CHALMERS
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Reclaimed asphalt pavement in concrete

A study of how concrete properties are changed when reclaimed asphalt pavement (RAP) is used as aggregate

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

VIKTOR BARK

Department of Civil and Environmental Engineering
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Master's Thesis BOMX02-17-53
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Department of Civil and Environmental Engineering
Division of Geology and Geotechnics
Research Group Road and Traffic
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Cross section of concrete cubes. Left 0 % RAP, Right 50 % RAP ©Viktor Bark

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ABSTRACT

Mass management is an important part of infrastructure projects. Old construction materials need to be recycled and reused to improve the sustainability and to decrease masses at landfill sites. In the Gothenburg region, large projects in an urban environment have increased the amount of reclaimed asphalt pavements (RAP) that needs to be managed. RAP can be recycled into new pavements, but today the volumes are higher than the demand. The aim of this study was to evaluate if RAP could be used as an aggregate in concrete. This could be one way to prevent an oversupply of these masses and to create a more efficient aggregate industry.

The study of the feasibility of using RAP in concrete was divided into different steps. The first was to do study visits at production facilities for concrete and asphalt pavements to get an understanding of the two sectors. The second was a literature review of the different materials and earlier studies of using RAP in concrete. The last was laboratory tests, where two concrete types (house construction, civil engineering) were evaluated by replacing fresh aggregate with RAP. For each concrete type, a reference mix and six mixes that contained RAP were evaluated. During the tests, compressive strength, flexural strength and workability were tested on each mix. In addition, the basic properties of the RAP material were measured.

The results showed that RAP could be mixed and handled as a fresh aggregate, and there were no difficulties to cast concrete that contained RAP. The workability of the fresh concrete was affected by the RAP aggregate. The concrete made for house constructions had a higher workability when RAP was added. The civil engineering concrete had a lower workability when RAP was added.

The test of the hardened concrete indicated a decrease in compressive and flexural strength when RAP was added to the mix. The fine RAP aggregate affected the strength more than the coarse RAP aggregate. However, the results indicated that low amount of RAP could be used within the two concrete types, and still be within the specified concrete strength classes.

The results of the study showed that RAP can be used in concrete in terms of handling, workability and strength. But, there is today not possible according to the latest standards, to use this type of recycled aggregate. However, further studies should be done to evaluate how RAP aggregate is in line with the requirements of the national aggregate standard and how other concrete properties are changed. This could enable a use of RAP in concrete if the studies indicate satisfying results.

Key words: Recycled aggregate, reclaimed asphalt pavement, sustainability, concrete

Återvunnet asfaltsgranulat i betong

En studie om hur betongens egenskaper ändras när återvunnet asfaltsgranulat används som ballast

Examensarbete inom masterprogrammet Infrastructure and Environmental Engineering

VIKTOR BARK
Institutionen för Bygg- och miljöteknik
Avdelningen för Geologi och geoteknik
Forskargrupp Väg och trafik
Chalmers tekniska högskola

SAMMANFATTNING

Masshantering är en viktig fråga inom dagens infrastrukturprojekt. Byggnadsmaterial måste återanvändas eller återvinnas för att förbättra hållbarheten och för att hindra att material når deponi. I Göteborgsregionen har stora ombyggnationer i stadsmiljö ökat mängden återvunnet asfaltsmaterial som behöver bearbetas. Asfaltsmassor kan återvinnas till nya asfaltsbeläggningar, men volymerna är idag större en behovet av dessa massor. Målet med studien var att utvärdera om asfaltsgranulat kan användas som ballastmaterial i betong. Detta skulle kunna vara ett sätt att minska överskottet av dessa massor, samt öka effektiviteten inom bergmaterialindustrin.

Arbetet med att undersöka möjligheterna att använda asfaltsgranulat i betong var indelat i flera delar. Den första, var att besöka produktionsanläggningar för både asfalt och betong, för att få en förståelse för de båda sektorerna. Den andra, var en övergripande litteraturstudie av de olika materialen, samt en studie av tidigare undersökningar av asfaltsgranulat i betong. Den sista, var en laboration där två olika betongtyper (hus, anläggning) testades med olika inbladningar av asfaltgranulat. För varje betongtyp göts en referensblandning samt ytterligare sex blandningar innehållandes olika mängder asfaltsgranulat. För varje blandning testades tryckhållfasthet, böjhållfasthet samt hanterbarhet. Dessutom undersöktes de grundläggande egenskaperna hos granulatet.

Resultatet visade att asfaltsgranulat kunde blandas och hanteras på samma sätt som vanlig ballast, utan några svårigheter att gjuta betong innehållandes granulat. Hanterbarheten av den färska betongen påverkades av inbladningen av asfaltgranulat. Husbetongen fick en ökad hanterbarhet när granulat adderades till blandningen. För anläggningsbetongen minskade hanterbarheten när granulat adderades.

Under testerna av den härdade betongen, indikerade resultaten att tryck- och böjhållfasthet minskade med ökad inbladning av asfaltgranulat i betongen. Inbladning av fint granulat påverkade hållfastheten mer än inbladning av grovt granulat. Testerna visade dock, att små mängder granulat kan adderas till båda betongtyperna men ändå uppfylla hållfastheten för den önskade hållfasthetsklassen.

Resultatet från studien visade på att asfaltgranulat kan avvändas i betong i avseende på hantering, hanterbarhet och hållfasthet. Dock finns det idag inte några möjligheter enligt den senaste ballaststandarden att använda denna typ av återvunnen ballast. Men ytterligare studier bör genomföras för att utvärdera hur asfaltgranulat möter de krav som finns i den nationella ballaststandarden, samt hur övriga betongegenskaper förändras. Detta skulle kunna öppna upp för möjligheterna att använda granulat i framtida betong om dessa undersökningar visar tillfredställande resultat.

Nyckelord: Återvunnen ballast, återvunnet asfaltsgranulat, hållbarhet, betong

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Preface

This Master's Thesis aimed to evaluate how concrete is affected by using recycled aggregate from reclaimed asphalt pavements. The study was done at the department of Civil and Environmental Engineering at Chalmers University of Technology and was done in collaboration with Skanska in Gothenburg. The work was performed between February and June 2017 and was the last part of the Master's Programme Infrastructure and Environmental Engineering.

First of all, I would like to thank the supervisors during the thesis Assistant Professor Mats Karlsson and Senior Lecturer Gunnar Lannér at the division of Geology and Geotechnics at Chalmers. Gunnar Lannér was also the examiner for the thesis.

I would also like to thank Marek Machowski, technician at the Division of Building Technology, that gave me support and guidance during the laboratory tests.

At Skanska, I first of all want to thank Bo Persson, that was my supervisor at the company. In addition, I want to thank Balasan Khachadoorian and Johan Hedman, that delivered technical support about concrete and provided materials for the test study.

Last, I want to acknowledge Claes Löfgren and the technical lab for road engineering in Gunnilse that supported me with knowledge about asphalt pavements and provided materials for the test study.

