	28,1
80 - 100	14,6
100 - 120	8,75
120 - 140	4,60
140 - 160	1,04
160 - 180	0,13
180 - 200	0,08
200 - 220	0

3.6.1.4 Tyre Spectrum

In OIA calculation, the tyre spectrum is considered i.e. the percentage distribution of the truck tyres under four distinguished tyre types (single air, double air, Broadband, super broadband). The tyre spectrum was chosen according to the RWS specifications. In the table 8, an illustration of the input tyre spectrum in OIA is shown. Attached to appendix 14, table 4.5, is the details of the tyre spectrum according to RWS specifications.

Table 8 : Tyre Spectrum

Tyre Types	Value
EL	39
DL	38
BB	23
SB	0

3.6.1.5 Category of Truck Intensity

Within the thesis scope, the category of truck intensity was not considered according to RWS specifications, because the essence of the OIA calculation is to compare variables of 4 various traffic intensities. Rather, various truck intensities was analysed as earlier stated.

3.6.1.6 Speed of Truck Traffic

The speed of truck traffic was chosen, according to the client specifications as earlier stated. The speed of the truck traffic is 80km/hr according to the client specifications which is also dependent on the Fv value.

The calculations and parameters earlier stated were mainly specifications from the client which served as a basis to calculate the base layer thickness in OIA. In the next chapter, detail calculation of the asphalt pavement construction is made.

3.6.2 Calculation of the Asphalt Pavement Construction

In order to calculate the base layer thickness for each traffic intensity, it is important to calculate the thickness of the other two asphalt layers i.e. top, binder layer. Nevertheless, within the research scope, the thickness of the top and binder layer is not calculated because only base layer mixes were produced. The thickness of the top and binder layer for Standard Mix i.e. (AC 22 Base/Bind 60% "RAP") used by DIBEC is used for the calculation :

- Top layer : 50 mm PA 16
- Binder layer : 45mm AC 16 Bind 35/50 60% "RAP"

For the calculation of each traffic intensity in OIA, the thickness of the top and binder layer remain constant, while the thickness of the base layer is variable i.e. subject to change depending on each asphalt variant. In order to calculate the base layer thickness, certain factors were taken into consideration which are namely the thickness of the hydraulic bound base, sand, etc.

3.6.2.1 Hydraulic Bound Base

In accordance to RWS specifications, the minimum layer thickness of standard hydraulic bound base is given as 200mm. Nevertheless, within the thesis scope, it was decided to increase this layer to 250mm to have better settlement. Thence, the hydraulic bound base used for the calculation is 250mm.

3.6.2.2 Subgrade

The subgrade of an asphalt pavement consists of natural sub-grade and foundation. The foundation consists of an improved subgrade, supplement, an embankment and a sand bed. With this, the pavement construction is schematized to a Linear elastic half space with an equivalent stiffness modulus. For the calculation of the base thickness in OIA, the equivalent stiffness modulus is determined based on the natural subgrade using the specifications of RWS. In appendix 14 table 6,1, a number of indicative values for equivalent stiffness modulus is given.

From the clients specifications, it was given that the natural subgrade is sand, thence the value of the E-modulus used in the calculation is 100 MPa. Having known the value of the E-modulus, it is important to determine the characteristic stiffness modulus. The value of the characteristic stiffness modulus is dependent on the type of foundation and material and it is calculated based on the RWS specification (appendix 14 table 6.2) .

According to the client specifications, the type of foundation is lightly bonden material and the material is a hydraulic bound base, thence the characteristic used in the calculation is the 600 MPa. With the values of the hydr. Bound base and the E –modulus, the characteristic deformation relation for each asphalt variant is calculated in excel (appendix 13) in order to give the relative stiffness and fatigue values which will be used to compare the base layer thickness of the 5 asphalt variants.

- 250mm hydr. bound base (600 Mpa)
- Sand (100Mpa)

Therefore, the obtained values from the calculation are then input into the OIA software to determine the base layer thickness of each asphalt variant depending on the various truck intensities.

3.6.2.3 Calculation of Base Layer Thickness

The base layer acts as a tensile zone in the asphalt pavement construction when spreading the load to the underlying layers. Therefore, the base layer under traffic intensity should be durable to stiffness and tear. In the base layer of asphalt pavement, asphalt concrete is applied which is commonly referred to as “AC”.

The calculation of the base layer thickness is made based on the traffic intensity category in accordance to the RWS specifications (appendix 14 table 5.2). The base layer thickness calculation for the truck intensity ; 1000 trucks, 5000 trucks, 10 000 trucks, 20 000 trucks is made according to the traffic category OL-C according to the client’s specification because it can accommodate highest traffic load.

More so, the thickness of the base layer mixes is calculated based on the RWS specifications (appendix 14 table 5.3) . This specification is given by RWS for calculating the base layer thickness , but it does not necessarily imply that the calculated base layer thickness within the thesis scope has to fall within this range. In a situation whereby the calculated base layer thickness exceeds the maximum value given by RWS, the thickness of the layer can be divided during application.

For the OIA calculation, it is also important that the thickness of the asphalt construction considering each asphalt variant should not exceed 500mm. This implies that, the thickness of the top, binder and base layer should not exceed the program limits i.e. 500mm. Having stated earlier that, the thickness of the top and binder given by the client is 50mm and 45mm respectively (chapter 3.6.2). With the calculated base layers for each asphalt variant, the summation of the total asphalt construction should not exceed 500mm. Thus, for the calculation of the base layer thickness of the 5 asphalt variants, the earlier justified parameters and results of the calculations were input into OIA. These parameters include the design of the asphalt pavement construction:

- Top layer : 50mm (PA 16)
- Binder layer : 45mm (AC 16 Bind 35/50 60% “RAP”)
- Base layer : Variable (i.e. it is subject to change according to each asphalt mix)
- 250mm hydr. bound base 600 Mpa
- Sand (100Mpa)

The specifications of the client inputted in OIA include :

- Design life span : 20 years
- Number of working Days : 270
- Axle spectrum : heavy spectrum
- Number of lanes : 2
- Truck speed : 80km/hr
- Lane width : 3,5m
- Distance wheel track to edge pavement: 1,0m
- Traffic growth percentage: 1,50%
- Reliability : 85%
- Permissible damage percentage : 15%

The detailed calculation for each asphalt mix is calculated and can be found in the appendix 13.

3.7 Sustainability : EcoChain

This chapter describes one of the factors considered to make a choice of sustainable asphalt mixes. EcoChain was used to make some crucial decisions during the production process, involving the selection of the product and the most sustainable suppliers by ranking each supplier relatively to the product sustainability, thence making a selection of the most suitable product. Conclusively, the EcoChain was used to compare the sustainability of the produced asphalt mixes. As a result of lack of the LCA data of rejuvenators from the supplier, the LCA of each asphalt mix could not be determined. Nevertheless, within the thesis scope, the measure of sustainability was divided into three main aspects i.e. determining the sustainability of three products in EcoChain namely ;

- AC 22 Base/Bind (80% RAP) without rejuvenator (represents the Reference Mix)
- AC 22 Base/Bind (80% RAP) + rejuvenator (represents the 4 mixes containing Rejuvenators)
- AC 22 Base/Bind(60% RAP) without rejuvenator (represents the Standard Mix used by DIBEC).

3.7.1 EcoChain Process Description

In order to check the sustainability of an asphalt mix using the software, processes were implored to input the required data. These are namely ; usage and emissions, purchase, transport, process, footprint and process, product etc. The compilation and working out of this data therefore yielded an output to determine if the mix is sustainable or not. In the proceeding paragraphs, a brief description about the processes are given.

3.7.1.1 Usage and emissions

At this stage the energy usage and emissions were captured, to determine the amount of energy required for the production of the new mixes.

3.7.1.2 Purchasing

The amount of purchased raw materials and rejuvenators were decided. This was to determine if the required raw materials were imported or not, due to the fact the amount of purchased raw materials has influence on the end product.

3.7.1.3 Transport

The transportation means of the purchased raw materials and resources were determined in order to define the ton-km travelled by the ships or trucks conveying the purchased raw materials stones, sand, rejuvenator etc.

3.7.1.4 Processes

The different production processes required for the production of the new asphalt mix were considered, to determine the energy allocation and emission involved for each process. The processes are namely ; warming of bitumen, electricity, cranes and shovel etc.

3.7.1.5 Footprint and Process

The energy usages and emissions were distributed over the processes, and the amount of footprints items used in each production process were defined in terms of the total energy consumed.

3.7.1.6 Product

The type and characteristics of three asphalt mixes were compared, by specifying the mix compositions, process distribution and production. More so, the materials per product composition were allocated from cradle to gate calculations, in order to manage the mix usage and its end of life scenario.

3.7.2 Life Cycle Analysis (LCA)

The essence of determining the sustainability of an asphalt mix is to analyze its Life Cycle Analysis (LCA). Within the thesis scope, the LCA of the mix was evaluated using the EcoChain flow chart on the next page (figure 40). The chart is based on the Process tree discussed in chapter 2.7.2.1. The sustainability of the mix was determined by considering the LCA of the virgin materials, energy, transport and processing in the Asphalt plant. All these data derived from the National Environmental Data base were inputted into the EcoChain software to check if the asphalt mixes are sustainable. During the research, the LCA data of the rejuvenators were unavailable, thence the LCA data of the bitumen, was used by altering the origin of the bitumen i.e. (transport), due to the fact that the production location of the rejuvenators differ from that of the rejuvenator.

In addition, it is important to know that the MKI is not a process, but rather an output, which shows the environmental cost of the mix i.e. determining if the mix is sustainable or not. Therefore, the MKI is an output of the EcoChain and the result can be found in chapter 4.8.2.

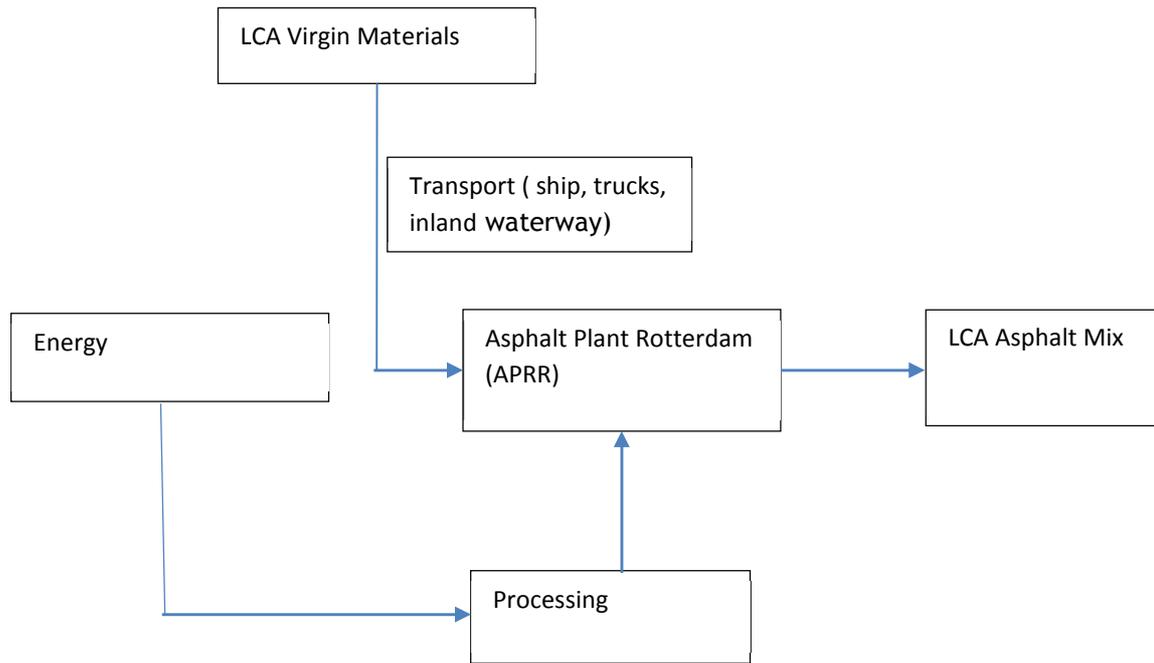


Figure 40 : EcoChain Flow Chart

Conclusively, the LCA of the Asphalt mixes was not determined as a result of unavailable LCA data of the rejuvenators from the suppliers. Thus, the technical duration of how long the mix is required to stay before it becomes aged was not analysed. Nevertheless, it is important the new asphalt mixes have a minimum technical lifespan of 20years, which is according to the client's specification. More so, according to the RWS specifications, it is important that base layer mixes have a minimum lifespan of 20years and a maximum lifespan of 20 years .

3.8 Cost Analysis

This chapter explains one of the factors which determine the choice of the most suitable asphalt mix i.e. the improved and most sustainable mix. In this chapter, the cost analysis of the 5 produced asphalt mixes is described. For this purpose, a general cost analysis is made in order to give an approximate overview of the production cost per ton. More so, it is important to understand that the cost analysis does not take into consideration the cost of mineral aggregates which is as a result of limited data/information from the suppliers, but rather considers the cost of the binder and cost of mix production in the asphalt plant. In this chapter, binder is a term used to refer to the bitumen or rejuvenator applied to the asphalt mix.

Nevertheless, to make an approximate cost analysis, research was made concerning the cost of mix production in the asphalt plant and the cost of binder per kilogram which was required for the further calculation. For the cost analysis, some parameters used for the calculation are namely :

- Ratio of binder required per mix.
- Percentage of binder.
- Cost of binder/kg (€).
- Cost of Mix without bitumen (€).
- Density (kg/m³).

Using the parameters above, Cost of binder/m², Cost of mix/m² and Cost of mix with binder/ton were calculated for each of the produced asphalt mixes. To obtain this cost analysis, sub calculations were made to determine the Binder required (kg/ton), Cost of binder in 1000kg, Volume required for each mix according to the result from OIA for each traffic intensity, Amount of mix required (kg/m²), Amount Binder required (kg/m²).

With the value from the parameters, a breakdown of the calculations is given in the next sub chapters. These values are standard gotten from client or the supplier. The ratio of binder required per mix was calculated earlier during the research, when the percentage of virgin materials required for the production of a new asphalt mix was calculated (appendix 11). The percentage of the binder is the ratio expressed in (%), while the density is the average density obtained from the asphalt mixes (appendix 16). The cost of the binder/kg (€) was obtained from the suppliers of each binder while the cost of mix without bitumen was obtained from the Asphalt Plant Amsterdam (APA). In table 9, value of the parameters used for the calculation are shown.

Table 9 : Parameters used for Cost Calculation

Parameter Mix	Ratio of binder required per mix.	Percentage of binder (%)	Cost of binder/kg (€).	Cost of Mix without bitumen (€).	Density (kg/m ³).
Mix 0	0,3	0,3 %	0,28	21,02	2395
Mix 1	0,3	0,3 %	2,00	21,02	2395
Mix 2	0,3	0,3 %	1,80	21,02	2395
Mix 3	0,3	0,3 %	1,10	21,02	2395
Mix 4	0,3	0,3 %	1,65	21,02	2395

3.8.1 Binder required (ton)

The binder per ton is calculated by considering the amount of Percentage of binder required per mix * 1000. The calculation illustration for the 5 mixes is as follows :

- Mix 0 : Percentage of bitumen* 1000
- Mix 1 : Percentage of RJ 1 * 1000
- Mix 2 : Percentage of RJ 2 * 1000
- Mix 3 : Percentage of RJ 3 * 1000
- Mix 4 : Percentage of RJ 4 * 1000

3.8.2 Cost of binder /1000kg

The cost of binder per 1000kg also refers to the cost of binder per ton which is either the cost of the bitumen or rejuvenator. It is calculated by considering the binder required (kg/ton) and the cost of binder/kg (€).The calculation illustration for the 5 mixes is as follows :

- Mix 0 : The cost of the binder per ton is calculated by multiplying the bitumen (kg/ton) * cost of bitumen/kg (€). The required bitumen (kg/ton) is 3 while the cost of bitumen/kg is € 0,28 (The cost of the bitumen was obtained from Asphalt Plant Amsterdam (APA)).

$$\text{Cost of bitumen/ton} = \text{Bitumen (kg/ton)} * \text{cost of bitumen/kg (€)}$$

- Mix 1 : The cost of the binder per ton is calculated by multiplying the RJ 1 (kg/ton) * cost of RJ 1/kg (€). The required RJ 1 (kg/ton) is 3 while the cost of RJ 1/kg is € 2,00. The cost of the RJ 1 was obtained from the supplier. The name of the supplier and the source of the cost are not stated for confidential purposes (appendix 7).

$$\text{Cost of RJ 1/ton} = \text{RJ 1 (kg/ton)} * \text{cost of RJ 1/kg (€)}$$

- Mix 2 : The cost of the binder per ton is calculated by multiplying the RJ 2 (kg/ton) * cost of RJ 2/kg (€). The required RJ 2 (kg/ton) is 3 while the cost of RJ 2/kg is € 1,80. The cost of the RJ 2 was obtained from the supplier. The name of the supplier and the source of the cost are not stated for confidential purposes (appendix 7).

$$\text{Cost of RJ 2/ton} = \text{RJ 2 (kg/ton)} * \text{cost of RJ 2/kg (€)}$$

- **Mix 3** : The cost of the binder per ton is calculated by multiplying the RJ 3 (kg/ton) * cost of RJ 3/kg (€). The required RJ 3 (kg/ton) is 3 while the cost of RJ 3/kg is € 1,10. The cost of the RJ 3 was obtained from the supplier. The name of the supplier and the source of the cost are not stated for confidential purposes (appendix 7).

$$\text{Cost of RJ 3/ton} = \text{RJ 3 (kg/ton)} * \text{cost of RJ 3/kg (€)}$$

- **Mix 4** : The cost of the binder per ton is calculated by multiplying the RJ 4 (kg/ton) * cost of RJ 4/kg (€). The required RJ 4 (kg/ton) is 3 while the cost of RJ 4/kg is € 1,65. The cost of the RJ 4 was obtained from the supplier. The name of the supplier and the source of the cost are not stated for confidential purposes (appendix 7).

$$\text{Cost of RJ 4/ton} = \text{RJ 4(kg/ton)} * \text{cost of RJ 4/kg (€)}$$

3.8.3 Cost of mix with binder /ton (€)

The cost of mix with binder/ton (€) also. It is calculated by considering the cost of mix without bitumen (€) and cost of binder/ ton (€). The calculation illustration for the 5 mixes is as follows :

- **Mix 0** : The cost of mix with binder per ton is calculated by the addition of cost of mix without bitumen (€) + cost of bitumen/ton (€). The cost of mix without bitumen (kg/ton) is €21, 02, while the cost of bitumen/ton is € 0,84 (Source : Asphalt Plant Amsterdam (APA)).

$$\text{Cost of mix with binder/ton} = \text{Cost of mix without bitumen (€)} + \text{cost of bitumen/ton (€)}$$

- **Mix 1** : For mix 1, the cost of mix with binder per ton is calculated by the addition of cost of mix without bitumen (€) + cost of RJ 1/ton (€). The cost of mix without bitumen (kg/ton) is €21, 02, while the cost of RJ 1/ton is € 6,00.

$$\text{Cost of mix with binder/ton} = \text{Cost of mix without bitumen (€)} + \text{cost of RJ 1/ton (€)}$$

- **Mix 2** : For mix 2, the cost of mix with binder per ton is calculated by the addition of cost of mix without bitumen (€) + cost of RJ 2/ton (€). The cost of mix without bitumen (kg/ton) is €21, 02, while the cost of RJ 2/ton is € 5,40.

Cost of mix with binder/ton = Cost of mix without bitumen (€) + cost of RJ 2/ton (€)

- **Mix 3** : For mix 3, the cost of mix with binder per ton is calculated by the addition of cost of mix without bitumen (€) + cost of RJ 2/ton (€). The cost of mix without bitumen (kg/ton) is €21, 02, while the cost of RJ 3/ton is € 3,30.

Cost of mix with binder/ton = Cost of mix without bitumen (€) + cost of RJ 2/ton (€)

- **Mix 4** : For mix 4, the cost of mix with binder per ton is calculated by the addition of cost of mix without bitumen (€) + cost of RJ 4/ton (€). The cost of mix without bitumen (kg/ton) is €21, 02, while the cost of RJ 4/ton is € 4,95.

Cost of mix with binder/ton = Cost of mix without bitumen (€) + cost of RJ 2/ton (€)

3.8.4 Volume of Mix required (m3)

The volume of mix required is calculated by considering the calculations of the base layer thickness of 5 variants made in OIA considering a traffic intensities of 1000 trucks, 5000 trucks, 10 000 trucks, 20 000 trucks, (chapter 3.6). The volume of each mix varies depending on the base layer thickness and it is expressed in m3.