Abbreviations

AD	Air-dry
CA	Coarse Aggregate
FA	Fine aggregate
FEM	Finite element analysis
ITZ	Interfacial transition zone
NCA	Natural coarse aggregate
OD	Oven-dry
OPC	Ordinary Portland Cement
PAH	Polycyclic Aromatic Hydrocarbons
RA	Recycled aggregate
RAP	Reclaimed Asphalt Pavement
SCC	Self-consolidating concrete
SS	Swedish standard
SSD	Saturated surface-dry
UN	United Nations
W/C Ratio	Water-cement ratio

1 Introduction

This chapter will present the background and the objective of the study. There will also be an overview of how the study has been performed.

1.1 Background

In infrastructure projects, mass management is important. Transportation of useless masses away from the project and transportation of new masses to the projects is both time-consuming and costly. In the Gothenburg region, these problems are common and large infrastructure investments upcoming years, will increase the importance to find a sustainable process for managing huge volumes of masses in infrastructure projects.

One part of this problem that has increased recent years is a large amount of reclaimed asphalt pavement (RAP) that needs to be managed due to reconstruction within the urban environment. The old masses can to some degree be reused, recycled or stored and the technology has enabled that almost all asphalt material can be recycled and become new asphalt pavements. However, since the reclaimed masses are larger than the demand, landfill or other applications are the only options.

The situation in the Gothenburg region is strained. There is a shortage of landfill sites, and due to the oversupply of asphalt material on the market, it is costly to get rid of reclaimed asphalt masses within projects. This situation will eventually increase the cost of the projects, which will hit the customers in the end.

There are also sustainability aspects of this issue. Reclaimed asphalt masses are a combination of aggregate and binder. Both aggregate and binder are produced from limited resources, and a sustainable usage of these are important. In addition, national environmental goals require an increased level of reuse and recycling in the construction industry. Both these points require improved fields of applications for recycled aggregate (RA) from asphalt pavements. This to improve sustainability in the aggregate industry.

One field of application, where reclaimed asphalt pavements could be used, is as an aggregate in the concrete industry. This application has been studied recent years, but there is a need of broadening the knowledge base and get more knowledge about how recycled aggregate from RAP affects the properties of concrete.

1.2 Objectives

This Master's thesis aims to improve the situation with an oversupply of asphalt masses and to find new ways to prevent RAP material end up at landfill sites. This will result in more sustainable construction projects.

To do this, the thesis aims to investigate the possibility to use reclaimed asphalt pavements (RAP) as an aggregate in concrete production. The purpose of the study is to give a broad understanding of both concrete and asphalt pavements, and to describe how the concrete properties are affected when recycled aggregate from RAP is used. In the thesis, these questions will be answered:

- How is asphalt recycled and reclaimed today?
- What are the properties of the reclaimed asphalt material?
- Can reclaimed asphalt be used as an aggregate in new concrete?
- What is the quality and what can this concrete be used for?
- Is this concrete a good alternative in a sustainable point of view?

1.3 Limitations

Concrete is a large subject with a lot of properties that could be evaluated. This thesis will only evaluate some of these, that decides if reclaimed asphalt pavements are feasible to use as an aggregate in concrete. Properties that are evaluated is workability, strength (compressive and flexural strength), gradation and basic properties of the RAP material. Other properties of concrete are not evaluated, even though some of them is mentioned in the literature review.

One factor that could affect the result is that only one type of RAP material has been used during the study. Variation in the results due to changes in binder content, gradation, unit weight, etc. is not evaluated

In the study, only two concrete recipes were evaluated. These were chosen since they are commercially available products that are normally used in the Gothenburg region. The effect of RAP as an aggregate on other recipes are not evaluated.

1.4 Method

To evaluate the possibility of using reclaimed asphalt material in concrete, the project was divided into two study visits, a literature review and a practical laboratory test. Below is a schematic picture of the process, see figure 1.

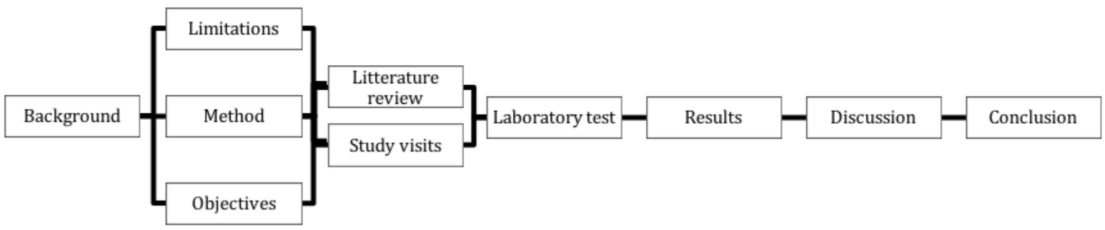

Figure 1 Work process during study

Study visits
The first part of the project were two study visits at a concrete plant and an asphalt plant. Both these were operated by Skanska, and are situated in the Vikan, Gothenburg. The study visits gave a basic understanding of both sectors within Skanska and the basic production process of concrete and asphalt pavements.

Literature review
The literature review was divided into five steps. This to get a broad understanding of the subject. The literature used was found through the Chalmers library literature database, traditional internet searches (Google, etc.) and books found at the city library. The five steps were:

The first step was to put the subject in a sustainable point of view. Sustainability of construction materials was studied, where the focus was on aggregate.

The second step was to get a basic understanding of the concrete material. To get that, the components and basic properties of concrete were studied.

The third step was to do further studies on the aggregate material in the concrete mix. This to understand the requirements of aggregate and to understand how the properties of aggregate, affects the concrete product.

The fourth step was to study the recycling process of asphalt pavements and the basic properties of RAP material.

The last step of the literature review was to investigate how RAP material is affecting the concrete properties. First, the Swedish aggregate standard was studied to see if there is a possibility to use a recycled aggregate, containing bituminous material, in concrete production. Second, earlier studies of the subject were reviewed and summarised.

Laboratory test

The practical laboratory tests were performed to evaluate how RAP material used as an aggregate, is affecting the properties of concrete. The tests were performed at the concrete laboratory at Chalmers Technical University during an eight weeks period in April and May 2017.

During the laboratory tests, 14 different mixes of concrete were evaluated. Seven of them were based on a concrete recipe made for house constructions, and seven were based on a civil engineering concrete. The concrete mixes were based on two commercial concretes that are common in Skanska's concrete production.

The effect of using RAP as an aggregate was evaluated in the same way for both concrete types. Where a part of the fresh aggregate was replaced with RAP material according to:

1. Reference mix (original recipe)
2. 25 % CA replaced
3. 50 % CA replaced
4. 25 % FA replaced
5. 50 % FA replaced
6. 25 % CA and FA replaced
7. 50 % CA and FA replaced

The properties that were tested during the laboratory tests were:

- Basic properties of the RAP material (gradation, unit weight, absorption, etc.)
- Workability (over time 5, 30 and 60 minutes)
- Compressive strength
- Flexural strength (Only for the civil engineering concrete)

The tests were performed according to Swedish standards and the test methods are further described in chapter 7. The standards used during the laboratory tests were:

- SS-EN 12350 *Testing fresh concrete:*
  -Part 2: Slump-test
- SS-EN 12 620 - *Aggregates for concrete*
- SS 13 72 07 - *Hardened concrete, compressive strength, conversion factors*
- SS-EN 1097 *Tests for mechanical and physical properties of aggregates:*
  -Part 5: Determination of the water content by drying in a ventilated oven
  -Part 6: Determination of particle density and water absorption
- SS-EN 12 390 - *Testing hardened concrete:*
  -Part 1: Shape, dimensions and other requirements for specimens and moulds
  -Part 2: Making and curing specimens for strength tests
  -Part 3: Compressive strength of test specimens
- SS-EN 196 – *Methods of testing cement*
  -Part 1: Determination of strength

2 Sustainability of construction materials.

In this chapter, an introduction of sustainability of construction material is described and how the work towards this goal is performed in Sweden. The chapter will also describe the aggregate industry and how sustainability is reached in this sector.

2.1 Sustainability

Due to the rising acidification problems during the late 60's, the first global meeting concerning the environment was held in 1972, in Stockholm. This was the first-time environmental issues were acknowledged as a global issue, rather than a local matter (Gröndahl & Svanström, 2011).

In 1987, the definition "sustainable development" was introduced for the first time. In the UN (United Nations) report "Our Common Future", also called the "Brundtland Report", the definition for "sustainable development" was defined as: (Gröndahl & Svanström, 2011)

"Sustainable development is development that meets the needs of the present, without compromising the ability of future generations to meet their own needs."

The Brundtland report was issued as a preparation work for the second global environmental conference 1992 in Rio de Janeiro. At the meeting, a sustainable development was set as a common goal for all nations (Gröndahl & Svanström, 2011).

Today, sustainable development is accepted goal for all UN nations. To be able to work and analyse the process towards sustainability, different models have been used. One common model is to divide sustainability into three dimensions: economic, environmental and social (Gröndahl & Svanström, 2011).

The economic dimension refers the economic system, property and the build society. The environmental dimension refers to the natural resources and the environmental diversity at the globe. The social dimension means the social resources between humans within politics, family and culture. The three dimensions can be presented in different ways and meanings, but they all represent a model where a "sustainable development" is where all these aspects are developed at the same time, see figure 2 (Gröndahl & Svanström, 2011).

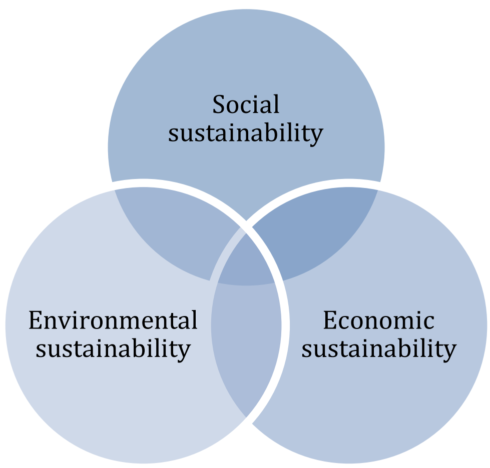

Figure 2 The three dimensions of sustainability

2.2 Sustainability in Sweden

In Sweden, the national environmental work is divided into different goals and policies. This section will give a short introduction to the environmental goals and which of them, that concerns the subject of this report.

Generation goal
The Riksdag (the Swedish Parliament) decided in the year 2000 that an environmental “generation goal" should be reached in 2020. This is a goal, that strives to give an overall platform of the work to achieve a sustainable future. The government definition of the generation goal is: (Swedish environmental protection agency, 2012)

“The overall goal of environmental policy is to hand over to the next generation a society in which the major environmental problems have been solved, without increasing environmental and health problems outside Sweden’s borders.”

Environmental objectives
To reach the generation goal, 16 environmental objectives is adopted. Each objective describes how the environment should be in 2020 (Swedish environmental protection agency, 2012). According to the National Board of Housing, Building and Planning, there are at least seven of these, that affects the construction and real estate sector. These are:

1. Reduced Climate Impact
2. Clean Air
3. Natural Acidification Only
4. A Non-Toxic Environment
5. Zero Eutrophication
6. A Good Built Environment
7. A Rich Diversity of Plant and Animal Life

Environmental milestones
To evaluate the progress of the objectives, the objectives are followed up every year, and 24 milestones are defined to improve areas where change is needed. The milestone that concern construction materials in the infrastructure and the building industry are the goal to reduce construction and demolition waste. This milestone aims to: (Miljömål.se, 2016)

“Measures are to be taken so that, by 2020, at least 70 percent by weight of non-hazardous construction and demolition waste is prepared for reuse, recycling and other material recovery.”

According to the Swedish environmental protection agency, this milestone is probably reached. However, the statistics from this area is today insufficient. There is also an uncertainty if asphalt material should be included in the statistics or not. Without asphalt, the recycling level is about 50 %. With asphalt included the recycling level is about 70 %. This since asphalt is recycled in a large amount and masses every year (Palm, o.a., 2015). The recycling process of asphalt pavements is further described in chapter 4.

Waste Hierarchy
There are different ways to reach the objectives and milestones concerning the environment and construction materials. In the European Union, a new framework for waste management was introduced in the year 2008 called Directive 2008/98/EC. The directive was introduced into the Swedish law in 2011.

The directive sets common definitions of waste and lay down several waste management principles. There is also a priority order of the waste management which the member states should work towards, called the waste management hierarchy. This is the order of how waste management should be a prioritised within law and politics (Swedish environmental protection agency, 2016).

In the waste management hierarchy, there are five different levels of waste. The hierarchy is a guideline in which order waste should be managed and should be followed both in a sustainable and economical point of view, see figure 3 (Swedish environmental protection agency, 2016).

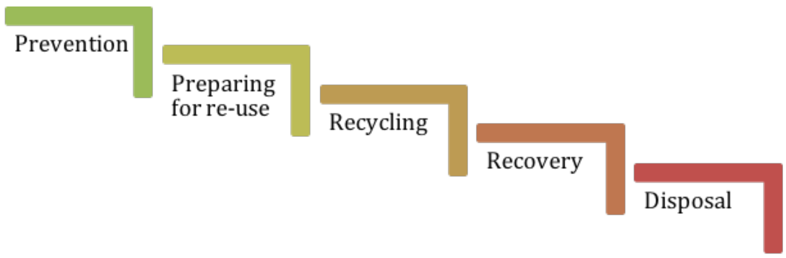

Figure 3 The waste management hierarchy

2.3 Sustainability in the aggregate industry

In this section, sustainability is described concerning the aggregate industry.

2.3.1 The aggregate industry

The aggregate production is a global industry that is worth $200 billion annually. The demand is about 26.8 billion tonnes per year, and the industry is estimated to grow by about 4.7 % each year. The concrete and asphalt industry is large consumers since the aggregate content is about 80 % of concrete volume and about 90 % of asphalt pavements volume (de Brito & Saikia, 2013).

In Europe, the aggregate industry is the most resource-intensive sector. In 2014, the consumed raw material from non-metallic minerals were about 40 % of the total material consumption in the EU countries. Most of this material was construction aggregate like sand and gravel (Eurostat, 2016).

Conventional aggregate is normally collected by different mining techniques trough blasting and dredging of bedrock. After extraction, the aggregate usually needs washing and blending to meet the requirements of gradation. The largest cost during production is normally fuel, labour and maintenance costs. To decrease these expenses, the mining production is normally situated close to the customer (de Brito & Saikia, 2013).

Since aggregate is only found where the geological is right, the material is not always found where it is needed. Countries as the Netherlands, have a lack of good rock to produce sufficient aggregate. This leads to long transportations and since aggregate is a heavy product, transports of 30-50 km, can double the price of the product (Khatib, 2016).