Thus, for the 5 mixes, the volume is calculated using the base layer thickness calculated as :

Volume (m3) : Base layer thickness for 1000 trucks (m) * 1* 1
 Base layer thickness for 5000 trucks (m) * 1* 1
 Base layer thickness for 10 000 trucks (m) * 1* 1
 Base layer thickness for 20 000 trucks (m) * 1* 1

The calculation procedure is done for mix 0 to 4 and the values altered for each mix is the base layer thickness depending on the traffic intensities. Table 10 on the next page, gives an overview of the calculation.

Table 10 : Calculation of Volume (m3)

Traffic intensity →	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix ↓				
Mix 0	0,14 * 1*1	0,198 *1*1	0,226* 1*1	0,256 * 1*1
Mix 1	0,112 *1*1	0,165 *1*1	0,19* 1*1	0,216 * 1*1
Mix 2	0,16 * 1*1	0,233 *1*1	0,27* 1*1	0,309 * 1*1
Mix 3	0,178 * 1*1	0,263 *1*1	0,308* 1*1	0,36 * 1*1
Mix 4	0,167 * 1*1	0,233*1*1	0,266* 1*1	0,301 * 1*1

3.8.5 Required Asphalt Mix (kg/m²)

This is the amount of mix required, for each base layer thickness according to the traffic load i.e. 1000 trucks, 5000 trucks, 10 000 trucks, 20 000 trucks of the 5 asphalt mixes, It is calculated as the density of the each asphalt mix (kg/m³) * volume (m³). The volume of each mix varies depending on the base layer thickness, while the density 2395 kg/m³ is constant for the 5 asphalt mixes.

Therefore for the 5 mixes, the amount of mix is calculated as :

Amount of Mix Required (kg/m²) : Volume (m³) for 1000 trucks * 2395 (kg/m³)
 Volume (m³) for 5000 trucks * 2395 (kg/m³)
 Volume (m³) for 10 000 trucks * 2395 (kg/m³)
 Volume (m³) for 20 000 trucks * 2395 (kg/m³)

The calculation procedure is done for mix 0 to 4 and the values altered for each mix was the volume depending on the traffic intensity. Table 11 on the next page, gives an overview of the calculation.

Table 11 : Calculation of Asphalt Mix Required (kg/m²)

Traffic Intensity →	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix ↓				
Mix 0	0,14 * 1*1* 2395	0,198 *1*1 *2395	0,226* 1*1*2395	0,256 * 1*1*2395
Mix 1	0,112 *1*1*2395	0,165 *1*1*2395	0,19* 1*1*2395	0,216 * 1*1*2395
Mix 2	0,16 * 1*1*2395	0,233 *1*1*2395	0,27* 1*1*2395	0,309 * 1*1*2395
Mix 3	0,178 * 1*1*2395	0,263 *1*1	0,308* 1*1	0,36 * 1*1
Mix 4	0,167 * 1*1*2395	0,233*1*1*2 395	0,266* 1*1*2395	0,301 * 1*1*2395

3.8.6 Binder Required (kg/m²)

Having calculated the amount of asphalt mix, which will be applied to each base layer in relation to the traffic intensity. It is important, that the amount of binder to be added to the mix is also calculated. The binder required is determined by multiplying the amount of asphalt mix * binder percentage. The amount of asphalt mix required varies depending on the base layer thickness while the binder percentage 0,3% is constant for the 5 asphalt mixes.

Thus, for the 5 mixes, the binder required in relation to each traffic intensity is calculated as :

Binder Required (kg/m²) : Amount of asphalt mix for 1000 trucks (kg/m²) * 0,3 (%)
 Amount of asphalt mix for 5000 trucks (kg/m²) * 0,3 (%)
 Amount of asphalt mix for 10 000 trucks (kg/m²) * 0,3 (%)
 Amount of asphalt mix for 20 000 trucks (kg/m²) * 0,3 (%)

The calculation procedure is done for mix 0 to 4 and the values altered for each mix is the amount of asphalt mix required depending on the traffic intensity. Table 12 gives an overview of the calculation.

Table 12 : Calculation of Binder Required (kg/m²)

Traffic Intensity 	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix 				
Mix 0	335 * 0,3 %	474 * 0,3 %	541 * 0,3 %	613 * 0,3 %
Mix 1	268 * 0,3 %	395 * 0,3 %	455 * 0,3 %	517 * 0,3 %
Mix 2	383 * 0,3 %	558 * 0,3 %	647 * 0,3 %	740 * 0,3 %
Mix 3	426 * 0,3 %	630 * 0,3 %	338 * 0,3 %	862 * 0,3 %
Mix 4	400 * 0,3 %	558 * 0,3 %	637 * 0,3 %	721 * 0,3 %

3.8.7 Cost of Binder/m² (€)

Having calculated, the binder required, the cost analysis is made to have an overview of its cost. The cost of the binder for each mix is dependent on the binder required according to the relative base layer thickness.

The cost of binder is determined by multiplying the binder required (kg/m²) *cost of the binder/kg (€). The cost of binder/kg (€) varies for the 5 mixes while the binder required for each mix also varies depending on the base layer thickness.

The cost of the binder for each asphalt mix to be used in the calculation is given as follows :

- Mix 0 : Cost of bitumen/kg = € 0,28
- Mix 1 : Cost of RJ 1/kg = € 2,00
- Mix 2 : Cost of RJ 2/kg = € 1,80
- Mix 3 : Cost of RJ 3/kg = € 1,10
- Mix 4 : Cost of RJ 4/kg = € 1,65

Thus, for the 5 mixes, the cost of binder/m² is calculated as :

Cost of Binder/m² (€) : binder required (kg/m²) for 1000 trucks * cost of binder/kg (€)
 binder required (kg/m²) for 5000 trucks * cost of binder/kg (€)
 binder required (kg/m²) for 10 000 trucks * cost of binder/kg (€)
 binder required (kg/m²) for 20 000 trucks * cost of binder/kg (€)

The calculation procedure is done for mix 0 to 4 and the values altered for each mix are the cost of binder and the amount of binder required (kg/m²) which depending on the traffic load and base layer thickness. Table 13 on the next page, gives an overview of the calculation.

Table 13 : Calculation of Binder (kg/m²)

Traffic Intensity →	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix ↓				
Mix 0	1,006 * € 0,28	1,423 * € 0,28	1,624 * € 0,28	1,839 * € 0,28
Mix 1	0,805 * € 2,00	1,186 * € 2,00	1,365 * € 2,00	1,552 * € 2,00
Mix 2	1,150 * € 1,80	1,674 * € 1,80	1,940 * € 1,80	2,220 * € 1,80
Mix 3	1,279 * € 1,10	1,890 * € 1,10	2,213 * € 1,10	2,587 * € 1,10
Mix 4	1,200 * € 1,65	1,674 * € 1,65	1,911 * € 1,65	2,163 * € 1,65

3.8.8 Cost of Mix/m² (€)

This gives the general cost overview of the each asphalt mix per m². Having calculated, the cost of mix with binder/ton and the amount of mix required.

In order to calculate the cost of the asphalt mix per m², the amount of mix required (kg/m²) is converted to ton by dividing the value by 1000 and then multiplying with the cost of mix with binder/ton (€). The cost of mix with binder/ton (€) varies for the 5 mixes while the amount of mix required varies depending on the base layer thickness.

The cost of the mix with binder/ton for each asphalt mix used in the calculation is given as follows :

- Mix 0 : Cost of mix with bitumen/ton = € 21, 86
- Mix 1 : Cost of mix with RJ 1/ton = € 27,02
- Mix 2 : Cost of mix with RJ 2/ton = € 26,42
- Mix 3 : Cost of mix with RJ 3/ton = € 24,32
- Mix 4 : Cost of mix with RJ 4/ton = € 25,97

Thus, for the 5 mixes, the cost of mix/m² is calculated as :

Cost of Mix /m2 (€) : (Amount of mix required for 1000 trucks) /1000 * Cost of mix with binder/ton (€)
 (Amount of mix required for 1000 trucks) /1000 * Cost of mix with binder/ton (€)
 (Amount of mix required for 1000 trucks) /1000 * Cost of mix with binder/ton (€)
 (Amount of mix required for 1000 trucks) /1000 * Cost of mix with binder/ton (€)

The calculation procedure is done for mix 0 to 4 and the values altered for each mix are the cost of mix with binder/ton and the amount of binder required (kg/m2) which depending on the traffic load and base layer thickness. Table 14, gives an overview of the calculation.

Table 14 : Calculation of Mix/m2 (€)

Traffic Intensity →	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix ↓				
Mix 0	(335/1000) * € 21,86	(474/1000) * € 21,86	(541/1000) * € 21,86	(613/1000) * € 21,86
Mix 1	(268/1000) * € 27,02	(395/1000) * € 27,02	(455/1000) * € 27,02	(517/1000) * € 27,02
Mix 2	(383/1000) * € 26,42	(558/1000) * € 26,42	(647/1000) * € 26,42	(740/1000) * € 26,42
Mix 3	(426/1000) * € 24,32	(630/1000) * € 24,32	(738/1000) * € 24,32	(862/1000) * € 24,32
Mix 4	(400/1000)* € 25,97	(558/1000))* € 25,97	(637/1000))* € 25,97	(721/1000))* € 25,97

With the calculation procedure, the Cost of 5 Mixes is determined for each base layer thickness in accordance to the relative traffic load. The detailed calculation can be found in excel sheet (appendix 17), while the overview of cost can be found in chapter 4.9.

3.9 Multi Criteria Analysis (MCA)

Within the scope of this research, four rejuvenators are compared according to certain criteria using the Multi Criteria Analysis (M.C.A). The main purpose of this comparison is to determine the most durable and sustainable asphalt mix by the addition of a certain rejuvenator. In addition five MCAs are done, to choose the mix which complies with all requirements considering durability and sustainability. The first MCA is based on the rejuvenator property, the second is based on the laboratory test, the third is based on the OIA calculation, the fourth is based on the EcoChain analysis and the fifth MCA is based on the Cost Analysis. With the results from these MCAs, the choice of the most suitable mix is made.

The outcome of the MCA analysis will basically depend on the assigned criteria and their weight factors. In order to choose the most suitable asphalt mix, all possible asphalt mixes will be listed using the important specifications. The MCA for the rejuvenator property, Test, OIA Calculation, EcoChain and Cost Analysis is carried out according to certain criteria and given weight, therefore the selection of the most suitable asphalt mix is based on the outcome of the result i.e. the mix which complies with the factors according to the criteria with the highest score. When taking into account the so-far known research specifications, it is possible to derive what are to be quantified by giving a certain weight, depending on its relative level of importance.

More so, options that are evaluated are shown in the same table. The evaluation of the mixes were done by setting scores to vary from (-2) until (+2), with (-2) being negative or undesirable effect and (+2) being the most desirable result in regards to a certain criterion. The 0 value in the evaluation shows neutral influence or no change from the initial situation. The result of the 5 MCAs, will determine the choice of the most sustainable mix i.e. a mix which fulfills the requirements of all aspects.

3.9.1 Criteria Weight Description

To choose the most suitable asphalt mix which fulfills all requirements, certain criteria is used to evaluate the research process. The weight of this criterion is applied along with the percentage of relative importance to the research. The criteria with utmost importance gets the higher percentage, while the criteria with lower importance gets lower percentages and the least important criteria gets the least percentage. The criteria description is applied to the 5 MCA's carried out within the research. In the following paragraphs, an evaluation of each factor is given in relation to the selected criteria.

3.9.1.1 Evaluation Criteria for Rejuvenator Properties

Table 15 : MCA Evaluation Criteria for Rejuvenator Properties

Criteria	Explanation	Evaluation
Recyclable “RAP” content	<p>This is a very important criteria because it is a part of the research requirements for each type of rejuvenator to aid the use of a high percentage of “RAP” content.</p> <p><i>This criteria is given 40% in relevance to the total score.</i></p>	<p>-2 – Rejuvenator which does not aid use of “RAP” content.</p> <p>0 – Rejuvenator which aids use of “RAP” content.</p> <p>+1– Rejuvenator which aids use of an average of “RAP” content.</p> <p>+2 –Rejuvenator which aids use of a higher percentage of “RAP” content.</p>
Design aspects (Sustainability) (Durability)	<p>The rejuvenator has to be durable in its applications with all design aspects of an asphalt, hence considering sustainability. With the application of the rejuvenator, the produced mix should be durable i.e. have an increased life span higher than that of normal asphalt lifespan. In this criterion, a negative score will not be taken into account, since all the design mixes are drawn to satisfy this criteria. Sustainability : With the addition of the rejuvenator/additive, the mix must be as good as old mix : regarding lifespan.</p> <p><i>This criteria is given 30% in relevance to the total score.</i></p>	<p>-2 – Rejuvenator does not comply with design aspects of asphalt mix regarding sustainability and i.e. least sustainable mix.</p> <p>+1– Rejuvenator complies with design aspects, thus sustainable mix which can be recycled using a little percentage of old asphalt granulate.</p> <p>+2 – Rejuvenator complies with all design aspects of asphalt, thus most sustainable mix which is recyclable, hence making use of a higher percentage of old asphalt granulate.</p>
Prosperity (CO2 emissions)	<p>For each type of mix, it is paramount that each rejuvenator added to the mix decreases the percentage CO2 emissions in the environment.</p> <p><i>This criteria is given 10% in relevance to the total score.</i></p>	<p>1 – A rejuvenator with the least CO2 emission reduction.</p> <p>0 – A rejuvenator which does not have any positive effects/changes on CO2 emission reduction.</p> <p>+1 – A rejuvenator which reduces CO2 emissions by a certain percentage.</p> <p>+2 – A rejuvenator which reduces CO2 emissions by a higher percentage.</p>
Cost -Investment)	<p>The need to produce/design an improved and sustainable mix is vital but on the other hand it is also crucial to take cost into consideration cost. This ensures the design mix is within the cost range of the client hence fulfilling all pros and cons. Thus, The cost of rejuvenator added to the mix has a relative effect on the cost.</p> <p><i>This criteria is given 5% in relevance to the total score.</i></p>	<p>2 – Most expensive rejuvenator above the clients cost range.</p> <p>-1 – A more expensive rejuvenator compared to others.</p> <p>+1 – A cheaper rejuvenator compared to others.</p> <p>+2– Cheapest and most sustainable/durable rejuvenator,</p>
Energy consumption	<p>This involves the ability of the rejuvenator to reduce the energy consumption i.e. allow a lower energy consumption during mix production and workability. Therefore, it is important for the rejuvenator to have the ability to enhance the workability of recycled asphalt.</p> <p><i>This criteria is given 5% in relevance to the total score.</i></p>	<p>-2– Rejuvenator with the highest energy consumption,</p> <p>+1 – Rejuvenator with a low energy consumption,</p> <p>+2 – Rejuvenator with the lowest energy consumption,</p>

Production in the asphalt Plant	A rejuvenator with a higher flashpoint is more suitable than one with a lower flash point. This is due to the fact that, a rejuvenator with a higher flashpoint, can be applied directly on "RAP" without the need of extra precautions during production in the Asphalt Plant and the risk of explosion can also be avoided.	-2 – Rejuvenator with a relatively low flashpoint. +1– Rejuvenator with a high flashpoint. +2 – Rejuvenator with the highest flashpoint.
Flash point	<i>This criteria is given 5% in relevance to the total score.</i>	
Type of Mix	This considers the ability of the rejuvenators to be applied to any pavement layer mix. Hence, it is important that the selected rejuvenator products can be applied to all mixes especially base layer mixes. This is due to the fact that, only based layer mixes are produced during the thesis scope.	-2 – Rejuvenator which cannot be applied in base layer mixes. +1 – Rejuvenator which can partially be applied to base layer mixes. +2 – Rejuvenator with can be applied to base layer mixes.
	<i>This criteria is given 5% in relevance to the total score.</i>	

3.9.1.2 Evaluation Criteria for Laboratory Tests

Table 16 : MCA Evaluation Criteria for Laboratory Tests

Criteria	Explanation	Evaluation
Stiffness	One of the factors required for the production of a suitable asphalt mix is the type test result. Stiffness as a criteria is important due to the fact that, the relative characteristics of a mix in regards to its resistance to stiffness depends on the mix sustainability, because a higher resistance to stiffness gives a better mix performance and vice versa. <i>This criteria is given 40% in relevance to the total score.</i>	-2 – Mix with the lowest resistance to stiffness. +1 – Mix with a high resistance to stiffness. +2 – Mix with the highest resistance to stiffness.
Fatigue	Fatigue as a criteria is important due to the fact that, the relative characteristics of a mix in regards to its resistance to fatigue depends on the mix sustainability, because a higher resistance to fatigue gives a better mix performance and vice versa. <i>This criteria is given 40% in relevance to the total score.</i>	-2– Mix with the lowest resistance to fatigue. +1– Mix with a high resistance to fatigue. +2 – Mix with the highest resistance to fatigue.
Resistance to permanent deformation	Resistance to permanent deformation as a criteria is important due to the fact that, the relative characteristics of a mix in regards to its resistance to permanent deformation is dependent on the mix sustainability. <i>This criteria is given 20% in relevance to the total score.</i>	- 2 – Mix with the lowest resistance to permanent deformation. +1– Mix with a low resistance to permanent deformation. +2– Mix with the highest resistance to permanent deformation.

3.9.1.3 Evaluation Criteria for OIA Calculation

Table 17 : MCA Evaluation Criteria for OIA Calculation

Criteria	Explanation	Evaluation
1000 trucks/ working day	The produced asphalt mixes need to accommodate a minimum number of certain traffic load per working day. Therefore this criteria examines if the asphalt mix can accommodate 1000 trucks. <i>This criteria is given 25% in relevance to the total score.</i>	-2 –Mix which cannot accommodate a traffic load of 1000 trucks +1 –Mix which can partially accommodate a traffic load of 1000 trucks. +2 – Mix which can accommodate a traffic load more than 1000 trucks.
5000 trucks/ working day	The produced asphalt mixes need to accommodate a minimum number of certain traffic load per working day. Therefore this criteria examines if the asphalt mix can accommodate 5000 trucks. <i>This criteria is given 25% in relevance to the total score.</i>	2– Mix which cannot accommodate a traffic load of 5000 trucks. +1 –Mix which can partially accommodate a traffic load of 5000 trucks. +2 – Mix which can accommodate a traffic load more than 5000 trucks.
10 000 trucks/ working day	The produced asphalt mixes need to accommodate a minimum number of certain traffic load per working day. Therefore this criteria examines if the asphalt mix can accommodate 10 000 trucks. <i>This criteria is given 25% in relevance to the total score.</i>	2– Mix which cannot accommodate a traffic load of 10 000 trucks. +1 –Mix which can partially accommodate a traffic load of 10 000 trucks. +2 – Mix which can accommodate a traffic load more than 10 000 trucks.
20 000 trucks/ working day	The produced asphalt mixes need to accommodate a minimum number of certain traffic load per working day. Therefore this criteria examines if the asphalt mix can accommodate 20 000 trucks. <i>This criteria is given 25% in relevance to the total score.</i>	2 –Mix which cannot accommodate a traffic load of 20 000 trucks. +1 –Mix which can partially accommodate a traffic load of 20 000 trucks. +2 – Mix which can accommodate a traffic load more than 20 000 trucks.

3.9.1.4 Evaluation Criteria for Sustainability : EcoChain

Table 18 : MCA Evaluation Criteria for EcoChain

Criteria	Explanation	Evaluation
Climate Change (CO2 emissions)	<p>Sustainability is of utmost importance within the thesis scope, this was therefore determined by using the EcoChain. With this, the amount of CO2 emitted during the production of each asphalt mix is determined. Thus, it is important that for a mix to be sustainable, the amount of CO2 emissions needs to be lower.</p> <p><i>This criteria is given 40% in relevance to the total score.</i></p>	<p>-2 – Mix with the highest CO2 emission. +1 – Mix with an average CO2 emission. +2 – Mix with the lowest CO2 emission.</p>
Environmental Cost Indicator (MKI)	<p>MKI is analysed in EcoChain because it considers the environmental cost of a mix. Thus, it is important that, for a mix to be sustainable, the MKI score needs to be lower.</p> <p><i>This criteria is given 40% in relevance to the total score.</i></p>	<p>-2 – Mix with the highest MKI score. +1– Mix with an average MKI score. +2 – Mix with the lowest MKI score.</p>
Energy Use (MJ)	<p>Energy Use is an aspect considered in EcoChain to determine the mix sustainability and with this, the amount of energy used in the production of each asphalt mix is determined. Therefore, a mix with a lower energy usage is considered more sustainable.</p> <p><i>This criteria is given 20% in relevance to the total score.</i></p>	<p>-2 – Mix with the highest energy usage. +1– Mix with an average energy usage. +2 – Mix with the lowest energy usage.</p>

3.9.1.5 Evaluation Criteria for Cost Analysis

Table 19 : MCA Evaluation Criteria for Cost Analysis

Criteria	Explanation	Evaluation
OIA Calculation	The result of the OIA calculation was selected as one of the criteria because, it was used to calculate the amount of mix required for each base layer per mix, the amount of binder required (kg/m ²), Cost of binder/m ² and cost of mix/m ² . Thus, it is important for this criteria that, the base layer thickness of the mix is suitable in regards to the OIA calculation. <i>This criteria is given 50% in relevance to the total score.</i>	-2– Mix with the least suitable base layer thickness in regards to OIA Calculation. +1–Mix with a suitable base layer thickness in regards to OIA Calculation. +2–Mix with the most suitable base layer thickness in regards to OIA calculation.
Cost of binder (€)	This is to analyze the cost of the various binders, which will be applied in the asphalt mixes. Therefore, the mix with the less expensive binder gets the highest score, while the mix with the most expensive binder gets the least score. <i>This criteria is given 25% in relevance to the total score.</i>	-2– Mix with the most expensive binder. +1– Mix with a quite expensive binder. +2– Mix with the least expensive binder.
Cost of mix (€)	This criteria analyses if the cost of the binder has a negative or positive effect on the total cost of the mix. This aspect considers the amount of an asphalt mix per m ² i.e. considering the aspects namely the base layer thickness per mix, amount of mix required per m ² for each traffic intensity, and the amount of binder required (kg/m ²) etc. Thus, the mix with the least cost (€) gets highest score and vice versa. <i>This criteria is given 25% in relevance to the total score.</i>	-2 –Most expensive mix. +1–Mix which is quite expensive. +2 – The cheapest mix .

3.9.1.5 Criteria Ranking Methodology

To determine the relative importance of criteria, a comparison matrix scale is determined as shown in the table 20. With this matrix scale, all the 5 asphalt mixes are given a score in relation to their importance to each criteria. These scores were worked out corresponding to their percentage of relevance . The MCA results can be found in (chapter 5).

Table 20 : Criteria weighing assessment scale

Descriptions	Scale (points)
Not suitable	-2
Neutral	0
Moderately suitable	1
Extremely suitable	2

4. Result

This chapter analyses the result of the activities executed in the Method considering all aspects discussed. With the critical analysis of the result, the choice of the most sustainable mix is made considering the bitumen extraction test, Penetration and R & B test. In this chapter, the percentage of bitumen added to the mix is justified. More so, the test result is also analysed comparing the mix which complies to each test requirement.

4.1 Mix Composition and Bitumen Properties

Table 21 gives an overview result of the bitumen composition test and the particle size distribution of the “RAP” at the beginning of the test. The details can be found in an excel sheet (appendix 18)

Table 21 : Mix Composition and bitumen properties

The table below shows the passing sieve percentage (%).

		[% (m/m) 'op]	[% (m/m) 'in]
	C31,5		
	C22,4		100
	C16		97,0
	C11,2		91,0
	C8		81,2
	C 5,6		69,2
	2 mm		51,3
	500 µm		35,1
	180 µm		17,3
	63 µm		9,3
Sand fractions			
	2,0mm - 500µm		38,4
	500µm - 180µm		42,1
	180µm - 63µm		19,5
	Bitumen content (in)	[% (m/m)]	5,4
	Softening point (Ring & Ball Test)	°C	71,5
	Penetration Test (25°C, 100g,5s)	0,1 mm	16,4
	Penetration Index (PI)		0,7

From the table 21, it is seen that :

Bitumen content in the “RAP” is 5,4%

R & B Test = 71,5 °C

Penetration Test = 16,4P.I. = 0,7

The result from the penetration test and R & B showed that the bitumen present in the “RAP” is quite hard. As a result of the low penetration and high softening point, it means that a softer class of bitumen was required to produce AC 22 Base 35/50. Thus, virgin bitumen of class 70/100 was added to the mix to obtain a bitumen class 35/50. The bitumen class 70/100 was chosen because it has better characteristics in terms of resistance to deformation than other soft bitumen classes such as 160/220. The percentage of virgin bitumen added to the mix is 0,3%. More details of the percentage/ratio of bitumen added to the mix can be found in appendix 11. From the Standard Regulation, there is no particular range for bitumen content in “RAP”, thus this value varies depending on the type of “RAP” used for the research. For the R & B test, 71,5 °C was obtained as the average result which is in accordance to the Standard Regulation that, the difference between the two temperatures obtained during the test should not exceed 1 °C for softening points below 80 °C. Moreso, the value of the Penetration test and P.I obtained were 16,4 and 0,7 respectively. This values comply to the Standard Regulation because, the average penetration value is between the unit (0,1mm) for the bitumen class 35/50, while the P.I is also between the P.I value range i.e -1,5 – 0,7 required for bitumen class 35/50.

4.2 Penetration Test

The first sample of aged bitumen had a penetration level of 16,1, while the second sample had a penetration level of 16,4 and the third sample had a penetration level of 16,7. The average result was therefore obtained as 16,4. These values are realistic because, they complied with the range given by the Standard Regulations i.e. Penetration at 25°C of bitumen class 35/50 was between (unit 0,1mm).

4.3 Ring and Ball Test

The first sample of aged bitumen had a softening point of 71,4 °C while the second sample had a softening point of 71,5°C and the third sample had a penetration level of 16,7. The average result was therefore obtained as 71,5 °C. These values are realistic because, they complied with the range given by the Standard Regulations i.e. the difference between the two temperatures obtained during the test does not exceed 1 °C for softening points below 80 °C.

4.4 Penetration Index

The P.I result obtained from the aged bitumen is 0,7. This value is realistic because, it complies with the range given by the Standard Regulations i.e. the P.I for bitumen class 35/50 should be between -1,5 to +0,7.

4.5 Stiffness Test

During the stiffness test, the resistance to stiffness of the 5 Mixes was tested, as earlier stated in the method. The results from the test was obtained for each asphalt Mix. The stiffness result was obtained for each prismatic asphalt sample. Thus, the stiffness result was quite large and could not be attached to the report. Nevertheless, an overview comparison of the 5 mixes is given in chapter 4.5.1, and the detailed result can be found in appendix 19.

4.5.1 Comparison of Mixes in relation to stiffness

The average results per mix, were computed in order to compare the stiffness modulus (E-modulus in MPA), and standard deviation results of the 5 mixes. The tests results are based on the Standard RAW Regulation 2015, i.e. the minimum and maximum required value of S_{min} & S_{max} for Asphalt Concrete base mixes in relation to the OL-C traffic category (appendix 9). According to the Standard RAW Regulation 2015, the minimum required value S_{min} and maximum S_{max} are 7000 MPa and 14000 MPa respectively, thus a suitable mix for this test needs to be $7000 \leq x \leq 14000$ Mpa.

From the graph below (figure 41), it is seen that, the 5 mixes lie within the S_{min} & S_{max} range. Nevertheless, the mix with the highest and lowest stiffness can be determined according to their relative values ; mix 0 has the maximum stiffness ($S_{max} = 13685$ MPa), while mix 2 has the minimum ($S_{min} = 7050$). According to the test, the mix 2 has the most suitable result in terms of stiffness characteristics because it has the lowest stiffness value. More so, the result of the lower stiffness is good because it suggests that the rejuvenator has decreased the hardness of the aged bitumen present in the "RAP" by changing its properties as it is in virgin bitumen. The detailed calculation for the mixes can be found in (appendix 19).

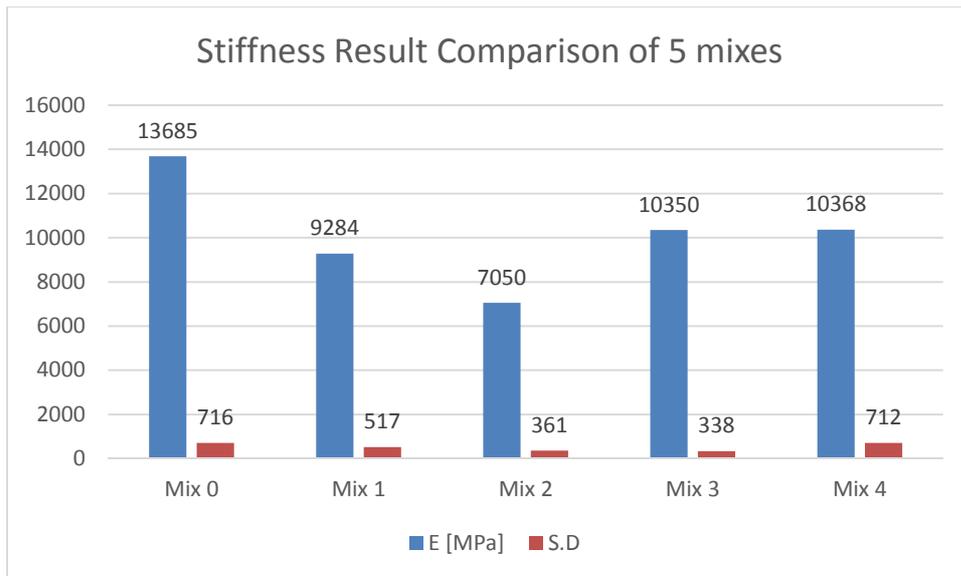


Figure 41 : Graphical Representation of Stiffness Test Result

4.3 Fatigue Test

During the test, unforeseen circumstances were encountered namely power outage, irregularity of the test samples etc., hence giving unrealistic results for mix 1 and 3. More so, some irregular results were not considered in determining the fatigue line because the test results were too much out of range. For this purpose, additional test samples were used to carry out the test to obtain realistic results, thus representing the additional test samples with a plus.

The best mixes are represented with plus, while the additional mixes are represented only with the number. The unrealistic individual results were extruded from determining the fatigue line because of their irregularity. The possible cause of the unrealistic results were within the mix composition, this was because some prismatic samples had a concentration of the large fraction of mineral aggregates in one place which causes a low binding property, thence resulting in a premature failure of the test sample. More so, the obtained result from the mix represented with plus are more realistic and were taken into consideration while the other result were disregarded for the MCA analysis.

The important parameters for this test are namely; strain at 1 000 000 cycles (ϵ_6) and the k_2 because they are the characteristics the fatigue line is based on. An illustration of the calculation for Mix 0, is shown in figure 42, and the fatigue line can be seen in (figure 43). A summarized computation of obtained results for the five mixes is given in the table 22. A detailed calculation for other mixes can be found in appendix 20.

Mix 0

Fatigue line $\ln(N) = A_0 + A_1 \cdot \ln(\epsilon)$	Fatigue line $N = k_1 \cdot \epsilon^{k_2}$	Characteristics
$q = A_0: 36,676$	$\log_{10} k_1: 15,928$	Number of specimen: 9
$p = A_1: -5,104$	$k_2: -5,104$	Cycles for strain-charact.: 1000000
$R^2: 0,965$		Mean value of E_{mi} [MPa]: 15683
$s_{xy}: 0,538$		strain-characteristics [$\mu\text{m}/\text{m}$]: 88,1

Figure 42 : Fatigue Result of Mix 0

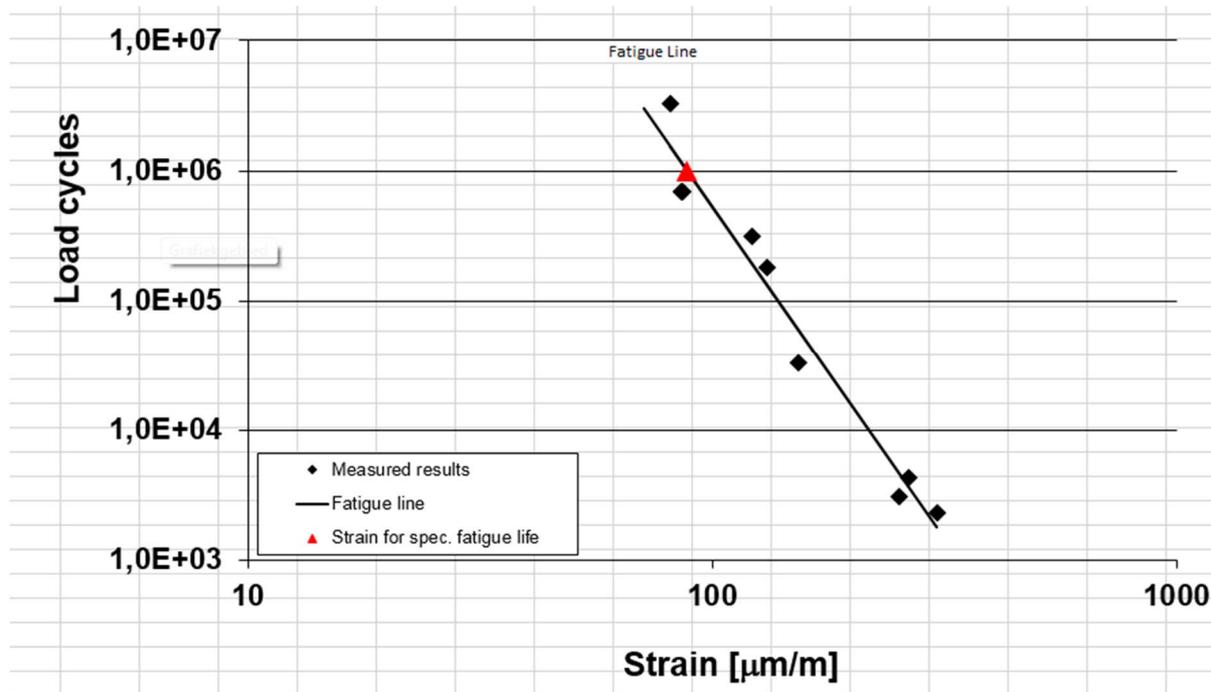


Figure 43 : Fatigue line for Mix 0

In the table below, an overview of fatigue test result obtained for the five asphalt mixes is made.

Table 22 : Computation of Fatigue Test Result for each mix

Mixes	k_2	ϵ_6 ($\mu\text{m}/\text{m}$)
Mix 0	-5,104	88,1
Mix 1	-5,045	100,8
Mix 1 plus	-5,471	114,0
Mix 2	-5,061	105,8
Mix 3	-4,504	78,4
Mix 3 plus	-5,177	88,4
Mix 4	-5,370	87,7

4.3.1 Comparison of Mixes in relation to fatigue

The average results per mix were computed in order to compare the ϵ_6 result of the 5 mixes. The tests results are based on the Standard RAW Norm, i.e. the minimum required value of ϵ_6 for Asphalt Concrete base mixes in relation to the OL-C traffic category (appendix 9). According to the Standard RAW Norm, the minimum required value of ϵ_6 is 90, thus a suitable mix for this test needs to result in $\epsilon_6 \geq 90$ ($\mu\text{m}/\text{m}$). From the graph below (figure 44), it is seen that mix 1plus has the highest value $\epsilon_6 = 114$ $\mu\text{m}/\text{m}$, while mix 3 has the lowest value $\epsilon_6 = 78,4$. Therefore, it is concluded that the Mix 1 plus has a higher and better fatigue resistance compared to the other mixes.

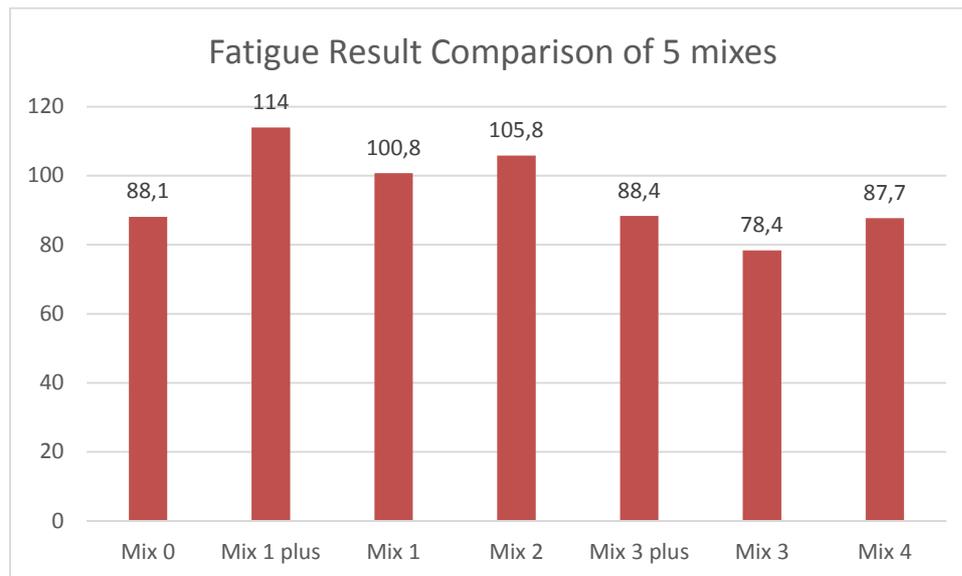


Figure 44 : Graphical Representation of Fatigue Test Result

4.4 Permanent Deformation test

The important parameter for this test is namely; f_c ($\mu\text{m}/\text{m}/\text{cycle}$). A summary of obtained results for Mix 0 is shown in table 23, while detailed calculation for other mixes can be found in appendix 21.

Table 23 : Result of Mix 0 for Permanent Deformation Test

Sample	Height (mm)	Diameter (mm)	Massa (g)	Density (kg/m ³)	f_c ($\mu\text{m}/\text{m}/\text{cycle}$)
T0-02	59,8	99,9	1109	2366	0,05
T0-03	59,8	99,8	1110	2371	0,04
T0-04	59,4	99,9	1104	2368	0,04

4.4.1 Comparison of Mixes in relation to permanent deformation

The average results per mix were computed in order to compare the f_c results of the 5 mixes. The tests results are based on the Standard RAW Norm, i.e. the maximum required value of f_c for Asphalt Concrete base mixes in relation to the OL-C traffic category (appendix 9). According to the Standard RAW Norm, the maximum required value for f_c is 1,4 , thus a suitable mix for this test needs to be $f_c \leq 1,4$.

From the graph below (figure 45), it is seen that the 5 mixes are within the highest value range of 0,2. For the permanent deformation test, the mix with the lower f_c value is described as the mix with the highest resistance to permanent deformation because, the lower the f_c value of a mix the better its performance. Nevertheless, according to the graph there is no significant difference between the f_c values of the asphalt mixes, thus a conclusion is made that all five mixes have a resistance to permanent deformation. Another cogent reason of the better resistance to deformation of all 5 mixes is as a result of the high 'RAP' content present in the mix which is due to the fact that mixes with high "RAP" require less bitumen because no light bitumen fractions are absorbed by the "RAP" due to the already 'pre coated' "RAP" with bitumen.

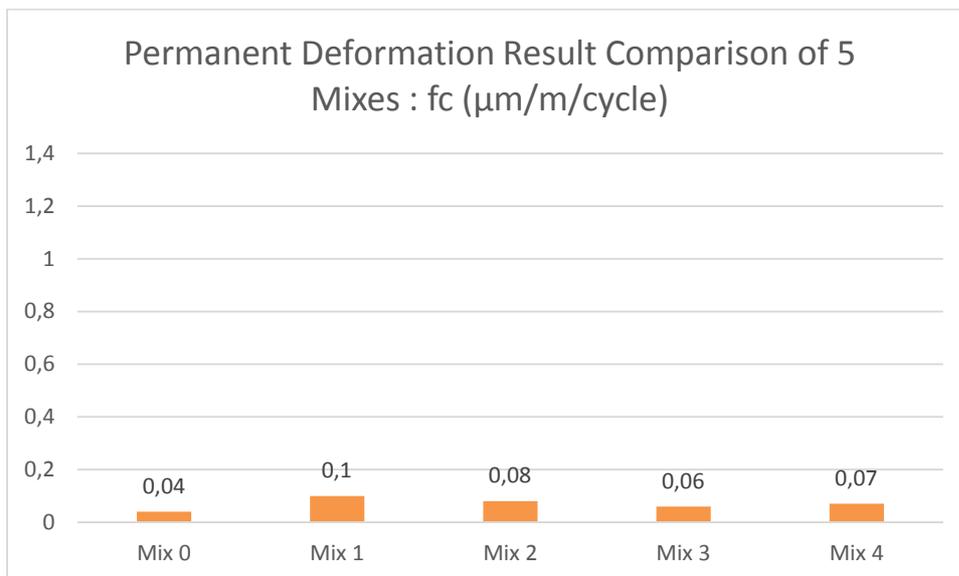


Figure 45: Graphical Representation of Permanent Deformation Test

4.5 Boundary Conditions

These include the boundary conditions taken into consideration for the production of the new asphalt mixes. They are attached to the result, because they are the boundary which were used for the production of the new asphalt mixes.