This also results in that when a quarry is depleted, a new one needs to be developed. Today many of the mines that were easy to access are depleted around Europe. Develop new quarries can be difficult and factors as multiple landowners, citizen opposition and urbanization are some of the issues that can prevent the production of aggregate. This results in that it can take up to 10 years to open a new production facility (Khatib, 2016).

2.3.2 Sustainability in the aggregate industry

In an environmental perspective, aggregate production is not a sustainable industry. Aggregate is a non-renewable resource that has a limited quantity in the world. (Bleischwitz & Bahn-Walkowiak, 2006). However, the global supply of aggregate can almost be considered unlimited due to the large quantities, even though the resources are not large everywhere (Khatib, 2016).

According to (Bleischwitz & Bahn-Walkowiak, 2006), the aggregate industry affects the environment in three ways: depletion of a non-renewal resource, environmental issues at extraction site and land use.

The CO_2 emissions from the aggregate production are low compared to the cement production. However, the increased demand has created a transportation need, which increases the CO_2 emissions and several ecological issues like: damaging biodiversity, damaging landscape, pollutant water, noise and dust. To prevent issues, planning and restoration of mining sites are important. To increase the sustainability in the aggregate industry, an increased efficiency and improved technologies are needed. One way of doing this is to increase the use of waste materials as aggregate in the concrete production (de Brito & Saikia, 2013).

2.3.3 Recycled aggregate

In the past, a large part of old construction materials was used as a landfill. Today aggregate from asphalt pavements and concrete construction is often recycled. This leads to a decreased amount of fresh aggregate needs to be produced (Khatib, 2016).

Aggregate that has been used as a bound material in construction can easily be reused with a low amount of reprocessing. Aggregate used as a bound material in concrete and asphalt pavement requires further processing since the aggregate can contain rest products that affect the properties and the potential for reuse (Khatib, 2016).

Whether recycled aggregate is put on a landfill or being reused is depending on different factors. Some of these are: availability of landfill, product acceptance, availability of a recycled product and the demand for sustainability (Khatib, 2016).

Additional barriers are: low cost of natural aggregate, a non-regular supply of RA, processes are needed to recover and sort the RA and that the physical properties could be limited of RA. However, there is also benefits from: lower transportation costs, lower environmental impact, reduced costs due to fewer landfill fees and that recycled aggregate is mostly found in urban areas close to new projects (World Business Council for Sustainable Development, 2009).

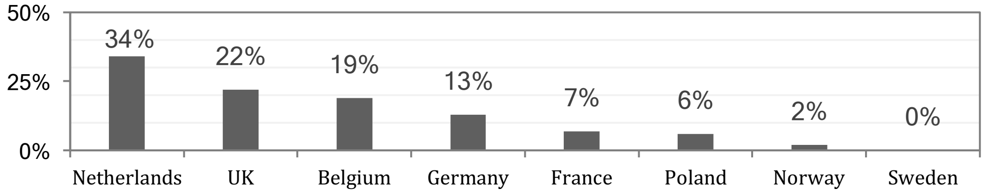

Figure 4 Recycled aggregate of the total production (European aggregates association, 2016)

In Europe, the total amount recycled and re-used aggregate is about 8.6 % of the total production of aggregate. The use of recycled aggregate varies between different countries and are related to the availability of fresh aggregate in the country. The amount of recycled aggregate for some of the European countries is presented in figure 4. (European aggregates association, 2016; Eurostat, 2016)

3 The basics about concrete

This chapter will introduce concrete and give a basic understanding of the material. The chapter will also present some of the main properties, components and how concrete is used in constructions.

3.1 What is concrete?

Concrete is an old building material that has been used in constructions for more than 2000 years. The main elements of concrete are cement, water and aggregate. In addition to that, various admixtures can be mixed into the concrete to achieve different properties (Burström, 2006).

Concrete is an all-round material due to its good properties in durability, abrasion resistance and formability. Which has led to that concrete is one of our most important building materials in constructions today (Burström, 2006).

In Sweden, the concrete production has been around 400000 m^3/month recent years. The division has been ¼ civil engineering concrete, and ¾ housing concrete and the trend shows an increase in production. The growth in production is due to large investments in house construction and is estimated to stay high upcoming years, see figure 5 (Svenska Betong, 2016).

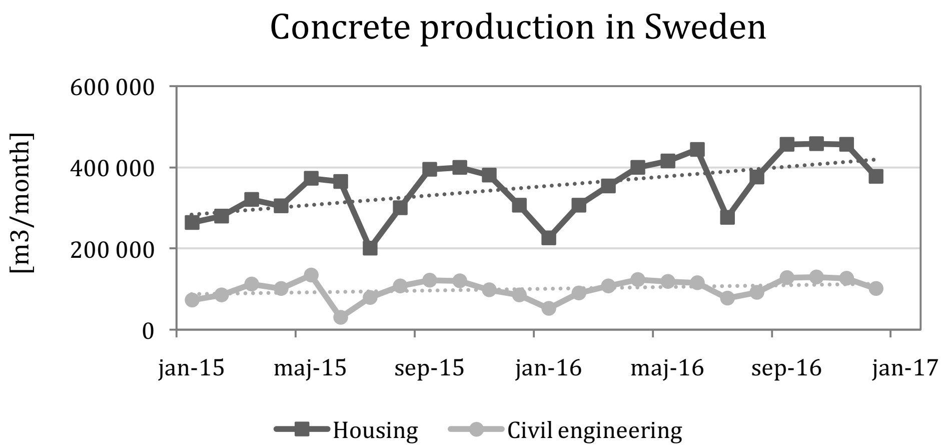

Figure 5 Concrete production in Sweden (Svenska Betong, 2016)

3.2 Concrete components

In this section, the components in concrete are described.

3.2.1 Cement

Cement is the material in concrete that binds the materials together. There are different types of cement materials. The most common one is Portland cement that is a mix of limestone and clay, that has been mixed and heated into a powder. Cement normally contain four main minerals, alite, belite, aluminate (C_3A) and a ferrite phase (C_4AF).

When mixed with water, cement is creating an exothermic reaction, called hydration, that will create heat, and the mixture will start a hardening process to become a solid material. In Sweden, there are three standard cement types: (Burström, 2006)

CEM I - Is clean Portland cement and is called "Portland cement". In the past in Sweden, cement types CEM I was also divided into classes according to the properties.

There were three classes: Std (Standard), rapid hardening (SH) and slow hardening concrete (LH). These are to some extent still used, but there are no specific regulations connected to these classes anymore.

CEM II – Must contain at least 65 % of Portland clinker cement. In addition, secondary materials, i.e. fly ash, limestone, silica dust, blast furnace slag or a mix of these, can be added. CEM II is called "Portland composite cement".

CEM III – Must contain between at least 20 %, and maximum 65 % Portland clinker cement. The rest should be blast furnace slag. CEM III is also called "Slag-cement".

3.2.2 Water

Water is an essential part of the concrete since it starts the hardening process. The water used in the concrete mix should be clean with no contaminations. Salt water should be avoided since the salt crystallisation can damage the concrete. However brackish water can be used for simple constructions (Burström, 2006).