4.5.1 Lack of LCA data from suppliers

The lack of information from the suppliers is set as a boundary condition because it limited some aspects within the thesis scope. During the research, the LCA data of the rejuvenators was required for the EcoChain input in order to determine the LCA of each asphalt mix. As a result of lack information, the LCA of each asphalt mix could not be critically analysed and determined, hence giving the option to have a grouped LCA analysis of the mixes containing rejuvenators, which was not really the primary purpose using EcoChain.

4.5.2 Transportation of rejuvenators

The transportation of rejuvenators is also set as a boundary condition. This is due to the fact that, according to the EcoChain analysis, the rejuvenators were not produced in the Netherlands and were required to be transported to the Asphalt Plant using various modes of transportation namely ships, trucks etc. With the modes of transportation, a longer travelling distance was required, thence giving a negative effect on the amount of CO₂ emissions, MKI score and energy usage required for the mix production in the asphalt plant.

4.5.3 Standard RAW Regulation

This is set as a boundary condition because, the production and testing of the new asphalt mixes need to be in accordance to the Standard RAW Regulation for asphalt production used in the Netherlands. More so, all rules set out for this regulation, need to be followed to ensure that the tests are properly executed.

4.5.4 Environmental requirements

This boundary condition was chosen due to the fact that, it was quite important for the asphalt mixes to be produced under environmental friendly conditions in the laboratory. This also makes sure that the rejuvenators added to the mixes are environmentally friendly. The environmental requirements was taken into consideration during the selection of the rejuvenator, by making sure that the selected rejuvenator is mostly produced from non-toxic resins.

4.5.5 The heating temperature of “RAP”

The heating temperature of “RAP” was set as a boundary condition because, the “RAP” needs to be heated and warmed up at a temperature between 150°C - 155°C for 2,5hours before the addition of the virgin binder to ensure the production of an homogenous mix.

4.5.6 Solubility of Rejuvenator

The solubility of rejuvenator was selected as a boundary condition because, during mix production it is necessary that, the rejuvenator is soluble with bitumen and also compatible with solvents like aromatics, ketones , alcohols etc.

4.5.7 Compatibility

Compatibility was selected as a boundary condition because, the type of rejuvenators applied to the asphalt mixes, needed to be compatible to enable adhesion promoters and warm mix asphalt.

4.5.8 Storage of Rejuvenators

The storage of rejuvenator was a boundary condition because, it is necessary to ensure that the rejuvenators were not excessively exposed to low temperature in the laboratory or storage rooms. This is because rejuvenators stored below 10°C needed to be warmed or mixed before use.

4.5.9 Safety/Environmental conditions

These include the safety and environmental conditions followed during the production of the asphalt mixes. It mainly includes the laboratory safety protocol according to the VCA regulations used in the Netherlands and the rejuvenator mixing protocol. The rejuvenator mixing protocol considers the safety conditions to be taken, when adding a rejuvenator to an asphalt mix in order to avoid accidents or explosions.

4.5.9.1 Laboratory Safety Protocol

This is one of the safety conditions carried out while working in the laboratory. This includes complying with the safety procedures during the sample production and test. This safety protocol are namely ;

- wearing use of safety hand gloves.
- wearing of laboratory clothing and shoes to avoid any accident.
- wearing of safety masks and safety glasses during asphalt mixing to avoid inhaling unpleasant odours and also to avoid any accidents.
- wearing of safety helmet and safety glasses during sawing and polishing of asphalt mixes.

These laboratory safety protocol and conditions were in accordance to the working conditions according to the VCA regulations used in the Netherlands. Attached to appendix 22 is a detail of the laboratory safety protocol and conditions followed during the thesis.

4.5.9.2 Rejuvenator Mixing Protocol

This safety condition takes into consideration the laboratory mixing protocol of the rejuvenator when recycling “RAP”. The essence of this, is to mimic as much as possible what happens at the asphalt plant but as well to ensure sufficient coating in the laboratory and avoid any accidents with the products. This safety condition takes into consideration the addition of the rejuvenator to the “RAP” when warming up the “RAP”. It involves using the EN Standard as a baseline for the rejuvenator mixing protocol, enabling the recycling of a high “RAP” percentage. The mixing protocol used is as follows;

- Drying and heating of the virgin aggregates at a normal mix temperature i.e. 150-155°C for 8 hours.
- Drying and warming up of the RAP at a temperature of 110°C -130°C for 2,5 hours.
- Addition of “RAP” in the mixer and the addition of rejuvenators for 30s
- Addition of virgin aggregates to the mix for 60s.
- Addition of the hot virgin binder and mix for another 90s.

These safety conditions were followed during the production of asphalt mixes in order to avoid any accidents. The mixing protocol for the rejuvenators and safety sheets used during the thesis can be found in (appendix 23)

4.5.9.3 Mix Production and Testing

This safety condition takes into consideration the activities during the asphalt mix tests. This includes complying with the safety procedures, during the asphalt sample production and test. This includes; following the test machine instructions as given by the manufacturer, non-interference with the test machines while working etc.

4.6 Test Control

At the beginning of the tests, samples of AC “RAP” were taken in order to obtain its composition i.e. bitumen content (%) and coarseness of the mineral aggregates. The obtained result was thence used to calculate the amount of virgin binder and materials required for the production of the new asphalt mixes.

During the production of the asphalt mixes i.e. the mixing procedure, it was noticed that some rejuvenators mixed properly with the “RAP” and mineral aggregates while others did not, which implies that during mixing, some asphalt mixes quickly turned black, whereas it took some extra time for the other mixes to turn black. The reason for this irregularity could not really be established because an equal ratio of bitumen/rejuvenator was added to all the asphalt mixes. Nevertheless, it was noticed that some rejuvenators were more viscous than others, causing the materials to be easily coated in the binder. This could have been the reason for some rejuvenators not easily coating with the virgin materials, but this doubt could not be established because there was no clear proof.

More so, during the laboratory testing of the asphalt mixes i.e. resistance to stiffness, fatigue and permanent deformation, some irregular test results were obtained and the cause of this irregularity was unknown. Therefore, an assumption was made that the cause of the irregularity in the result could be from the bitumen content (%) obtained from the “RAP” at the beginning of the research. In order to clear these doubts or assumptions, it was decided to control the bitumen content present in the asphalt mixes. This control was executed by taking prismatic samples from each asphalt mix to determine the bitumen content (%) present and also to check if the earlier obtained results were correct.

The binder was extracted from each sample i.e. from the 5 asphalt variants using the extraction procedure. The result obtained from the extraction procedure was quite irregular because there was a distinctive bitumen content (%) from the 5 variants.

Therefore, to buttress the reason for this irregularity, sample of the same AC “RAP” used at the beginning of the research, was taken to determine the bitumen composition (%) and the coarseness of the mineral aggregates. The sample was divided into three proportions in order to obtain an average result, as earlier done at the beginning of the research. It was thence discovered that, the bitumen content (%) obtained at the beginning of the research was higher than the (%) obtained at the end of the result. The average bitumen content (%) obtained from the RAP samples at the beginning of the research was 5,4% while the amount obtained at the end was 4,2% which is quite a significant difference.

Conclusively, it was discovered that the distinctive results, could be as a result of variations in the AC “RAP”. The tables below give the result overview of the obtained bitumen content (%) at the beginning of the research, from the mix samples and also at the end of the research. Further analysis of the bitumen content obtained at the end of research, can be found in appendix 24.

Table 24 : Result of Bitumen Content Obtained from “RAP” Samples At the Beginning of the Research

“RAP” Samples	Bitumen content (%)
Sample 1	5,1
Sample 2	6,0
Sample 3	5,1

Table 25 : Result of Bitumen Content Obtained from Asphalt Mixes After the Completion of Test

Mixes	Bitumen content (%)
Mix 0	4,1
Mix 1	4,1
Mix 2	4,3
Mix 3	4,0
Mix 4	3,8

Table 26 : Result of Bitumen Content Obtained from "RAP" Samples After the Completion of Test.

"RAP" Samples	Bitumen content (%)
Sample 1	4,5
Sample 2	4,4
Sample 3	4,2

4.7 Ontwerp Instrumentarium Asfaltverhardingen (OIA Calculation)

For the OIA calculation, the result obtained from chapter 3.6 is input into the software to make the calculation of the base layer thickness of each asphalt mix. Apart from the input results, there are certain parameters put into consideration to have an overview of the base layer thickness. These are namely the fatigue (ϵ_6), the relation between the fatigue line (k), r2, stiffness, standard deviation and healing factor. These parameters have earlier been analysed in the method except the healing factor which is the effect of the resting periods of the asphalt mixes. Nevertheless, the healing factor does not really have an influence on the OIA calculation.

All the values for each mix in relation to these parameters are compared but the main parameters which has an influence on the OIA calculation are the stiffness and fatigue. OIA combines both parameters into one important result i.e. the layer thickness. The results from the produced mixes asphalt mixes are represented with 0, 1plus, 1, 2, 3plus, 3 and 4. The result of mix 1 plus and mix 3 plus is more realistic than mix 1 and mix 3 due to the fact that the values gotten are more aligned in the fatigue line. The variant G i.e. standard mix is also analysed in the OIA calculation, its base layer thickness is used to compare the base layer thickness of the produced asphalt variants. The G variant represents the Standard mix : AC 22 Base/Bind 35/50 (60% "RAP") used by DIBEC to compare innovative base layer mixes. For the OIA calculation, it is also important that the thickness of the asphalt construction considering each asphalt variant should not exceed 500mm as earlier stated in (chapter 3.6.2.3).

The values in the table 27, are obtained from the test results of stiffness and fatigue (appendix 19 and 20). The table below, gives an overview of data input of the produced asphalt mixes in OIA. With these data the base layer thickness for each asphalt mix is calculated . The detailed calculation can be found in appendix 25.

Table 27 : Comparison of Parameters for OIA Calculation.

	0	1 plus	1	2	3 plus	3	4	G
e6	88	114	101	106	88	78	88	121
k	-5,10391	-5,4708	-5,0453	-5,0613	-5,1772	-4,5044	-5,3698	-5,00087
r2	0,9652	0,9603	0,8267	0,9265	0,8367	0,7399	0,915	
stiffness	13685	9284	9284	7050	10350	10350	10368	9353
standard deviation	716	517	517	361	338	338	712	
healing factor	1,19	1,66	1,66	1,82	1,48	1,48	1,27	2,28

The essence of this table is to find the mix with which the base layer thickness correlates with the Standard Mix used by DIBEC to compare innovated base layer mixes. From table 27, an assumption is made that mix 1 plus is the best mix with the most suitable base layer thickness because its stiffness and fatigue values correlate with the value of the G variant : AC 22 Base/Bind 35/50 (60% "RAP"). Nevertheless, to make a sound assumption, the result obtained from the OIA calculation is tabulated and further translated graphically.

4.7.1 Graphical Result

The result derived from the OIA calculation are tabulated below (table 28). This gives an overview of the calculated base layer thickness (mm) for each mix in relation to the traffic intensity. From the table, it is seen that all mixes have a layer thickness for each traffic load except Mix 3. The mix 3, has no result for 5000, 10 000 and 20 000 number of trucks because, the results for this calculations exceeds the program limits of the maximum layer thickness specification of 500 mm for the total asphalt construction.

Table 28 is further translated into a graph. With the graph, the value of stiffness and fatigue are taken into consideration to make a selection of the mix with the most suitable base layer thickness according to DIBEC's regulations. More so, the graphical data shows the influence of tested mixes on the base layer thickness, considering the traffic load on express roads (i.e. a total 1000 -20,000 trucks per day).

Table 28 : Base layer Thickness in Relation to Traffic Load

	0	1 plus	1	2	3plus	3	4	G	minimum
1000	140	112	161	160	178	305	167	102	60
5000	198	165	247	233	263 *		233	163	60
10000	226	190	292	270	308 *		266	192	60
20000	256	216	346	309	360 *		301	224	60

The value on the x-axis represent the traffic load i.e. number of trucks while the value on the y-axis represent the thickness of the base layer in mm.

The G represents the standard base mix : AC 22 Base/Bind 35/50 (60% "RAP") used by DIBEC to compare newly innovated base layer mixes. The values derived from the calculations are compared to the base layer thickness of variant G-value. According to the graph on the next page (figure 46). It is seen that, the only mix with the graphical line parallel to the variant G is Mix 1 plus (figure 46).

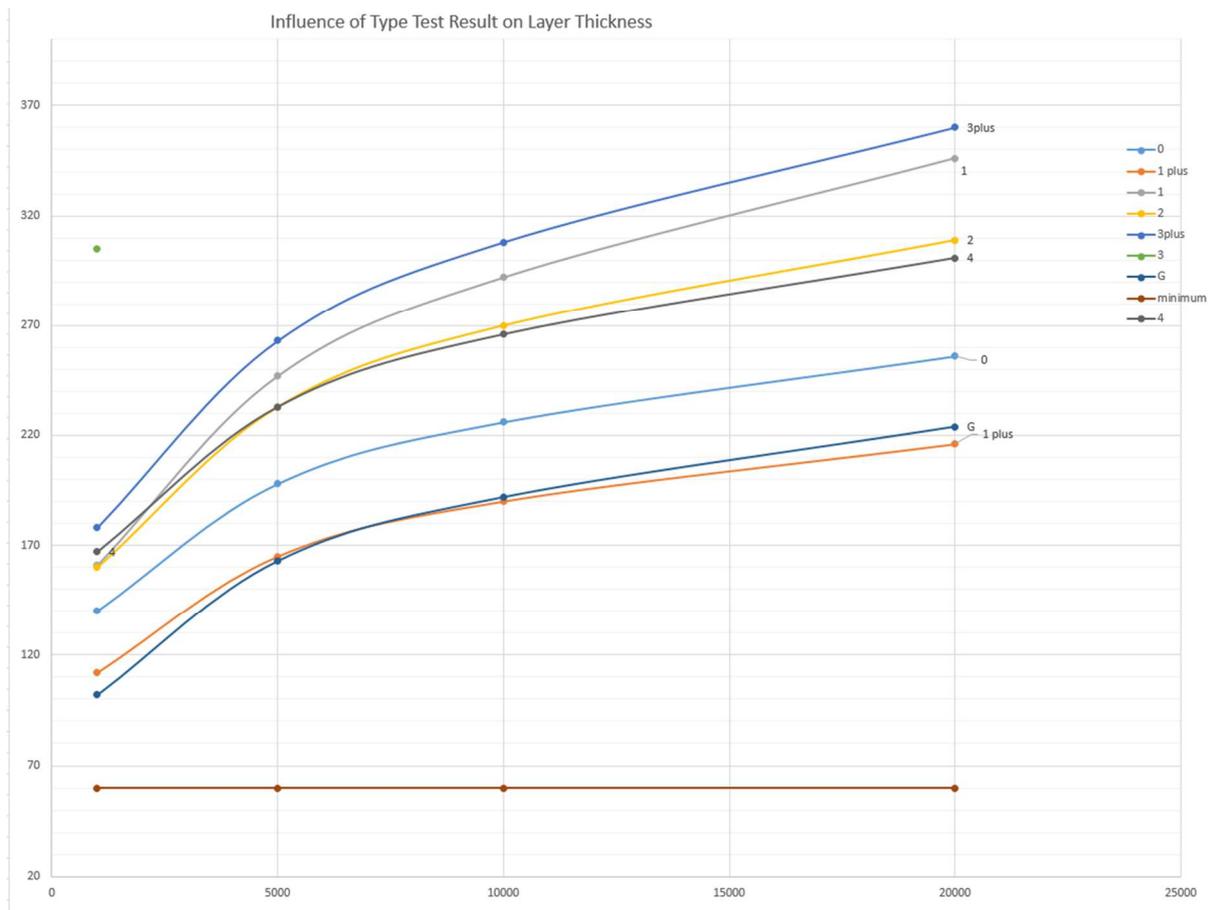


Figure 46 : Graphical Illustration of OIA Calculation

4.7.2 Conclusion OIA Result

The selection of a suitable mix in regards to the OIA calculation is dependent on the combined values of stiffness moduli and fatigue resistance. Therefore any of the five mixes in which the stiffness and fatigue value lies within the value range of Standard Mix (G) is considered suitable for this purpose.

According to the graph, (figure 46) it is seen that the only mix with its stiffness and fatigue value within the range value of the G variant is Mix 1 plus. Thus, it is concluded that mix 1 plus is the most suitable mix amongst the 5 mixes in terms of the OIA calculation. More so, it can also be seen that the required base layer thickness for Mix 1 plus is smaller than other mixes, which is quite cheaper in terms of cost. A more detailed graphical illustration can be found in appendix 15.

Another important aspect noticed in the graph result is that, the mix without rejuvenator i.e. mix 0 has a significant better result than some mixes with rejuvenator. This result was unexpected, due to the fact that a mix with rejuvenator was supposed to have better or improved characteristics than a mix without rejuvenator. Nevertheless, a sound conclusion cannot be made concerning the characteristics of mix 0 being better than some mixes with rejuvenators. This is because the tests were performed 2 to 8 weeks after producing the asphalt samples, and it is uncertain that its better result continues over a longer period of time.

4.8 Sustainability : EcoChain

In this chapter, the results gotten from the data input from process description (chapter 3.7.1) is analyzed to compare the sustainability of three asphalt mixes. As earlier stated, sustainability plays a vital role in the thesis because it is important for the clients and contractors. Therefore, to check if the produced mixes are sustainable, a general overview of the 3 kinds of products analyzed are namely ; AC 22 Base/Bind (80% "RAP") without rejuvenator, AC 22 Base/Bind (80% "RAP") + rejuvenator and AC 22 Base/Bind (60% "RAP") without rejuvenator. During the data input into the EcoChain software, these three products were represented with the numbers as follows:

BN014 : AC 22 Base/Bind (80% "RAP") + No rejuvenator

BN015 : AC 22 Base/Bind (80% "RAP") + rejuvenator

BN016 : AC 22 Base/Bind (60% "RAP") + No rejuvenator

BN014 : AC 22 Base/Bind (80% "RAP") + No rejuvenator

This product represents the mix 0 i.e. reference mix produced during the experiment.

BN015 : AC 22 Base/Bind (80% "RAP") + rejuvenator

This product represents the Mix 1, 2, 3 and 4 produced during the experiment. The mix with 80% "RAP" was taken into consideration, because one of the objectives of the research is to produce mixes with higher "RAP" percentage. Thus, with 80% "RAP" in an asphalt mix, the addition of an extra virgin bitumen was quite unreasonable, as a result of the high percentage of aged bitumen present. Therefore, the use of rejuvenators was rather an option to substitute for the virgin bitumen and simultaneously increase the "RAP" percentage in the mix.

BN016 AC 22 Base/Bind (60% "RAP") + No rejuvenator

This product represents the standard mix mostly produced in the asphalt plants, due to the fact that the production of asphalt mix with high "RAP" percentage is quite challenging in the asphalt plants because the capacity of production tons/ hour goes down and the homogeneity of the mix becomes constant.

In the following paragraphs, the results derived from the input data of three products ; BN014 : AC 22 Base/Bind (80% "RAP") without rejuvenator, BN015 : AC 22 Base/Bind (80% "RAP") + rejuvenator, BN016 : AC 22 Base/Bind (60% "RAP") without rejuvenator are evaluated to make a critical comparison. The aim of the comparison is to check the outcome of these products in regards to sustainability considering climate change (CO2 emissions), environmental cost indicator (MKI), energy consumption, etc.

4.8.1 Climate Change (kg CO2/ton)

This parameter calculates the amount of CO2 emissions released to the environment. The three products are compared to evaluate their effect on climate change which is either positive or negative. The obtained result is further discussed in the paragraph below.

For the three products, the amount of CO2 emitted was determined by taking into consideration three main aspects, namely; transport, materials and processes, whereby each aspect considers all the necessary requirements. The transport includes the conveyance of materials required for production from the winning location to the asphalt plant using trucks, inland waterway vessels, transoceanic ship etc. The “RAP” was not transported due to the fact that it is present in the asphalt plant, thus does not require any means of transportation. The materials includes the virgin materials required for the production of the mixes namely the “RAP”, stones, sand, filler, bitumen, rejuvenators etc. More so, the processes consists of the production procedure in the asphalt plant namely ; exhalation, warming up of minerals, moisture evaporation etc. Conclusively, having considered all aspects the outcome of the CO2 emissions from the three products are; BN014- 30,660, BN015- 30,961, and BN016- 35,954 (kg CO2/ton) respectively, with the highest emissions coming from the asphalt production processes and the least emissions from the materials which is as a result of the use of more “RAP” and less virgin materials (figure 47, 48 and 49).

According to the analysis of CO2 emissions on the three products, it is concluded that the product which emits the least CO2 is the BNR014, which is due to the fact that the mix requires less use of virgin materials, thence having a positive impact on the amount of virgin materials transported to the asphalt plant and the production processes. Secondly, BN015 : AC 22 Base/Bind (80% “RAP”) + rejuvenator , emits 0,3% CO2 more than BN014, due to the origin of the material transport i.e. the rejuvenator is imported into the Netherlands, while the bitumen used in the production of BNR014 is transported within the Netherlands. The details of the Climate Change for each product can be found in (appendix 26).

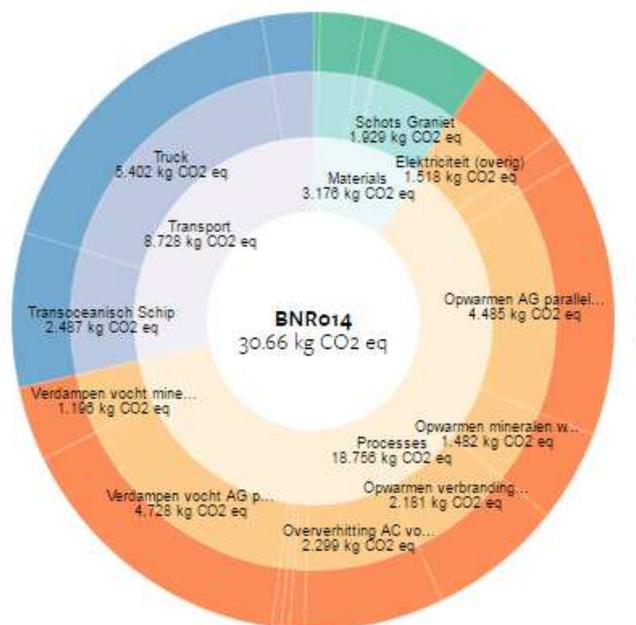


Figure 47 : BNR014 (AC 22 Base/Bind (80% “RAP”) + No rejuvenator

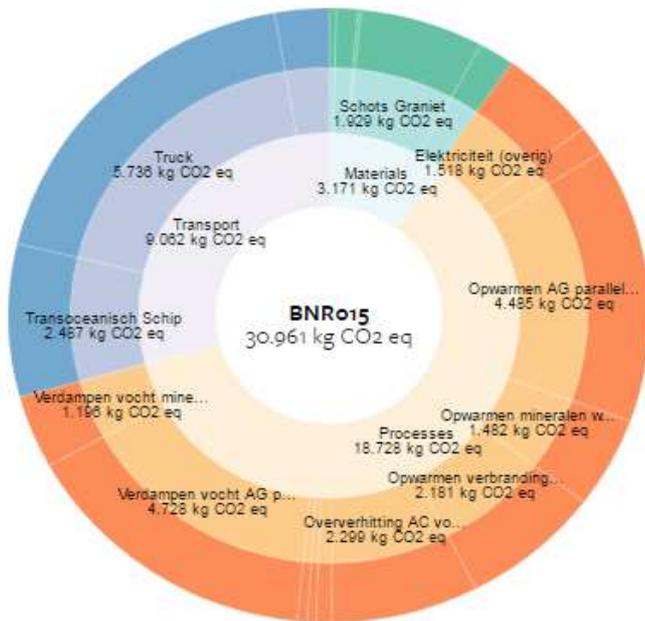


Figure 48 : BNR015 (AC 22 Base/Bind (80% "RAP") + rejuvenator

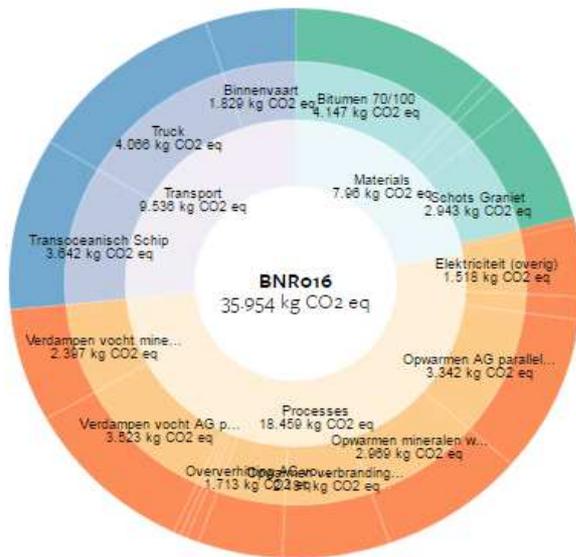


Figure 49 : BNR016 (AC 22 Base/Bind (60% "RAP") + No rejuvenator

4.8.2 MKI (Environmental Cost Indicator: (EUR/ton)

For the three products, the environmental cost indicator (MKI), was calculated based on the Standard used in the Netherlands taking into consideration three main aspects namely; transport, materials and processes, whereby each aspect considers all the necessary requirements. The transport includes the conveyance of materials required for production from the winning location to the asphalt plant using trucks, inland waterway vessels, transoceanic ship etc. The “RAP” was not transported due to the fact that it is present in the asphalt plant as earlier stated. The materials includes the virgin materials required for the production of the mixes namely the “RAP”, stones, sand, filler, bitumen, etc. More so, the processes comprised of the production procedure in the asphalt plant namely; exhalation, warming up of minerals, moisture evaporation etc. Conclusively, having considered all aspects, the MKI of the three products are; BNR014 -€3,071/ton, BNR015- €3,091/ton and BNR016- €4,044/ton respectively (figure 50, 51 and 52).

According to the MKI analysis on the three products, it can be concluded that BNR014, has a lower environmental cost than other mixes. Nevertheless, BNR015 with Rejuvenator has a higher MKI because it emits a higher percentage of CO₂ than BNR014. The details of the MKI for each product can be found in the appendix (appendix 26)

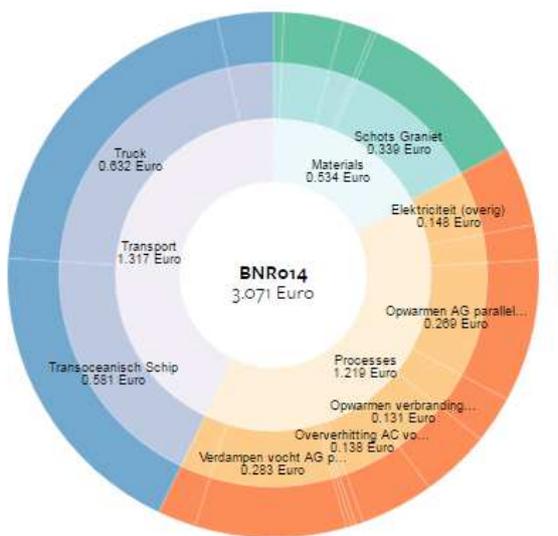


Figure 50 : BN014 (AC 22 Base/Bind (80% “RAP”) + No rejuvenator

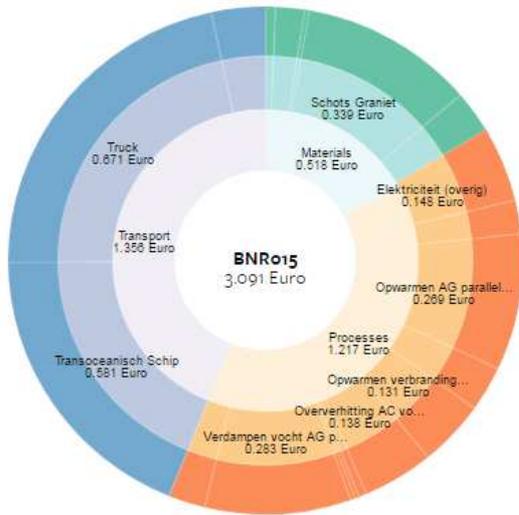


Figure 51 : BNR015 (AC 22 Base/Bind (80% “RAP”) + rejuvenator

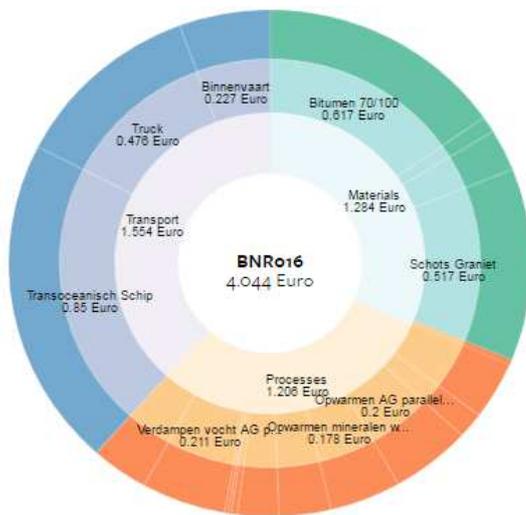


Figure 52 : BNR016 (AC 22 Base/Bind (60% “RAP”) + No rejuvenator

4.8.3 Energy (MJ).

For the three products, the amount of energy required for the production of the mixes was calculated Mega Joules (MJ) by considering three main aspects namely; transport, materials and processes, whereby each aspect considers all the necessary requirements. The transport includes the conveyance of materials required for production from the winning location to the asphalt plant using trucks, inland waterway vessels, transoceanic ship etc. The “RAP” was not transported due to the fact that it is present in the asphalt plant. The materials includes the virgin materials required for the production of the mixes namely the “RAP”, stones, sand, filler, bitumen, etc. More so, the processes includes the production procedure in the asphalt plant namely; exhalation, warming up of minerals, moisture evaporation etc. Conclusively, having examined all aspects, the energy used by the three products are BN014- 669.353, BN015- 674.532, BN016- 1,375 (MJ) respectively with the highest energy use coming from the process while the least energy coming from the transport (figure 53, 54 and 55).

According to the Energy use analysis of the three products, it can be concluded that BNR014 uses the least thence having a positive impact on the amount of raw materials transported to the asphalt plant and the production processes energy while BNR016 uses the most energy. The details of the Energy use for each product can be found in (appendix 26).

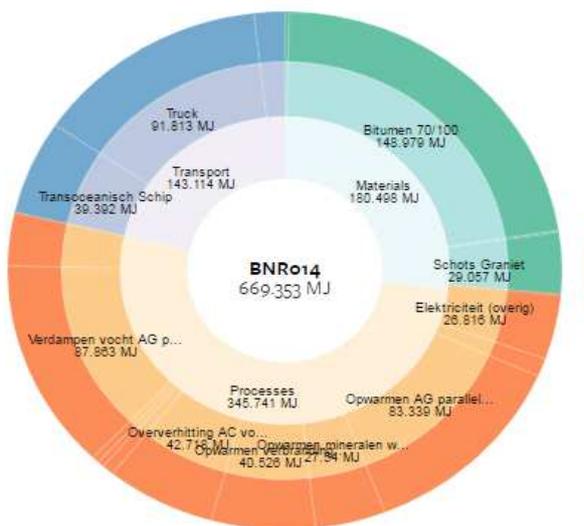


Figure 53 : BN014 (AC 22 Base/Bind (80% “RAP”) + No rejuvenator

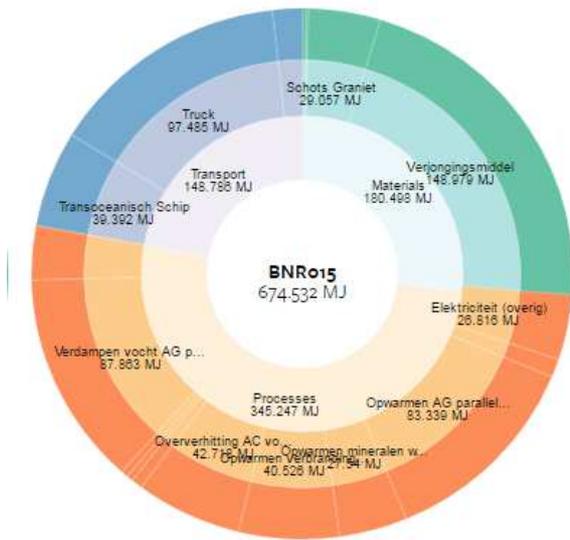


Figure 54 : BNR015 (AC 22 Base/Bind (80% “RAP”) + rejuvenator

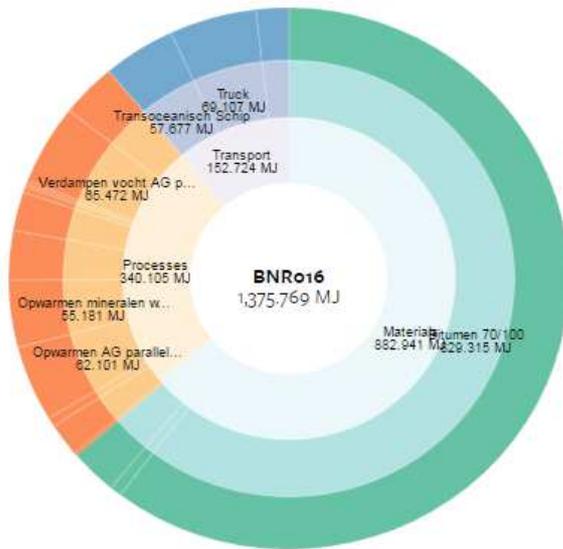


Figure 55 : BNR016 (AC 22 Base/Bind (60% “RAP”) + No rejuvenator

The table 29, shows a comparison of all the products i.e. produced asphalt mixes and Standard mix AC 22 Base/Bind 60% “RAP” considering the three important aspects.

Table 29 : Comparison of All Products

Product	Climate Change (kg CO2/ton)	MKI (€)	Energy (MJ)
BN014: AC 22 Base/Bind (80% RAP) + NO Rejuvenator.	30,660	3,071	669.353
BN015 : AC 22 Base/Bind (80% RAP) + rejuvenator.	30,961	3,091	674.532
BN016: AC 22 Base/Bind (60% RAP) + NO Rejuvenator.	35,964	4,044	1,375.769

4.8.4 Conclusion EcoChain Result

Conclusively, having analyzed the 3 aspects namely; climate change, MKI and energy use. The product BN014: AC 22 Base/Bind (80% “RAP”) + NO Rejuvenator, is cheaper and emits less CO2 into the environment compared to other mixes. Nevertheless, the mix cannot be considered sustainable on the long run, due to the fact it has a low penetration and high softening temperature. Therefore, after a long period of time, the bitumen in the mix ages and becomes harder, which hereby results in cracking failure.

4.9 Cost Analysis

This chapter gives an overview of calculation earlier outlined in chapter 3.8. The cost analysis, within the research scope takes into consideration the actual cost price of the mixes when produced in the asphalt plant which is mostly in tons.

4.7.1 Binder required (ton)

Table 30, gives an overview calculation of the binder required (ton) for each asphalt mix, using the illustration earlier stated in chapter 3.8.1. According to the table, it is seen that all the asphalt mixes require the same quantity of binder i.e. 3tons for production in the asphalt plant. The detailed calculation can be found in appendix 17 .

Table 30 : Binder Required (ton)

Asphalt Mixes	Percentage	Binder (ton)
Mix 0	0,3%	3
Mix 1	0,3%	3
Mix 2	0,3%	3
Mix 3	0,3%	3
Mix 4	0,3%	3

The values from the table 30, are further translated into a graphical illustration to show the amount of binder required for the production of each asphalt mix. According to figure 56, it is seen that the same amount of binder (ton) is required for the production of the 5 asphalt mixes in the asphalt plant.

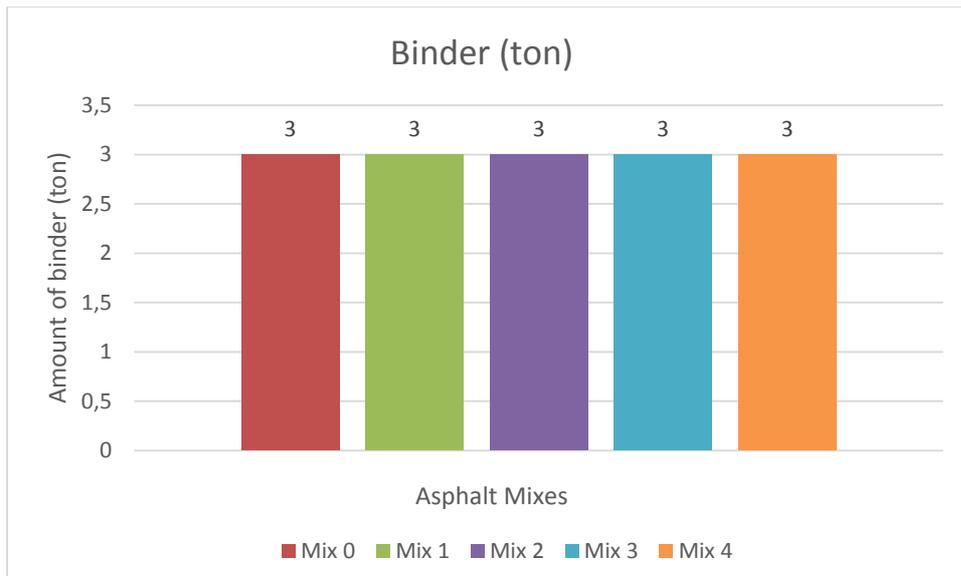


Figure 56 : Graphical Illustration of binder (ton)

4.7.2 Cost of binder/1000kg

Table 31, gives an overview calculation of the cost of binder/1000kg required for each asphalt mix. This is also equivalent to the cost of the binder per ton. From the table below, it is seen that the cost of binder/kg (€) vary for each asphalt mix, thence having an effect on the binder cost per ton. More so, it can be seen that mix 2 has the most expensive binder which is as a result of the rejuvenator cost, while mix 0 has the least expensive binder i.e. bitumen. The detailed calculation can be found in appendix 17

Table 31 : Cost of binder/1000kg

Asphalt Mixes	Binder (ton)	Cost of binder/kg (€)	Cost of binder/1000kg
Mix 0	3	€ 0,28	€ 0,84
Mix 1	3	€ 2,00	€ 6,00
Mix 2	3	€ 1,80	€ 5,40
Mix 3	3	€ 1,10	€ 3,30
Mix 4	3	€ 1,65	€ 4,95

The values from the table 31, are further translated into a graphical illustration to show the cost of binder/kg (€) and the cost of binder/ton (€). According to figure 57 and 58, it is seen that the cost of binder required for the production of Mix 1 in the asphalt plant is higher than other mixes.