The mix of water and cement is called the cement paste. The proportions between these elements are the largest factor determining what properties the concrete will get. The relationship between cement and water is therefore an important factor to specify and is named as the water-cement ratio, also called w/c ratio. The w/c ratio value is calculated according to equation 1: (Burström, 2006)

$$W/C\ Ratio = \frac{W}{C}\ [-]$$
$$W = Amount\ of\ water\ [kg] \tag{1}$$
$$C = Amount\ of\ cement\ [kg]$$

3.2.3 Aggregate

Aggregate is a general term for granular material including sand, gravel and crushed stone. Conventional aggregate in concrete consists of natural stones like granite, limestone and diabase. These could be found naturally in the environment, called natural gravel or can be produced by crushing (Burström, 2006).

A change from natural gravel to crushed stone is ongoing since the natural sources are found at glaciofluvial deposits, which also is important groundwater reservoirs that need to be protected. Today the distribution between the sources are 20 % natural gravel and 80 % crushed stone, in Sweden (SGU, 2017).

In Sweden, the size of aggregate is divided into coarse aggregate (CA) and fine aggregate (FA). Where CA is stone particles >4 mm and FA is particles ≤ 4 mm. In addition, the aggregate is labelled as: (Burström, 2006)

- Filler ≤ 0.125 mm
- Sand ≤ 4 mm
- Fine gravel ≤8 mm
- Stone ≥8 mm

When making concrete the variation in the size of the aggregate is vital and varies depending on the application. Natural aggregate and crushed stones normally differ from the preferred gradation. Therefore, they need to be sorted in different fractions to make it easier to mix them and achieve an ideal gradation. The ideal distribution of the aggregate is achieved when the smaller fractions, fills up the caverns between the larger stones and when a thin layer cement paste cover all the particles (Burström, 2006).

The aggregate gradation is often presented by a gradation chart. The chart shows the distribution of the fractions of the aggregate. This is done by sieving the aggregate through different sieve sizes, and the material on each sieve is weighed. The passing percentage is calculated and plotted on a chart, which figure 6 is an example of (Burström, 2006).

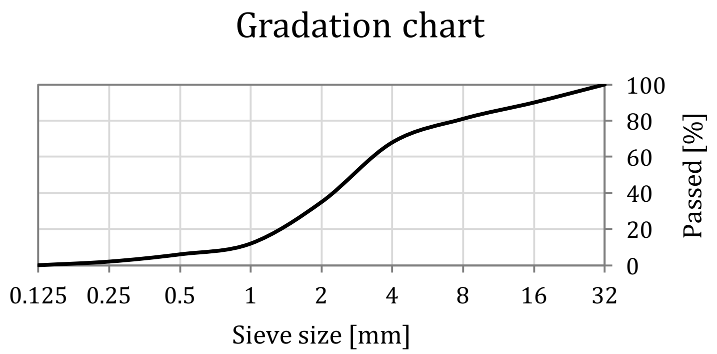

Figure 6 Example of gradation chart

The quality of the stone in aggregate needs to be appropriate when used in concrete. In Sweden, most of the bedrock and natural gravel is good enough, but there are porous stone types that should be avoided. The aggregate should also be clean and homogeneous to avoid problems during hardening of the concrete and to achieve sufficient strength (Burström, 2006). A further description of aggregate and how it affects the quality of the concrete is found in chapter 3.6.

3.2.4 Admixtures

Different admixtures can be added the concrete mixture, to add different and better properties of the concrete. The admixtures are divided into two different types, chemical and mineral admixtures. Chemical admixtures can be added to both fresh and hard concrete. The admixtures are named due to what feature it adds to the concrete mix. Some of the chemical admixtures are: (Burström, 2006)

Superplasticizers – Is the most common admixture that affects the texture of the fresh concrete. Due to the higher workability, a lower amount of water can be used in the mixture, which will lead to a higher strength.

Water-reducing – Is an admixture that will decrease the friction between the particles in the concrete. This will give the same result as superplasticizers, which is higher workability and lower amount of water needed which will give higher strength.

Air-entrainment – Is added to the concrete mixture to create microscopic air cells. These cells will give space to the water when it expands during freezing, which will prevent the concrete from freeze-thaw damage.

Accelerating – Will accelerate the concrete strength and hardening process. However, since the admixture is a chloride, corrosion can be a problem that needs to be evaluated.

Set-retarding – Will prevent the concrete mix to start the strength and hardening process. This admixture is often used in hot weather conditions or when there is a long transportation of the concrete mix.

Mineral admixtures are added to the concrete mixture to improve the features of the mix. The most common admixtures are: (Burström, 2006)

Silica dust – Is a by-product of the steel industry that is a fine silica powder. Silica dust will improve the stability of the concrete and is often used in high-strength concrete.

Fly ash – Is a by-product from coal power stations and thermal power stations. Fly ash consists mainly of aluminium silicate glass and improves the properties of the concrete. Some of these are higher strength, more durable and a higher workability (Thomas, 2007).

Granular blast furnace slag – Is a by-product from iron production and consist mainly of the oxides CaO, SiO_2, Al_2O_3 and MgO. This is basically the same chemical components as Portland cement, but the proportions differ. Slag will improve the properties of the concrete mix. Some of them are higher strength, better workability, less cement required and increased resistance to chloride penetration (Burström, 2006).

3.3 Fresh Concrete

Fresh concrete is the term that describes the concrete mix before it starts the hardening process. The properties of the fresh concrete are important to reach a desired result of the finished product. Properties that are essential for fresh concrete is workability, consistency and stability.

Workability refers to the ability to work, transport and finishing the product as desired. To achieve this, the fresh concrete should be able to mix to a homogenous mass, fill the forms and enclose the steel reinforcement.

The workability is difficult to measure and is affected by water content, cement content, type and size of aggregate and types of admixtures in the concrete mix. To evaluate the workability, the consistency is often measured (Burström, 2006).

The consistency of the of the fresh concrete mix is closely related to the workability of the mix. The consistency is mainly decided by the amount of water in the mix, and a small increase in the proportion of water can lead to a looser mix.

There are various ways to measure the consistency. In Sweden, the consistency measured by a slump test when testing loose concrete. When testing rigid concrete, a Vebe test is used and when testing a very loose mix a flow table test is used. The consistency is graded according to the European standard SS-EN 206-1, see table 1 (Burström, 2006).

Table 1 Consistence classes (Burström, 2006)

Consistence class	Slump test [mm]
S1	10-40
S2	50-90
S3	100-150
S4	160-210
S5	>210

Consistence class	Flow table test [mm]
F3	420-480
F4	490-550
F5	560-620
F6	>630

The stability of the fresh concrete is a measure of the ability of the concrete mix to stay homogeneous. A concrete mix with low stability could lead to separation of between the different components of the mix. The separation issue is called segregation can be divided into three types: Water segregation, aggregate segregation and cement segregation. Common for all these is that the concrete mix becomes a non-uniform mix that will impair the properties of the finished concrete product.

The cause of segregation could be incorrect proportions, transportations and too long vibration of the mix. To prevent segregation accurate mixing recipes, proper handling is vital. However, admixtures added to the mixture could prevent some of the issues (Burström, 2006).

3.4 Hardening process of concrete

When water is added to cement, an exothermic reaction starts which will create heat. This reaction will initiate the hydration of the cement material, which will create a solid material and get strength (Burström, 2006).

The hydration process can be divided into four phases, where the strength and the stiffness of the concrete develops. In phase 1, the setting process is started, but the mix is still workable. In phase 2, the strength development accelerates but the concrete is sensitive to external stresses. In phase 3, most of the hydration process I finished and the concrete is strong and no longer sensitive to external stresses. In phase 4, the hydration of the concrete is finished, and the concrete has reached its full strength (Burström, 2006).

3.5 Hardened concrete

When looking at the properties of hardened concrete, compressive strength is most vital. This property is essential in many applications but will also give a picture of general quality. In this chapter, the properties of strength, durability and what factors that will affect these on concrete will be presented.

Strength
Concrete is a mixed material between hardened cement paste and aggregate material. In general, the aggregate material is stronger than the cement, which means the strength of the concrete is dependent on the quality of the cement paste. This results in, that a cement paste that contains higher levels of cement i.e. a low w/c ratio will have a higher strength than a concrete with a high w/c ratio.

Generally, as long the concrete mix is homogeneous and contain quality components, the strength is decided by the w/c ratio in the concrete mix. A sketch of the relationship between w/c ratio a compressive strength can be seen in figure 7 (Burström, 2006).

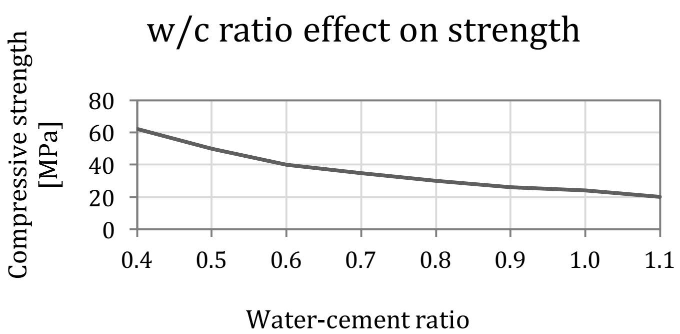

Figure 7 Typical relationship between w/c ratio and compressive strength

In Sweden, the compressive strength of concrete is evaluated on a cubic or cylindrical sample. The samples are normally cubes of 150x150x150 mm or a cylinder of diameter 150 mm and a length of 300 mm. The sample is normally tested after 28 days (5 days of wet storage, 23 days of dry storage) (Burström, 2006).

The strength of the concrete is classified according to European standards. The classes are: C16/20, C20/25, C25/30, C28/35, C30/37, C32/40, C40/50, C45/55, C50/60, C54/65, C55/67, C58/70 and C60/75. The numbers represent the lowest compressive strength during testing. The first value is the cylindrical test value and the second is the cubic test result. Both are stated since the cylindrical compressive strength is normally 85 % of the cubical value (Burström, 2006). The compressive strength (f_c) of concrete is given by equation 2:

$$f_c = \frac{F}{A_c} \ [MPa] \tag{2}$$

$F = Maximum\ load\ at\ failure$ [MN]

$A_c = Cross - sectional\ area$ [m^2]

Durability and exposure classes

The durability of the concrete is affected by the surrounding environment. Temperature variations, water, snow, chemicals and carbon dioxide is some of the factors that can damage and reduce the lifetime of the concrete. In Sweden, the concrete structures are normally most affected by freezing and thawing action, corrosion of reinforcement and chemical aggression (Burström, 2006).

According to the European standards, the environmental aggression to concrete is divided into different classes according to the type of risk. There are 6 different classes, which have 3-4 subcategories. In total, there are 18, so-called exposure classes:

- No risk of corrosion (X0)
- Risk of carbonation induced corrosion. (XC1-XC4)
- Risk of chloride-induced corrosion from other than sea water. (XD1-XD4)
- Risk of chloride induced corrosion from sea water. (XS1-XS3)
- Risk of freeze-thaw attack (XF1-XF4)
- Chemical attack (XA1-XA3)

The exposure class is normally decided by the constructor and is set according to the environment the concrete will be exposed to. The exposure classes are connected to different requirements regarding the type of cement, admixtures, w/c ratio, etc. These are specified in standard SS137003:15 - Application of EN 206 in Sweden (Burström, 2006).

3.6 The effect of aggregate properties on concrete

This section will describe how the aggregate properties will affect the properties of both fresh and hardened concrete.

3.6.1 Workability of fresh concrete

The properties of fresh concrete are dependent on all the components in the concrete. The factors that refer to the aggregate is gradation, shape and surface texture, maximum aggregate size and filler content.

Aggregates that are used in concrete is normally described d/D, which describes the smallest and largest fraction of the aggregate. As described earlier, the aggregate is normally divided into fine and coarse fractions. The gradation on the fine aggregate has a larger effect on the fresh properties. Too much small particles will lead to increased amount of water needed, and excessively large particles will decrease the workability. The gradation of the coarse aggregate has less effect on the fresh concrete, but for both fractions a continues gradation with all particles sizes represented is desired (Svensk Byggtjänst, 2017).

Even though the gradation chart of the aggregate describes the amount of each fraction that is represented in material, the shape and texture can differ. The texture is normally described by the angularity and the roughness of the surface. The angularity is the amount of rounded edges and roughness describes how smooth the surface of the aggregate is. The shape of aggregate is often described by the relationship between length, width and thickness. These are described by flakiness index and elongation index which is given by equation 3 and 4: (Svensk Byggtjänst, 2017)

$$Flakiness\ index = \frac{width}{thickness}\ [-] \tag{3}$$

$$Elongation\ index = \frac{length}{thickness}\ [-] \tag{4}$$

The shape and texture of the aggregate primarily affect the workability of the fresh aggregate. Generally, a high flakiness and elongation index will decrease the workability and amount of water needed. The same applies to aggregate with sharp edges and rough surface of the particles (Svensk Byggtjänst, 2017).

The maximum aggregate size (d_{max}) decided according to the application, reinforcement density and production method. Normally the maximum size should be lower than the smallest free distance between reinforcement but should be lower if the concrete should pass many layers of reinforcement (Svensk Byggtjänst, 2017).

3.6.2 Strength of hardened concrete

Normally, the aggregate within the concrete will not affect the concrete strength. This since the strength of the stone material is much higher than the strength of the cement paste or the bonding between the cement paste and the aggregate. Somewhere between a compressive strength between 2-2.5 times the required strength of the concrete is suitable for the aggregate which means that aggregate with a compressive strength of 100 MPa is sufficient for most applications (Svensk Byggtjänst, 2017).

However, different properties can affect the adhesion between the aggregate and the cement paste. The adhesion is affected both by physical and chemical properties. Surface coatings of clay, mud, (Svensk Byggtjänst, 2017) bituminous material, (Brand & Roesler, 2016) etc. can adversely affect the bonding.

3.6.3 Other factors that affect concrete properties

Conventional aggregate made of stone is not a solid material. There are pores in the stone material that could either be enclosed within the particle or open to the surface of the stone. (Neuwald, 2008) Normally, natural aggregate contains more pores and have a higher porosity than crushed aggregate. This due to the weathering process of the natural gravel (Svensk Byggtjänst, 2017).

Water absorption refers to the ability of the aggregate absorb water until the pores are full. Absorption is defined in the percentage of the OD (Oven-dry) weight. Too large absorption of the aggregate can give unwanted abilities during casting of the concrete. This since the water will be absorbed and decrease the free water in the mix. This can lead to early hardening of the concrete and an incorrect w/c ratio of the mix (Svensk Byggtjänst, 2017).