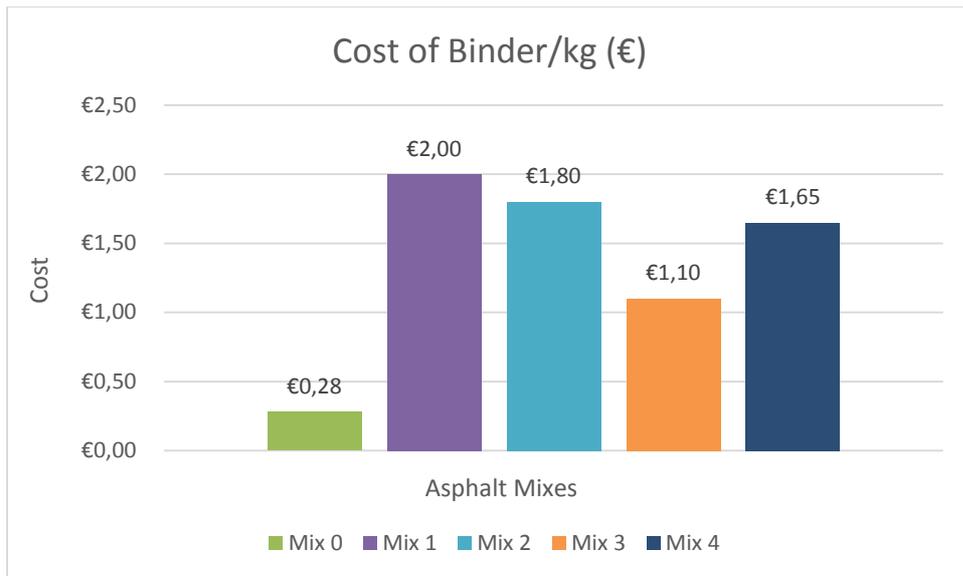


Figure 57 : Graphical Illustration of Cost of binder/kg (€)

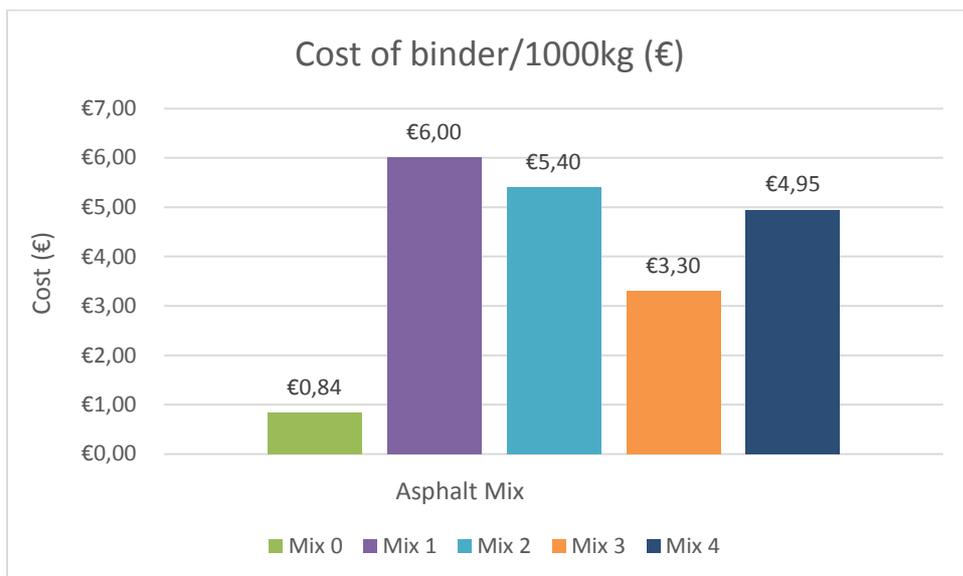


Figure 58 : Graphical Illustration of Cost of binder/1000kg (€)

4.7.3 Cost of mix with binder /ton (€)

Table 32, gives an overview calculation to the cost of the mix with binder/ton (€). From the table, it is seen that the cost of mix without bitumen is constant for the 5 asphalt mixes while cost of binder/1000kg i.e. per ton (€) vary for each asphalt mix, thence having an effect on the binder cost per ton. Hence, it implies that the cost of mix with binder/ton (€) will vary for each asphalt mix because it is a summation of the cost of mix without bitumen + cost of binder/ton (€). The detailed calculation can be found in appendix 17.

Table 32 : Cost of mix with binder/ton (€)

Mixes	Cost of binder/kg (€)	Cost of Mix without bitumen (€)	Cost of binder/1000kg	Cost of mix with binder /ton (€)
Mix 0	€ 0,28	€ 21,02	€ 0,84	€ 21,86
Mix 1	€ 2,00	€ 21,02	€ 6,00	€ 27,02
Mix 2	€ 1,80	€ 21,02	€ 5,40	€ 26,42
Mix 3	€ 1,10	€ 21,02	€ 3,30	€ 24,32
Mix 4	€ 1,65	€ 21,02	€ 4,95	€ 25,97

The cost of mix with binder/ton (€) is further translated into graphical illustration, to give a clear distinction between the 5 asphalt mixes. In figure 59, it is seen that the cost of mix 1 with binder, is the most expensive i.e. € 27,02 while the least expensive is Mix 0 i.e. € 21,86 which is as a result of the relatively lower bitumen cost.

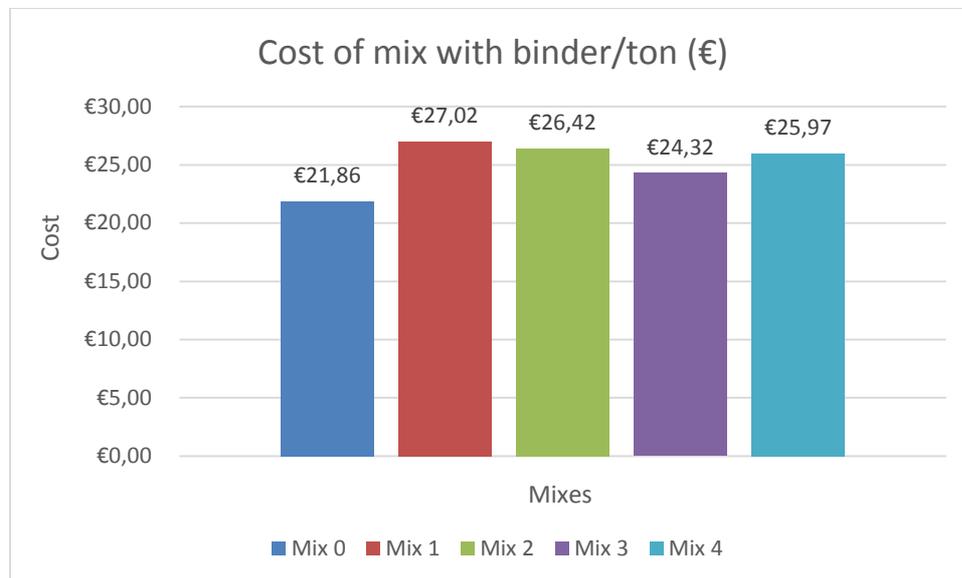


Figure 59 : Graphical Illustration of Cost of binder/1000 kg (€)

4.7.4 Volume of Mix Required (m3)

Table 33, gives an overview calculation to the volume of mix required considering the base layer thickness of 5 asphalt mixes obtained in OIA considering a traffic load of 1000 trucks, 5000 trucks, 10 000 trucks, 20 000 trucks. From the table 33, it is seen that the volume of mix required for the 5 asphalt variants varies depending on its relative base layer thickness and the traffic intensity. The detailed calculation to the volume of mix required (m3) can be found in appendix 17.

Table 33 : Volume of mix required (m3)

Mixes	Volume of Mix Required (m3)			
	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix 0	0,14	0,20	0,23	0,26
Mix 1	0,11	0,17	0,19	0,22
Mix 2	0,16	0,23	0,27	0,31
Mix 3	0,18	0,26	0,31	0,36
Mix 4	0,17	0,23	0,27	0,30

In figure 60, the volume of mix required (m3) for 5 asphalt variants is further translated into a graphical illustration, to show the volume of asphalt mix required for each asphalt mix which is dependent on two factors namely ; the base layer thickness and traffic intensity. From the graph, it is seen that the volume of mix required (m3) varies for the 5 variants, depending on the factors earlier stated.

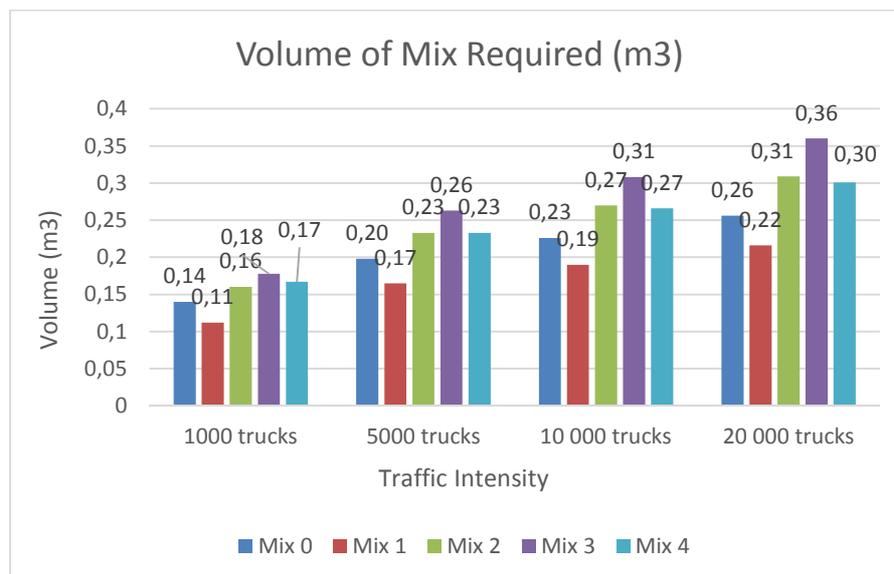


Figure 60 : Volume of Mix Required (m3)

4.7.5 Required asphalt mix (kg/m²)

Table 34, gives an overview calculation to the required asphalt mix (kg/m²) considering the volume of mix required (m³) and the density (kg/m³) of the 5 asphalt variants as stated in chapter 3.8.5. From the table below, it is seen that the density of the 5 variants is constant. Nevertheless, the required asphalt mix (kg/m²) for the 5 variants differ as a result of the variation in the volume of mix required (m³). The detailed calculation to the required asphalt mix (kg/m²) can be found in appendix 17

Table 34 : Required asphalt mix (kg/m²)

Mixes	Density (kg/m ³)	Volume of Mix Required (m ³)				Required Asphalt Mix (kg/m ²)			
		1000 trucks	5000 trucks	10 000 trucks	20 000 trucks	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix 0	2395	0,14	0,20	0,23	0,26	335	474	541	613
Mix 1	2395	0,11	0,17	0,19	0,22	268	395	455	517
Mix 2	2395	0,16	0,23	0,27	0,31	383	558	647	740
Mix 3	2395	0,18	0,26	0,31	0,36	426	630	738	862
Mix 4	2395	0,17	0,23	0,27	0,30	400	558	637	721

In figure 61, the required asphalt mix (kg/m²) for 5 asphalt variants is further translated into a graphical illustration. From the graph, it is seen that the required asphalt mix varies because the volume of mix required differ for each variant.

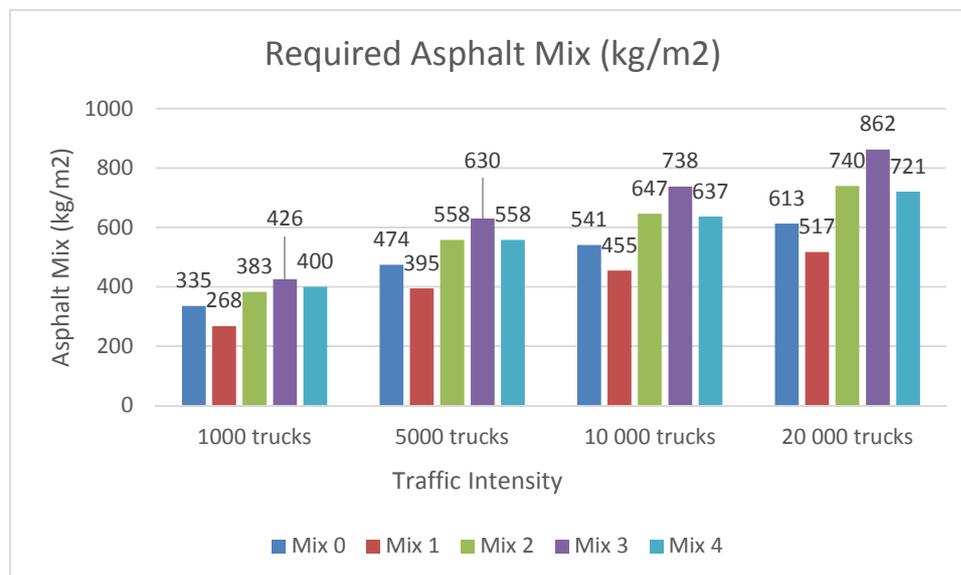


Figure 61 : Required Asphalt Mix (kg/m²)

4.7.6 Binder required (kg/m²)

Table 35, gives an overview calculation of the binder required (kg/m²) for each asphalt variant. This was calculated by considering the required asphalt mix (kg/m²) and the ratio of binder required per mix. From the table below, it is seen that the ratio is constant for the 5 variants. Nevertheless, binder required (kg/m²) differ for each asphalt mix, as a result of the variation in the required asphalt mix (kg/m²). The detailed calculation of the binder required (kg/m²) can be found in appendix 17.

Table 35 : Required asphalt mix (kg/m²)

Mixes	Ratio	Binder Required (kg/m ²)			
		1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix 0	0,3	1,006	1,423	1,624	1,839
Mix 1	0,3	0,805	1,186	1,365	1,552
Mix 2	0,3	1,150	1,674	1,940	2,220
Mix 3	0,3	1,279	1,890	2,213	2,587
Mix 4	0,3	1,200	1,674	1,911	2,163

In figure 62, the binder required (kg/m²) for 5 asphalt variants is further translated into a graphical illustration. From the graph, it is seen that the binder required (kg/m²) varies for each asphalt variant, as a result of the alteration of the required asphalt mix.

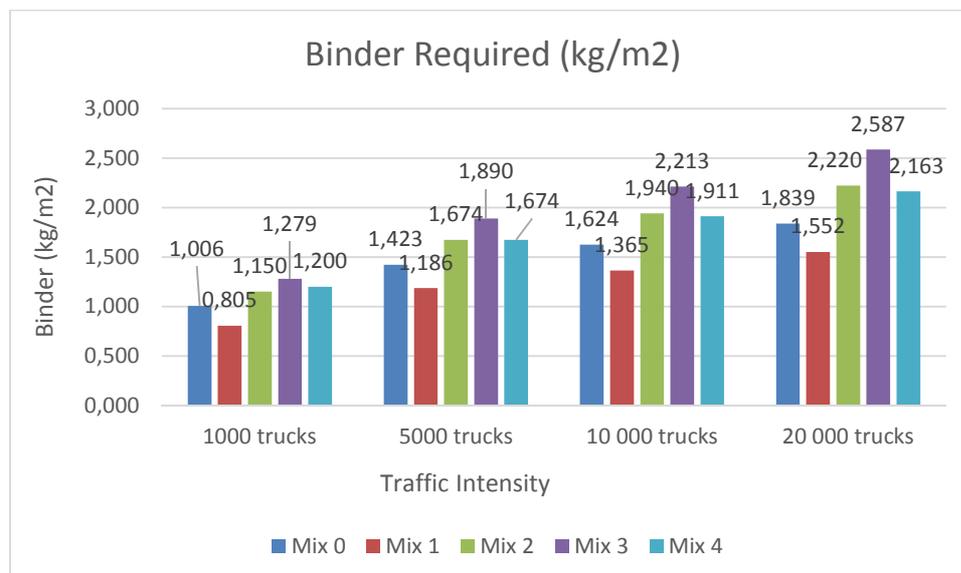


Figure 62 : Binder Required (kg/m²)

4.7.7 Cost of binder/m2 (€)

Table 36, gives an overview calculation to the cost of binder (€) for each asphalt variant, considering the binder required asphalt mix (kg/m2) and the cost of binder/kg (€). From the table below, it is seen that the cost of binder/kg (€) and the binder required (kg/m2) varies for each variant. Thence, leading to a variation in the cost of binder/m2 (€) of the 5 asphalt mixes. The detailed calculation of the binder required (kg/m2) can be found in appendix 17.

Table 36 : Cost of binder/m2 (€)

Mixes	Cost of binder/kg (€)	Binder Required (kg/m2)				Cost Binder/m2 (€)			
		1000 trucks	5000 trucks	10 000 trucks	20 000 trucks	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix 0	€ 0,28	1,006	1,423	1,624	1,839	€ 0,28	€ 0,40	€ 0,45	€ 0,52
Mix 1	€ 2,00	0,805	1,186	1,365	1,552	€ 1,61	€ 2,37	€ 2,73	€ 3,10
Mix 2	€ 1,80	1,150	1,674	1,940	2,220	€ 2,07	€ 3,01	€ 3,49	€ 4,00
Mix 3	€ 1,10	1,279	1,890	2,213	2,587	€ 1,41	€ 2,08	€ 2,43	€ 2,85
Mix 4	€ 1,65	1,200	1,674	1,911	2,163	€ 1,98	€ 2,76	€ 3,15	€ 3,57

In figure 63, the cost of binder/m2 (€) for the 5 asphalt variants is further translated into a graphical illustration. From the graph, it is seen that the cost of binder/m2 (€) differs for each asphalt variant as a result of the cost of binder/kg (€) and binder required (kg/m2) depending on the base layer thickness.

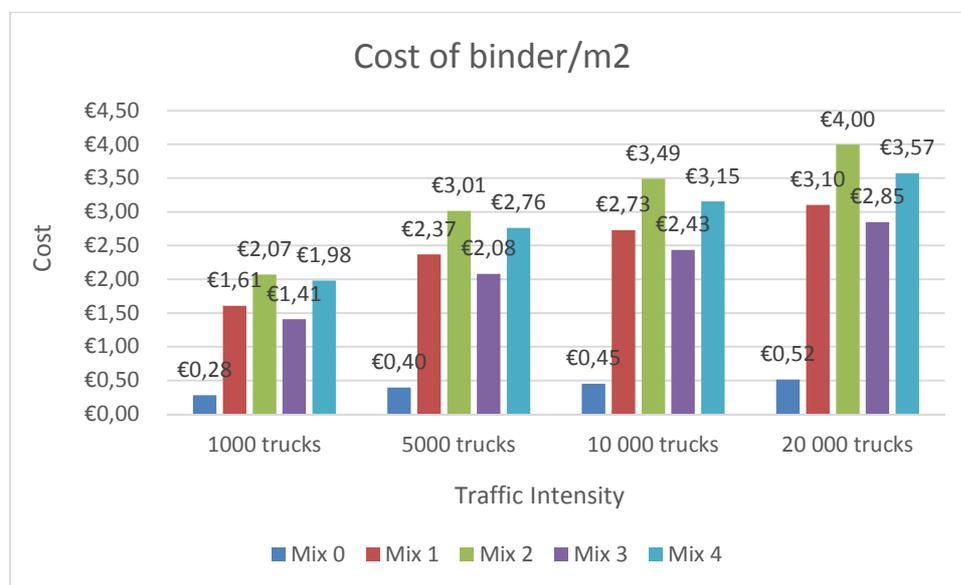


Figure 63 : Cost of Binder/m2 (€)

4.7.8 Cost of mix/m2 (€)

Table 37, gives an overview calculation to the cost of mix/m2 (€) for each asphalt variant. This gives a general analysis on how much it cost to produce the 5 variants in the asphalt plant incorporating all the analysis earlier made. It also gives a comparison on the least and the most expensive asphalt mix. This analysis is made by considering the required asphalt mix (kg/m2) and the cost of mix with binder/ton (€). The cost of the 5 variants are compared in regards to the base layer thickness according to the traffic intensity. From the table below, for production in the asphalt plant, it is seen that mix 0 is the least expensive, while mix 3 is the most expensive. The detailed calculation of the cost of mix/m2 (€) can be found in appendix 17.

Table 37 : Cost of Mix/m2 (€)

Mixes	Cost of mix with binder /ton (€)	Required Asphalt Mix (kg/m2)				Cost of Mix/m2 (€)			
		1000 trucks	5000 trucks	10 000 trucks	20 000 trucks	1000 trucks	5000 trucks	10 000 trucks	20 000 trucks
Mix 0	€ 21,86	335	474	541	613	€ 7,33	€ 10,37	€ 11,83	€ 13,40
Mix 1	€ 27,02	268	395	455	517	€ 7,25	€ 10,68	€ 12,30	€ 13,98
Mix 2	€ 26,42	383	558	647	740	€ 10,12	€ 14,74	€ 17,08	€ 19,55
Mix 3	€ 24,32	426	630	738	862	€ 10,37	€ 15,32	€ 17,94	€ 20,97
Mix 4	€ 25,97	400	558	637	721	€ 10,39	€ 14,49	€ 16,54	€ 18,72

In figure 64, the cost of mix/m2 (€) for the 5 asphalt variants is further translated into a graphical illustration. From the graph, it is seen that the cost of mix/m2 (€) differs for each asphalt variant depending on the thickness of the base layer. Nevertheless, it is important to note that the production cost of Mix 1 containing Rejuvenator 1 is almost equivalent to Mix 0 i.e. the Reference Mix containing only bitumen, even though it's relative rejuvenator cost was the highest amongst the other rejuvenators. Further explanation concerning the equivalence will be made in the conclusion.

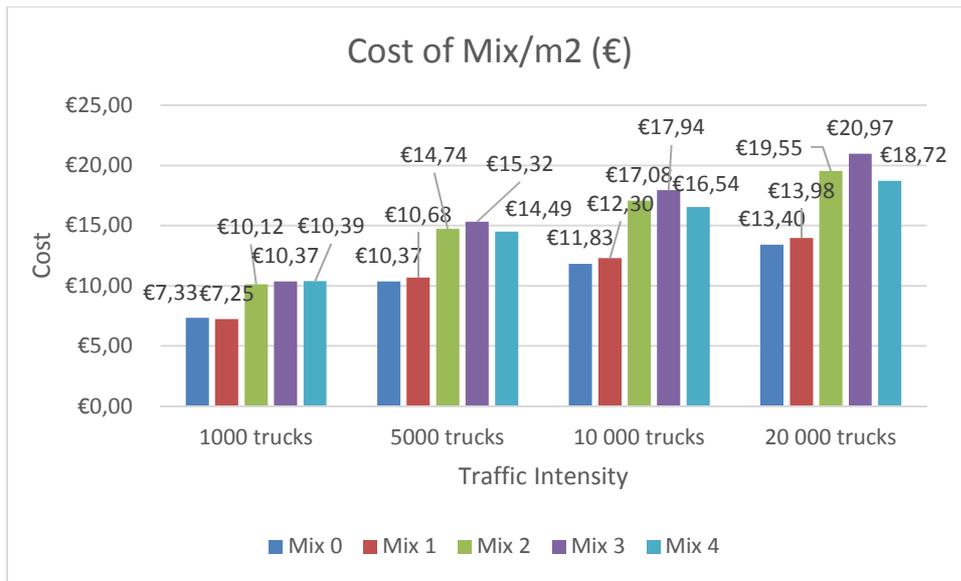


Figure 64 : Cost of Mix/m² (€)

4.7.8 Conclusion Cost

In chapter 4.7.2, from table 31 and figure 57, it is seen that the cost of binder/kg (€) of Mix 1 was the highest amongst the 5 asphalt mixes which is as a result its relative rejuvenator cost, while Mix 0 has the least cost, which is as a result of the bitumen cost. Nevertheless, figure 64 which gives a general graphical illustration of the cost analysis, shows that the production cost of Mix 1 is almost equivalent to Mix 0.

In addition, from the illustration above, the binder applied in Mix 1 i.e. rejuvenator 1, was the most expensive of all rejuvenators while the binder applied in Mix 3 i.e. rejuvenator 3 was the least expensive. Nevertheless, doing the final analysis it was realized that the production cost of Mix 1 in the asphalt plant was relatively cheaper than the other mixes containing rejuvenators while Mix 3 with the least expensive rejuvenator, became the most expensive in terms of production in the asphalt plant.

Therefore, it can be concluded that the cost of binder does not really have an influence on the production cost of the mix in the asphalt plant i.e. the most expensive binder does not actually imply that its relative production cost will be relatively high.

5. Multi Criteria Analysis (M.C.A)

5.1 Criteria Ranking Methodology

In this chapter the result of the MCA is analyzed using the criteria weighing assessment scale as described in the method (chapter 3.9).

Table 38 : Criteria weighing assessment scale

Descriptions	Scale (points)
Not suitable	-2
Neutral	0
Moderately suitable	1
Extremely suitable	2

5.1.1 MCA Result Based on Rejuvenator Properties

The table below gives a score overview of each rejuvenator based on the assessment scale, the rejuvenator with a score of 2, means that it is extremely suitable for that criteria, while a rejuvenator with a weight score of 0 is neutral. In the table below, no rejuvenator is given a negative score because all the rejuvenators fulfill most criteria.

Table 39 : Rejuvenator Property score according to assessment scale

Criteria	Sub-criteria	Rejuvenator 1	Rejuvenator 2	Rejuvenator 3	Rejuvenator 4
Recyclable "RAP" content. (40 %)		2	2	1	1
Design aspects. (30 %)	Sustainability	0	2	2	2
	Durability	2	2	2	2
Prosperity (20 %)	CO2 emissions	0	2	2	1
	Cost investment	1	1	1	2
	Energy consumption	2	2	2	2
Production in Asphalt Plant(10 %)	Flashpoint	1	2	1	1
	Type of mix	2	2	2	1

Table 40 : Calculation of Assessment for Rejuvenator Properties

Criteria /Sub-Criteria	Criteria/Sub-criteria Weight	Weight factor	Final Score	Rejuvenator 1	Rejuvenator 2	Rejuvenator 3	Rejuvenator 4
Recyclable “RAP” content	100	40	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{40}\right) * 100 = 5$	$\left(\frac{2}{40}\right) * 100 = 5$	$\left(\frac{1}{40}\right) * 100 = 2,5$	$\left(\frac{1}{40}\right) * 100 = 2,5$
		Total I		5	5	2,5	2,5
Design aspects							
Sustainability	50	30	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{0}{30}\right) * 50 = 0$	$\left(\frac{2}{30}\right) * 50 = 3,33$	$\left(\frac{2}{30}\right) * 50 = 3,33$	$\left(\frac{2}{30}\right) * 50 = 3,33$
Durability	50		Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{30}\right) * 50 = 3,33$			
		Total II		3,33	6,66	6,66	6,66
Prosperity							
CO2 emission	60	20	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{0}{20}\right) * 60 = 0$	$\left(\frac{2}{20}\right) * 60 = 6$	$\left(\frac{2}{20}\right) * 60 = 6$	$\left(\frac{1}{20}\right) * 60 = 3$
Cost -Investment	20		Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{1}{20}\right) * 20 = 1$	$\left(\frac{1}{20}\right) * 20 = 1$	$\left(\frac{1}{20}\right) * 20 = 1$	$\left(\frac{2}{20}\right) * 20 = 2$
Energy consumption	20		Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{20}\right) * 20 = 2$			
		Total III		3	9	9	7
Production in Asphalt Plant							
Flashpoint	70	10	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{1}{10}\right) * 70 = 7$	$\left(\frac{2}{10}\right) * 70 = 14$	$\left(\frac{1}{10}\right) * 70 = 7$	$\left(\frac{1}{10}\right) * 70 = 7$
Type of mix	30		Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{10}\right) * 30 = 6$	$\left(\frac{2}{10}\right) * 30 = 6$	$\left(\frac{2}{10}\right) * 30 = 6$	$\left(\frac{1}{10}\right) * 30 = 3$
		Total IV		13	20	13	10

5.1.1.1 Final assessment Result based on Rejuvenator Property

Table 41, shows the final result based on rejuvenator property . The essence of this table is to analyze the rejuvenator based on their relative properties in accordance to the assessment scale. The final result is calculated thus :

$$(\text{Score on assessment scale} \div \text{weight factor}) * (\text{sub criteria/criteria weight})$$

With the result from the calculation, the rejuvenator with the highest score is regarded as the most suitable in this aspect. The rejuvenator 2 coloured in green because, it has the highest score and is therefore regarded as the most suitable rejuvenator in relation to its properties. A detailed calculation on the outcome of the final result can be found in appendix 27.

Table 41 : Final Result of assessment based on Rejuvenator Property

Criteria	Sub-criteria	Rejuvenator 1	Rejuvenator 2	Rejuvenator 3	Rejuvenator 4
Recyclable "RAP" content. (40 %)		5	5	2,5	2,5
Design aspects. (30 %)	Sustainability	0	3,3	3,3	3,3
	Durability	3,3	3,3	3,3	3,3
Prosperity (20 %)	CO2 emissions	0	6	6	3
	Cost investment	1	1	1	2
	Energy consumption	2	2	2	2
Production in Asphalt Plant(10 %)	Flashpoint	7	14	7	7
	Type of mix	6	6	6	3
Total		24,3	40,6	31,1	26,1

5.1.1.2 Graphical Illustration

The result obtained from table 41, is translated into a graph, in order to give a better illustration of the Rejuvenator and their relative properties.

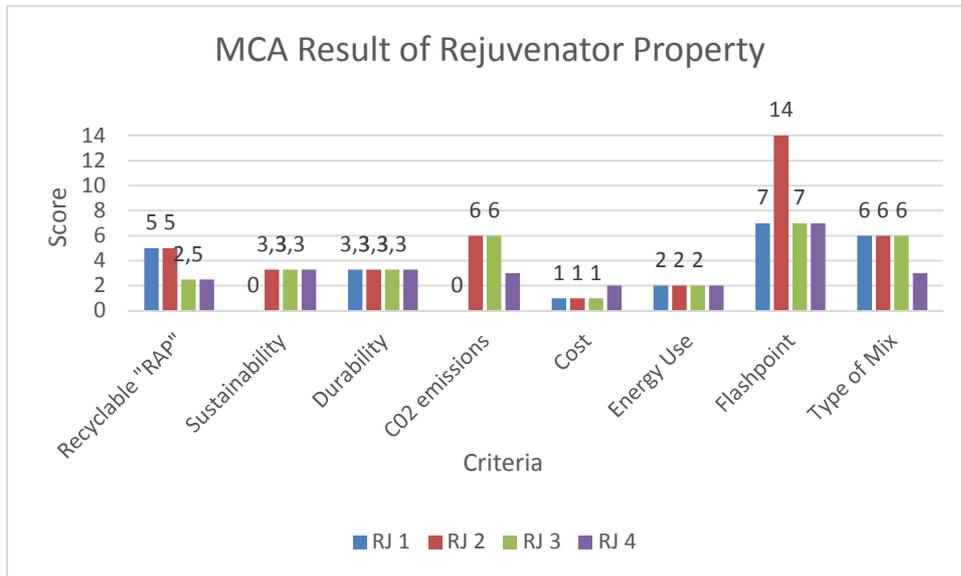


Figure 65 : Graphical Illustration of Rejuvenator Property.

5.1.1.3 Conclusion

It is seen according to the graph that all rejuvenators have the almost the same score based on each property, thus there is no significant difference between the products. Nevertheless, RJ2 has the most suitable result based on flashpoint therefore, it can be assumed that this product will produce better results than other rejuvenators when applied to mixes in the asphalt plant as a result of the high flashpoint. Moreover, as a result of the high flashpoint of the rejuvenator, the risk of explosion will be avoided during its production in the asphalt plant.

5.1.2 MCA Result Based on Laboratory Tests

The table below gives a score overview of each asphalt mix based on the assessment scale in regards to test result, the mix with a score of 2, means that it complies with the test requirement is criteria, while a mix with a score of 0 or 1 shows that it neutrally or partially complies the test.

Table 42 : Mix score according to assessment scale based on Laboratory Tests

Criteria	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
Resistance to Stiffness (40 %)	0	2	1	1	1
Resistance to Fatigue (40 %)	1	2	1	0	0
Resistance to Permanent deformation (20 %)	2	2	2	2	2

Table 43 : Calculation of Assessment for Laboratory Tests

Criteria /Sub-Criteria	Criteria/Sub-criteria Weight	Weight factor	Final Score	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
Stiffness	100	40	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{0}{40}\right) * 100 = 0$	$\left(\frac{2}{40}\right) * 100 = 5$	$\left(\frac{1}{40}\right) * 100 = 2,5$	$\left(\frac{1}{40}\right) * 100 = 2,5$	$\left(\frac{1}{40}\right) * 100 = 2,5$
		Total I		0	5	2,5	2,5	2,5
Fatigue	100	40	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{1}{40}\right) * 100 = 2,5$	$\left(\frac{2}{40}\right) * 100 = 5$	$\left(\frac{1}{40}\right) * 100 = 2,5$	$\left(\frac{0}{40}\right) * 100 = 0$	$\left(\frac{0}{40}\right) * 100 = 0$
		Total II		2,5	5	2,5	0	0
Resistance to permanent deformation	100	20	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{20}\right) * 100 = 10$	$\left(\frac{2}{20}\right) * 100 = 10$	$\left(\frac{2}{20}\right) * 100 = 10$	$\left(\frac{2}{20}\right) * 100 = 10$	$\left(\frac{2}{20}\right) * 100 = 10$
		Total III		10	10	10	10	10

5.1.2.1 Final Result of assessment based on Laboratory Tests

Table 21 shows the final result based on laboratory test . The essence of this table is to analyze the mixes based on their compliance with test requirements in accordance to the assessment scale. The final result is calculated thus :

$$(\text{Score on assessment scale} \div \text{weight factor}) * (\text{sub criteria/criteria weight})$$

From the result, the mix with the highest score is regarded as the most suitable in this aspect. Mix 1 result is coloured in green because, it has the highest score and is therefore regarded as the mix which has the most compliance with the test properties. A detailed calculation on the outcome of the final result can be found in appendix 27.

Table 44 : Final Result scale based on Laboratory Tests

Criteria	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
Resistance to Stiffness (40 %)	0	5	2,5	2,5	2,5
Resistance to Fatigue (40 %)	2,5	5	2,5	0	0
Resistance to Permanent deformation (20 %)	10	10	10	10	10
Total	12,5	20	15	12,5	12,5

5.1.2.2 Graphical Illustration

The result obtained from table 44, is translated into a graph, in order to give a better illustration of the laboratory test result.

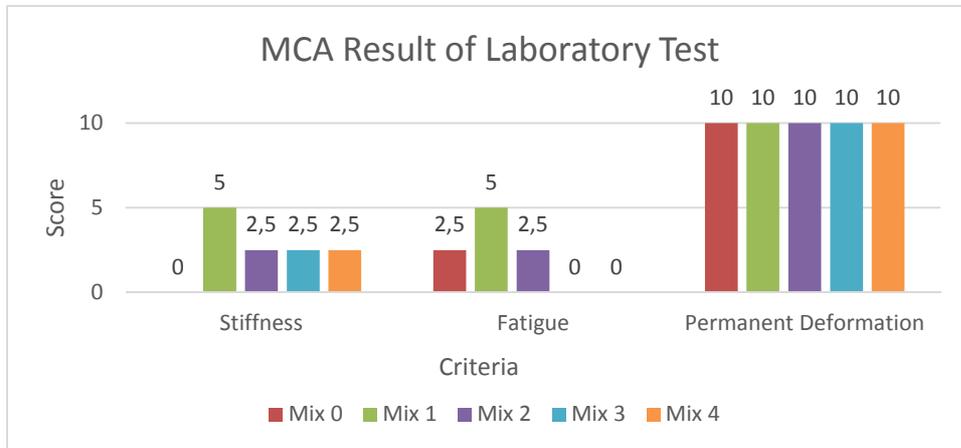


Figure 66 : Graphical Illustration of Laboratory Test

5.1.2.3 Conclusion

According to figure 66, all mixes have the same results of permanent deformation test. Therefore it can be said that all produced mixes have resistance to permanent deformation. For the stiffness and fatigue test, it is seen that mix 1 has the most suitable result i.e. has the most resistance to fatigue and stiffness. Thus, it can be said that the best mix according to the test is Mix 1.

5.1.3 MCA Result Based on OIA Calculation

The table below gives a score overview of each mix based on the assessment scale, the mix with a score of 2, means that it is in compliance with the design traffic load, while a mix with -2 means that it is not in compliance with the design traffic load for each criteria.

Table 45 : Mix score according to assessment scale based on OIA Calculation

Criteria (Truck load/working day)	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
1000 trucks (25 %)	1	2	-2	-2	-2
5000 trucks (25 %)	1	2	-2	-2	-2
10 000 trucks (25 %)	1	2	-2	-2	-2
20 000 trucks (25 %)	1	2	-2	-2	-2

Table 46 : Calculation of Assessment of OIA Calculation

Criteria /Sub-Criteria	Criteria/Sub-criteria Weight	Weight factor	Final Score	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
1000 trucks	100	25	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{1}{25}\right) * 100 = 4$	$\left(\frac{2}{25}\right) * 100 = 8$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{-2}{25}\right) * 100 = -8$
		Total I		4	8	-8	-8	-8
5000 trucks	100	25	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{1}{25}\right) * 100 = 4$	$\left(\frac{2}{25}\right) * 100 = 8$	$\left(\frac{-2}{25}\right) * 100 = 4$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{-2}{25}\right) * 100 = 4$
		Total II		4	8	-8	-8	-8
10 000 trucks	100	25	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{1}{25}\right) * 100 = 4$	$\left(\frac{2}{25}\right) * 100 = 8$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{-2}{25}\right) * 100 = -8$
		Total III		4	-8	-8	-8	-8
20 000 trucks	100	25	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{1}{25}\right) * 100 = 4$	$\left(\frac{2}{25}\right) * 100 = 8$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{-2}{25}\right) * 100 = 4$
		Total IV		4	8	-8	-8	-8

5.1.3.1 Final Result of assessment based on OIA Calculation

Table 47, shows the final result based on OIA calculation. The essence of this table is to analyze the mixes based on their compliance with design traffic load in accordance to the assessment scale. The final result is calculated thus :

$$(\text{Score on assessment scale} \div \text{weight factor}) * (\text{sub criteria/criteria weight})$$

From the result, the mix with the highest score is regarded as the mix which can accommodate traffic load for all criteria. Mix 1 result is coloured in green because, it has the highest score and is therefore regarded as the mix which can accommodate all traffic loads. A detailed calculation on the outcome of the final result can be found in appendix 27.

Table 47 : Final Result of Mix Based on OIA Calculation

Criteria (Truck load/working day)	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
1000 trucks (25 %)	4	8	-8	-8	-8
5000 trucks (25 %)	4	8	-8	-8	-8
10 000 trucks (25 %)	4	8	-8	-8	-8
20 000 trucks (25 %)	4	8	-8	-8	-8
Total	16	32	-32	-32	-32

5.1.3.2 Graphical Illustration

The result obtained from table 47, is translated into a graph, in order to give a better illustration of the OIA calculation.

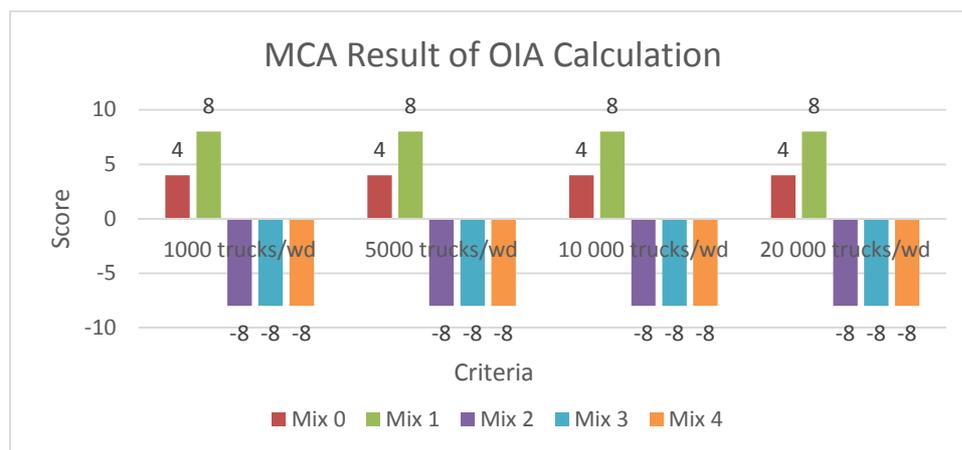


Figure 67 : Graphical Illustration of OIA Calculation

5.1.3.3 Conclusion

Mix 1 is the most suitable in regards to OIA Calculation, because it the base layer thickness is suitable for the various traffic intensities. According to figure 67, it is seen that base layer thickness of mix 2, 3 and 4 cannot accommodate the relative traffic intensities.

5.1.4 MCA Result Based on EcoChain

The table below gives a score overview of each mix based on the assessment scale, the mix with a score of 2, means that it complies with all requirements in regards to EcoChain, while a mix with a score of 1 means that it does not fully comply with all requirements in regards to EcoChain.

For the sustainability assessment in EcoChain, each rejuvenator was not separately analyzed but were rather grouped together because the individual LCA data of the each product was not yet available.

Table 48 : Mix score according to assessment scale based on EcoChain

Criteria	Mix 0 (Reference Mix)	Mix with Rejuvenator
Climate Change : CO2 emissions (40 %)	2	1
Environmental Cost Indicator (MKI) (40 %)	2	1
Energy Use (20 %)	2	1

Table 49 : Calculation of Assessment for EcoChain

Criteria /Sub-Criteria	Criteria/Sub-criteria Weight	Weight factor	Final Score	Mix 0 (Reference Mix)	Mix with Rejuvenator
Climate change : CO2 emissions	100	40	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{40}\right) * 100 = 5$	$\left(\frac{1}{40}\right) * 100 = 2.5$
		Total I		5	2.5
Environmental Cost Indicator	100	40	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{40}\right) * 100 = 5$	$\left(\frac{1}{40}\right) * 100 = 2,5$
		Total II		5	2,5
Energy Use	100	20	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{20}\right) * 100 = 10$	$\left(\frac{1}{20}\right) * 100 = 5$
		Total III		10	5

5.1.4.1 Final Result based on Assessment for EcoChain

Table 50, shows the final result based on EcoChain. The essence of this table is to analyze the mixes based on their sustainability in accordance to EcoChain. The final result is calculated thus :

$$(\text{Score on assessment scale} \div \text{weight factor}) * (\text{sub criteria/criteria weight})$$

From the result, the mix with the highest score is regarded as the mix which is more sustainable than others and complies with all aspects of EcoChain. Mix 0 result is coloured in green because, it has the highest score and is therefore regarded as the most suitable mix in this aspect. A detailed calculation on the outcome of the final result can be found in appendix 27.