To understand absorption and how to minimise the effect of it, the different moisture states of aggregate needs to be known. Depending on the moisture state aggregate could either absorb or release water to the concrete mix. There are four different states that aggregate can be in: Oven-dry (OD), Air-dry (AD), Saturated surface-dry (SSD) and wet, see figure 8 (Neuwald, 2008).

Oven-dry aggregate is the state where all moisture has been removed from the pores in the aggregate. This means that no water in neither the internal pores or the external pores. This state is only achieved in a laboratory during heating of the aggregate. This state will give the maximum absorption of the aggregate.

Air-dry aggregate is the state when the surface of the aggregate is dry, but the pores might be partly filled with water. This state is common during the summer in aggregate stockpiles. This state will absorb water from the concrete mix.

Saturated surface-dry is the state where the surface is dry, but all the pores within the aggregate are filled with water. This state is only possible in a laboratory and is the state where the aggregate will neither absorb or release water to the concrete mix.

Wet aggregate is the state where all the pores are filled with water, and the surface of the aggregate is wet. This means that there is free water on the aggregate that will add water to a concrete mix.

The moisture state and porosity is vital during mixing of the concrete mix. All free water on the aggregates needs to be included in the water content in the mix (Svensk Byggtjänst, 2017). If the aggregate is dry and can absorb water, water needs to be added to the mix to keep the desired water content (Neuwald, 2008). However, the aggregate materials in Sweden normally have a low porosity which means low absorption ability. Therefore, absorption is normally negligible for Swedish aggregates (Svensk Byggtjänst, 2017).

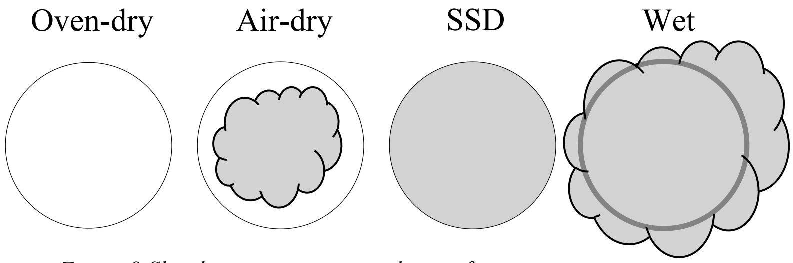

Figure 8 Sketch over moisture condition of aggregate

4 Reclaimed Asphalt Pavements (RAP)

This chapter will introduce the asphalt pavement material. The chapter will also describe the components and introduce the recycled material, reclaimed asphalt pavement (RAP).

4.1 What is asphalt?

Just like concrete, asphalt is a mix of different components. The mix consist of aggregates and binder and the mix is also called asphalt concrete. The asphalt concrete creates a strong and durable material and is flexible which is enables smooth surfaces that can be used in various areas. The most common field of application for asphalt is as a pavement material on car roads, airport runways and bicycle paths. But it can also be used as floor materials in and around buildings, industries, etc. (European asphalt pavement association, 2017).

Paved asphalt roads are normally built in different layers. The layers are designed to withstand external forces and prevent deformations of the asphalt pavement. The materials and thickness of the layers can vary between different designs, but normally there are four different layers on modern roads. Normally the surface layer and a part of the base layer contain binder material, see figure 9 (Agardh, 2016).

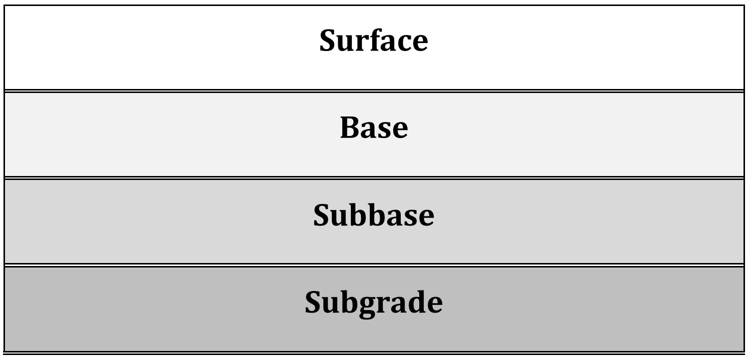

Figure 9 Cross section of asphalt road layers

4.2 Asphalt components

This section will describe the different components in asphalt pavements.

4.2.1 Aggregate

Aggregate is the stone material in the asphalt mix and intends to withstand stresses. This material is the load supporting part of the asphalt material. Aggregate is about 80 % of the asphalt volume and needs to be selected to withstand stresses both from traffic and the environment.

The aggregate for asphalt pavements has similar requirements as concrete aggregate, and the stone material is often produced at the same quarry. Generally, the stone material needs to be of good quality, of a high strength and porous stone types are not used. The aggregate size used in asphalt pavements varies between layer and type of pavement. Fractions between 0-32 mm are used in Sweden and are mostly crushed stone, even though natural gravel is used to some extent (Svenska Kommunförbundet, 2004).

4.2.2 Binder

Binder is the material in asphalt that binds the aggregates together. The most common binder used in asphalt is bitumen, that is a petroleum product produced from crude oil. In older pavements, PAH (Polycyclic Aromatic Hydrocarbons) binder is common (Svenska Kommunförbundet, 2004).

PAH is harmful both for environment and health and is not produced in Sweden since 1973. However, PAH can still exist in older pavements and pavements prior to 1975 should always be tested. How the asphalt masses should be managed depends on the PAH level in the asphalt material. An agreement between the environmental administrations of Malmö, Gothenburg and Stockholm. The recommendations are: (Miljöförvaltningen Göteborgs Stad, 2017)

> 1000 ppm - Hazardous waste that needs to be transported and handled at a class 1 landfill.

300-1000 ppm – Can be recycled and reused within or below new pavement in infrastructure projects. The project needs to be above ground water level, not be situated in a sensitive area and consultation with the environmental administration is needed.

70-300 ppm – Can be recycled and reused within or below new pavement in infrastructure projects. The project needs to be above ground water level, and consultation with the environmental administration is needed.

< 70 ppm – The asphalt material can be recycled and reused without limitations unless there are sensitive areas where consultation with the environmental administration is needed.

4.3 Asphalt recycling

This section will describe the processes of asphalt recycling.

4.3.1 Recycling process

Conventional recycling of asphalt contains various methods and processes. The asphalt material could either be used directly in-place where it was reclaimed. It can also be reclaimed and recycled at an asphalt plant. Both these methods also include different processes to achieve the desirable quality of the pavement. In figure 10, is a sketch over the conventional recycling processes of asphalt pavements (Svenska Kommunförbundet, 2004).