Table 50 : Final Result based on Assessment for EcoChain

Criteria	Mix 0 (Reference Mix)	Mix with Rejuvenator
Climate Change : CO2 emissions (40 %)	5	2,5
Environmental Cost Indicator (MKI) (40 %)	5	2,5
Energy Use (20 %)	10	5
Total	20	10

5.1.4.2 Graphical Illustration

The result obtained from table 50, is translated into a graph, in order to give a better illustration of the EcoChain Analysis.

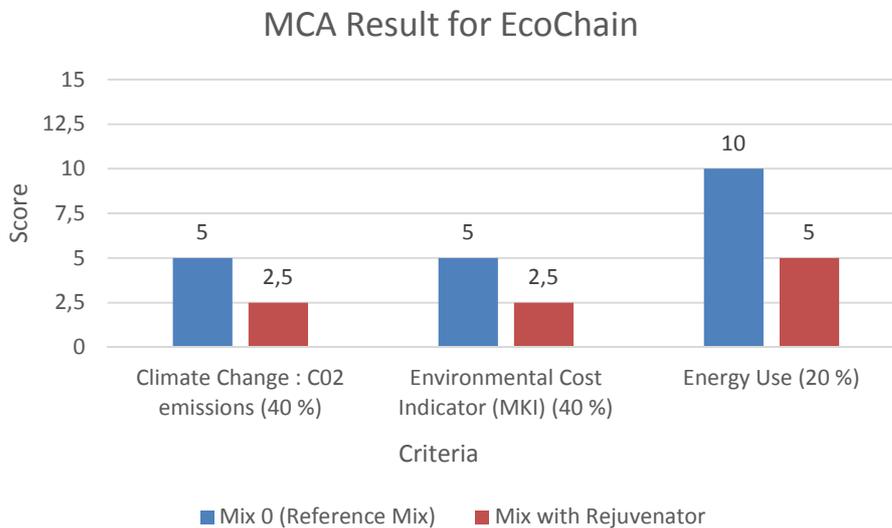


Figure 68 : Graphical Illustration of EcoChain

5.1.4.3 Conclusion

Mix 0 without rejuvenator, has the best results in regards to EcoChain, considering the amount of CO2 emissions, the environmental cost indicator and Energy Use. According to the graph, it shows that Mix 0 is better in all the considered aspects compared to Mix 1 with rejuvenator. Thus, it is regarded as the most suitable mix for EcoChain analysis.

5.1.5 MCA Result Based on Cost Analysis

The table below gives a score overview of each mix based on the assessment scale, the mix with a score of 2, means that the mix is more cost efficient than the other mixes, while a mix with -2 means that it is not cost efficient

Table 51 : Mix score according to assessment scale based on Cost Analysis

Criteria	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
OIA Calculation (50 %)	1	2	-2	-2	-2
Cost of binder (€) (25 %)	2	-2	-2	1	1
Cost of mix/m2 (€)(25 %)	2	2	1	-2	1

Table 52 : Calculation of Assessment for Cost Analysis

Criteria /Sub-Criteria	Criteria/ Sub-criteria Weight	Weight factor	Final Score	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
OIA Calculation (50 %)	100	50	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{1}{50}\right) * 100 = 2$	$\left(\frac{2}{50}\right) * 100 = 4$	$\left(\frac{-2}{50}\right) * 100 = -4$	$\left(\frac{-2}{50}\right) * 100 = -4$	$\left(\frac{-2}{50}\right) * 100 = -4$
		Total I		2	4	-4	-4	-4
Cost of binder (€) (25 %)	100	25	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{25}\right) * 100 = 8$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{1}{25}\right) * 100 = 4$	$\left(\frac{1}{25}\right) * 100 = 4$
		Total II		8	-8	-8	4	4
Cost of mix/m2 (€)(25 %)	100	25	Score on Assessment scale/ Weight factor * (criteria/sub-criteria weight)	$\left(\frac{2}{25}\right) * 100 = 8$	$\left(\frac{2}{25}\right) * 100 = 8$	$\left(\frac{1}{25}\right) * 100 = 4$	$\left(\frac{-2}{25}\right) * 100 = -8$	$\left(\frac{1}{25}\right) * 100 = 4$
		Total III		8	8	4	-8	4

5.1.5.1 Final Result of assessment based on Cost Analysis

Table 32 shows the final result based on cost . The essence of this table is to analyze the mixes based on their relative cost in accordance to the assessment scale. The final result is calculated thus :

$$(\text{Score on assessment scale} \div \text{weight factor}) * (\text{sub criteria/criteria weight})$$

From the result, the mix with the highest score is regarded as the mix which is cost efficient in regards to each criteria. Mix 1 is coloured in green because, it has the highest score and is therefore regarded as the mix which has the least cost in comparison to the other asphalt mixes. A detailed calculation on the outcome of the final result can be found in appendix 27.

Table 53 : Final Result of Mix Based on Cost Analysis

Criteria	Mix 0	Mix 1	Mix 2	Mix 3	Mix 4
OIA Calculation (50 %)	2	4	-4	-4	-4
Cost of binder (€) (25 %)	8	-8	-8	4	4
Cost of mix/m2 (€)(25 %)	8	8	4	-8	4
Total	18	4	-8	-8	4

5.1.5.2 Graphical Illustration

The result obtained from table 53, is translated into a graph, in order to give a better illustration of the Cost Analysis.

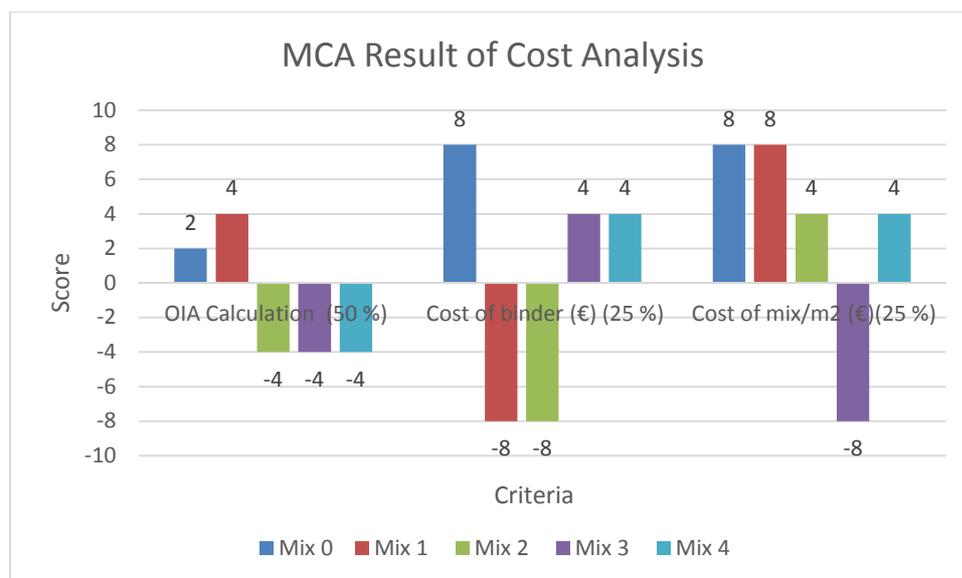


Figure 69 : Graphical Illustration of Cost Analysis

5.1.5.3 Conclusion

The cost of the mix is based on three parameters namely the OIA calculation i.e. required thickness of the asphalt base layer, cost of binder (€) and the cost of mix/ton (€). From the result in table

According to the General Cost Analysis, Even though the cost of the rejuvenator 1 is the most expensive, it does not literally mean that the mix which contains rejuvenator 1 will be the most expensive mix. This is due to the fact that some of the other rejuvenators require more dosage and the higher the dosage of the mix the more stiffer the mix becomes which means that the asphalt layer thickness will be more for the mix.

total cost of the expensive. It can be seen that it is almost as efficient as the Mix 0 which contains only bitumen. The mix 0 is cheaper than other mixes comparing the cost required for the application of specific thickness of base layer.

5.2 General MCA Analysis

The general MCA analysis shows an overview of all aspects considered during the research process. At the beginning of the research, it was stated that the choice of the most sustainable mix is dependent on the result of the 5 MCAs. More so, it was stated, that a mix which will be considered sustainable within the thesis scope needs to have the best results considering the factors Rejuvenator Properties, Laboratory Test, OIA Calculation, EcoChain and Cost.

The general analysis shows the obtained result from all aspects, thence analyzing if any of the asphalt mixes exhibited the best characteristics in the aspects earlier stated. From the MCA result of each aspect, it is seen that the obtained results differ significantly depending on each mix. Table 54, gives an overview of the asphalt mixes which exhibited the best or most suitable characteristics considering each aspect.

Table 54 : Overview of MCA Result of all aspects

Aspects	Result
Rejuvenator Property	Rejuvenator 2
Laboratory Test	Mix 1
OIA Calculation	Mix 1
EcoChain	Mix 0
Cost	Mix 0

Therefore, it is concluded that a sustainable mix cannot be chosen amongst the produced asphalt mixes because as earlier stated, the during the research process that the choice of the most sustainable mix depends on a Mix which complies or exhibits the best characteristics considering the factors analysed. In this situation, it is seen that there is No Mix, which exhibits the best characteristics in all the aspects. Thus, it is concluded that none of the produced mixes can be considered Sustainable. Further analysis is made in the Discussion and Conclusion.

6. Discussion

The variation in “RAP” was one of the challenges faced during the production of asphalt mixes because this caused the presence of the distinctive bitumen content in the mix, hence producing undesired test result. At the beginning of the tests, samples of AC “RAP” were taken in order to obtain its composition i.e. bitumen content (%) and coarseness of the mineral aggregates. The obtained result was thence used to calculate the amount of virgin binder and materials required for the production of the new asphalt mixes. On the long run, it was discovered that the bitumen content (%) obtained at the beginning of the research was higher than the amount obtained at the end of the research.

Secondly, the standard procedure used to determine the bitumen content is incomplete because the R & B and Penetration Test is a basic test of bitumen properties. In practice, for the production of mixes with 50-60% “RAP”, the basic test is used to decide the bitumen property. On the other hand, for mixes with a higher “RAP” percentage i.e. 80% and higher, it is uncertain to determine if these basic tests provide enough information about the bitumen properties obtained from “RAP”. This is due to the fact that considering the black rock behavior of aged bitumen, the AC “RAP” with highly aged bitumen acts like a rock and it is uncertain if the aged bitumen mixes properly with the virgin bitumen. The AC “RAP” is composed of a stone skeleton which is fixed with a binder, mortar (mix of sand, filler and bitumen). With the low penetration and high softening point of the aged bitumen, it is uncertain that there was a bonding effect between the aged bitumen and the virgin bitumen. Nevertheless, there is a quest to know if additional bitumen properties need to be determined and if advanced tests such as the DSR (Dynamic Shear Rheometer) can be introduced during the laboratory testing.

In addition, the manner of “RAP” winning is insufficient because on the basis of theory, the application of “RAP” from a top layer mix has better performance than “RAP” from a base layer as a result of the presence of the high bitumen content. Thus, it is important to know from which layer the “RAP” was obtained i.e. top, binder or base layer. Therefore, there is a quest of how the origin, winning and properties of the “RAP” can be controlled i.e. specifically checking or controlling the asphalt layer which the “RAP” originates from and also the mineral aggregates.

Furthermore, the sustainability of a mix does not only regard the technical requirements, because on the basis of technicality it can be assumed that mix 0: AC 22 Base/Bind 80% “RAP” without rejuvenator will have the worse results than mixes with rejuvenators as a result of its low penetration and high melting temperature, but the thesis result has shown otherwise. Mix 0: AC 22 Base/Bind 80% RAP without rejuvenator proves to be more sustainable and significantly shown better result than some other mixes with rejuvenators in regards to many aspects considered namely ; EcoChain, OIA Calculation, Type tests etc. which was quite unexpected.

Nevertheless, there is a quest of what will happen to Mix 0 : AC 22 Base/Bind 80% “RAP” + No Rejuvenator after a longer period of time if it is considered durable. This is due to the fact that the tests were performed 2 to 8 weeks after producing the asphalt samples, and it is uncertain that its better result continues over a longer period of time. This is because the mix contains no rejuvenator, which will improve the flexibility and revitalize the bitumen, there is a possibility that bitumen will age and harden hence decreasing the mix sustainability.

On the other hand, the mix with the rejuvenators probably did not produce better or desired results because as earlier mentioned the tests were carried out 2-8 weeks after production. Thus, it can be assumed that if the asphalt mixes had stayed longer in the Climate Control Storage, the mineral aggregates, RAP and binder will have more time to settle, hence producing better results or characteristics. With the limited time frame of the thesis, it is uncertain if there was a good bonding effect between the aged and virgin bitumen.

7. Conclusion & Recommendations

7.1 Conclusion

The bitumen content obtained from the “RAP” at the beginning of the research was 5,4 %, This bitumen content was used to calculate the percentage of virgin bitumen and rejuvenator which was added to the produced asphalt mixes. During the production of the samples, there was some segregation noticed during the mixing process because the mineral aggregates did not get easily coated with the bitumen and this gave some doubts about the observed less bonding effect in the mixes. The testing the bitumen content afterwards proved this doubts, because both asphalt mix samples and RAP had lower bitumen content than expected.

During the tests i.e. stiffness, fatigue and permanent deformation, some of the asphalt mixes produced some unexpected results compared to others. The cause of these unexpected result were unknown, but assumptions were made, that the reason for the irregularity in test result could be as a result of incorrect determined bitumen content from the “RAP” at the beginning of the research. After the completion of the test, to do some verifications, samples of the “RAP” were taken to extract the bitumen. After the extraction process, it was discovered that the percentage of the bitumen present (4,2%) in the RAP was significant lower than the previous result (5,4%).

Thirdly, during the production of the test samples, the same proportion of rejuvenators was added to all mixes in order to get an equal mass of each mix. During the test, it was discovered that mix 2 : AC 22 Base/Bind (80% RAP) + rejuvenator 2 exhibited a more constant stiffness result than other mixes and the reason to this was unknown. On the long run, eventually the supplier recommended half the proportion of the rejuvenator than actually used, which meant that mix 2 : AC 22 Base/Bind (80% RAP) + rejuvenator 2 contained twice the required proportion of rejuvenators than other mixes.

More so, the selection of the most sustainable mix depends on a mix which complies to all the aspects analyzed during the research, which are namely the mix with; best rejuvenator property, best characteristics in terms of laboratory testing, best characteristics in comparison to the OIA calculation, most sustainable in terms of EcoChain and also cost efficient. From the obtained results regarding these aspects, there was no mix out of the 5 produced asphalt mixes which excellently complied with all these aspects. Nevertheless, a reflection which can be made is that each mix complies to certain aspect. According to the test result, mix 1 characteristics complied to resistance to fatigue, while mix 2 obtained an improved stiffness and all the five mixes complied to the highest resistance in permanent deformation.

In addition, from the cost analysis, it was realized that the cost of binder of Mix 1 was the highest amongst the mixes containing rejuvenators while the binder applied in Mix 3 was the least expensive. Nevertheless, doing the final analysis, it was realized that the production cost of Mix 1 in the asphalt plant was relatively cheaper than the other mixes containing rejuvenators, while Mix 3 with the least expensive rejuvenator became the most expensive in terms of production in the asphalt plant. Thus, it was realized that, the cost of binder does not really have an influence on the production cost of the mix in the asphalt plant i.e. the most expensive binder does not actually imply that its relative production cost will be relatively high.

Furthermore, on basis of the OIA calculation, mix 1 plus : AC 22 Base/Bind 80% “RAP” + Rejuvenator 1 had the best performance because the calculated base layer thickness was similar to the AC 22 Base/Bind 35/50 (60% “RAP”) i.e. standard mix used by DIBEC to compare innovated base layer. In regards to sustainability i.e. EcoChain result, the reference mix i.e. mix 0 : AC 22 Base/Bind (80%) “RAP” without rejuvenator had better results in terms of CO₂ emissions, MKI score and Energy use than the mixes with rejuvenators and the Standard mix : AC 22 Base/Bind 60% “RAP” based on the transportation influence of the binder.

Conclusively, the ability to produce an asphalt mix with a high percentage of “RAP” is possible (80%) but there are technical challenges, this is because it is difficult for the mineral aggregates in the mix to properly bind together, due to the fact that only 20% of virgin materials (bitumen) will be added to the mix. More so, producing a mix with 80% “RAP” in the asphalt plant is challenging because the capacity of production in tons/hour decreases as a result of heating and drying of a high “RAP” percentage, thence taking more time in the current facilities.

7.2 Recommendation

Most of the produced mixes did not meet the test requirements, as a result of presumed high bitumen content initially used. The newly obtained bitumen content from the “RAP” can be used as a basis to calculate the amount of bitumen or rejuvenator required to be added to the new mix.

Secondly, the “RAP” to be used in the production of the new mixes should be more consistent, under control and also come from one source i.e. the storage of RAP in the Asphalt Plant Depot should be in accordance to a particular period of years. For example, AC “RAP” obtained from base layers (1-5 years) should be stored separately from AC “RAP” obtained from base layers of (5- 10 years) etc. to have more homogeneity in the mixes, hence avoiding obtaining varying bitumen content. In addition, the properties of the “RAP” need to be known by considering its origin, the asphalt layer from which the “RAP” was retrieved etc. , to avoid similar results as obtained during the tests. In order, to obtain better end results from the asphalt mixes, more bitumen properties need to be known which implies that only the R & B and Penetration Test is insufficient to determine the accurate bitumen content in the “RAP”. The advanced DSR (Dynamic Shear Rheometer) test should be introduced to test the additional properties of the aged bitumen from the “RAP”, because considering the black rock behavior of aged bitumen, the AC “RAP” with highly aged bitumen acts like a rock and it is uncertain if the aged bitumen mixes properly with the virgin bitumen i.e. creating a bonding effect.

Furthermore, The research should have been stopped to control and check its possible causes, when there was a strange observation during the asphalt mixing process. Referred is to the mineral aggregates which did not mix properly with the bitumen during the production of the test samples. In this research, this was impossible as a result of the limited time frame. More so, a longer time frame is required for the execution of the research, in the view of the fact that the topic sustainability is really broad and a lot of factors need to be taken into consideration before making a lot of assumptions and obtaining undesired results.

Conclusively, it is also important as contractors to put emphasis on the request of the LCA data of the rejuvenators from the suppliers before the commencement of the research to check the Life Cycle Analysis of the product i.e. determining if it is really sustainable.

To sum up with, most LCA data is dependable on the transport influence which hereby has an effect on the mix's sustainability . To avoid this dependency, the product origin like renewability should have more influence on the product sustainability.

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9. Appendices

Appendix 1 : Type of asphalt mixes used in the road construction sector

Appendix 2 : Bitumen class Properties

Appendix 3 : 80% RAP

Appendix 4 : NEN Norms for Mineral Aggregates

Appendix 5 : Extra Information on Mineral Aggregates

Appendix 6 : Branch Representative Mixes

Appendix 7 : Rejuvenator Encryption

Appendix 8 : Standard RAW Norms for Tests

Appendix 9 : Traffic Category Class Division

Appendix 10 : Standard RAW Norms for Asphalt Production

Appendix 11 : Measurement of Virgin Materials

Appendix 12 : Sieve Analysis

Appendix 13 : OIA Calculation of Mixes

Appendix 14 : OIA Parameter Table

Appendix 15 : OIA Calculation

Appendix 16 : Density of Samples

Appendix 17 : Cost Analysis

Appendix 18 : Mix Composition

Appendix 19 : Stiffness Test Result

Appendix 20 : Fatigue Test Result

Appendix 21 : Permanent Deformation Test Result

Appendix 22 : Laboratory Safety Rules

Appendix 23 : Mixing Protocol

Appendix 24 : Bitumen Content

Appendix 25 : OIA Detailed Calculation

Appendix 26 : EcoChain Result

Appendix 27 : MCA Result