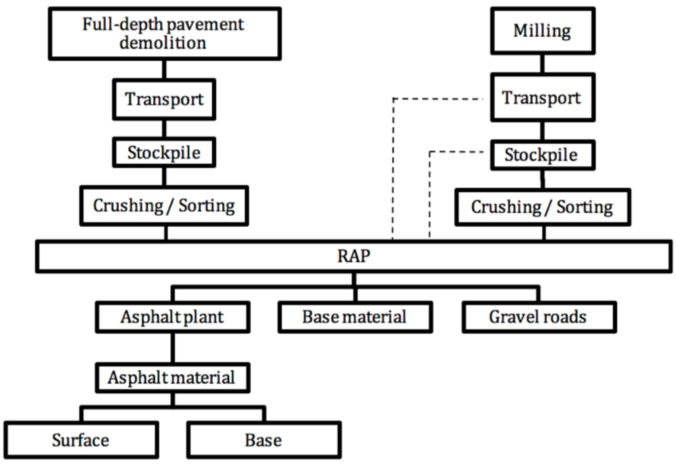

Figure 10 Recycling process asphalt material

Asphalt pavements can be recycled up to 100 %, and the main application is in new asphalt pavements, where old masses are blended with the new asphalt material. This is the best use of old asphalt materials since the costly bituminous material in the recycled masses is reused (Nordisk vägforum, 2017). Other applications of the asphalt material are normally: base material, subbase material, gravel road wearing coarse, landfill, shoulder material and temporary road constructions (Svenska Kommunförbundet, 2004).

In Sweden, the asphalt production between 2008-2015 has been around 7-8 million tonnes per year. In 2015, 1.6 million tonnes originated from recycled asphalt (European asphalt pavement association, 2017).

4.3.2 Reclaiming process

Reclaiming
Asphalt that has been reclaimed is called reclaimed asphalt pavement (RAP). RAP is mostly aggregate and bituminous materials, but can also contain additional admixtures and decay products from the traffic. The most common methods to obtain RAP is through milling of the top layer of the pavement, or through a full-depth pavement demolition (Jacobson, 2002)

Milling also called cold planning is a method where the top layer of the pavement is milled using a milling machine. This method is used to construct a new coating of the pavement or to increase and restore the friction of the pavement (Asphalt Recycling and Reclaiming Association, 2001).

Since milling is done layer by layer, it is a way of separating different layers of the pavement. This could be useful when separating layers containing PAH from clean layers (Svenska Kommunförbundet, 2004).

Full-depth pavement demolition is a method where all the pavement and some of the underlying layers are reclaimed. This material will be more mixed and normally contain less bituminous than the milled masses. The full-depth masses are normally crushed and are suitable to use as unbound layers due to its lower bituminous levels (Svenska Kommunförbundet, 2004).

Crushing
After the reclaiming process, the asphalt material needs to be crushed. This process does not intend to crush the stone material once again. Instead, the aim is to separate the RAP that is tied together by the bitumen, into smaller fractions. The crushing is easiest during cold weather since the hot weather glues the bitumen together once again.

After the crushing process, the RAP material is sieved into desirable fractions. Normally fractions between 0-8 and 0-22 mm are used as new asphalt layers. Larger fractions are used as unbound material (Svenska Kommunförbundet, 2004).

Stockpiling
The best use of RAP is when it's used right after the reclaiming and crushing process. However, to achieve an effective recycling process, stockpiling is necessary. Stockpiling of RAP can be managed in different ways. Separating masses with different pollution levels, fractions, aggregate quality and bitumen levels, is methods to make the recycling process more effective (Svenska Kommunförbundet, 2004).

Storage of RAP is regulated by Swedish law. Stockpiling of RAP less than 3 years can be classified as an interim storage of RAP. A longer time than 3 years is classified as landfill material, and a tax charge is applied (Svenska Kommunförbundet, 2004). In

Sweden, the charge is 500 SEK/tonnage of RAP according to the law (1999:673) about hazardous waste.

When choosing a site for RAP Stockpiling, there are different aspects that need to be considered. The site should be situated so that long transportation to and from the site is prevented. A hydrological evaluation is also needed to prevent pollutions. However, studies have shown that soaking leaching is low on RAP that is not containing PAH (Svenska Kommunförbundet, 2004).

4.3.3 Asphalt recycling in Sweden

In the Swedish road system, there are about 300 million tonnes of pavement. In addition to that, there are about 10 million tonnes of new asphalt that is constructed each year. Since there is a large amount of materials, an effective recycling of material is important.

In Sweden, the interest of recycling of asphalt, have been growing the last 30 years, and today almost all asphalt material is recycled and reused. In the last decade about 1-1.5 million tonnes of an asphalt material has been recycled each year. Most of the material is reused as new asphalt pavement which stands for about 66 % of the total amount. The rest has been used as unbound road material and landfill (Trafikverket, 2015).

In the national road system, the amount of RAP that can be mixed in into new asphalt is regulated by The Swedish Transport Administration (Trafikverket). In hot recycling, up to 40 % of the asphalt could be RAP, depending on application and layer of the pavement. In semi-hot recycling, up to 30 % RAP can be used (The Swedish Transport Administration, 2015).

4.4 RAP properties

The properties in RAP is varying from where it originates from. Gradation, moisture content, unit weight, binder content and quality of the material differs from different samples.

Gradation
Generally, the aggregate gradation does not differ significantly between different samples of RAP. However, the milled material usually contains more fine material according to (Jacobson, 2002). In the same study, the author also states that some of the larger fractions, from the unbound layers, in the full-depth masses is crushed during the crushing process of the material. This results in less number of large fractions in this type of RAP, see figure 11.

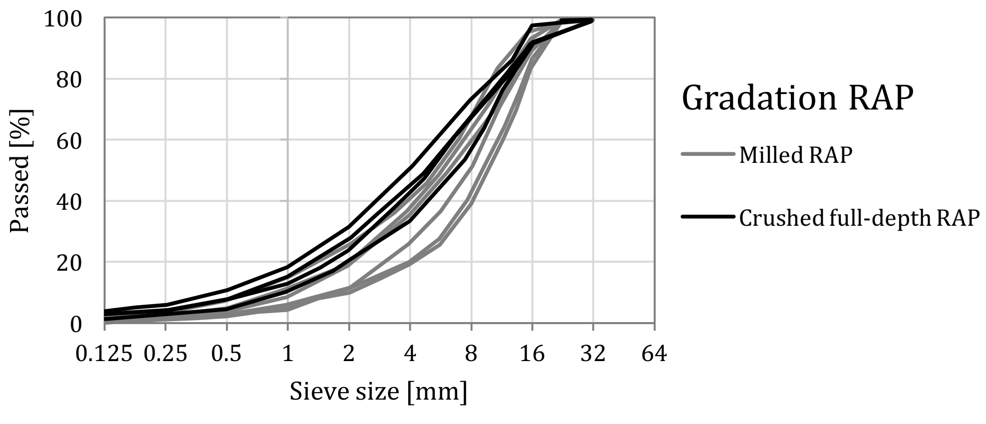

Figure 11 Typical gradation of RAP (Jacobson, 2002)

Binder content

The amount and quality of bitumen are depending on the age of the pavement, but also how the RAP has been processed. Old pavements normally contain less amount of bitumen, and the bitumen is also harder due to ageing.

The binder content differs between the reclaiming methods. Milled RAP, normally contains high levels of bitumen since there are no unbound materials in the top layer. This makes the milled RAP suitable for recycling into new asphalt (Jacobson, 2002).

In the full-depth masses, there is less binder, since the top pavement layer is mixed with the layers below, that contain less binder. Differences in binder content from 22 different samples from Swedish roads, is presented in figure 12 (Jacobson, 2002). According to this data the average binder content for milled RAP was 5.6 %, and for the full-depth RAP, the content was 3.8 %.

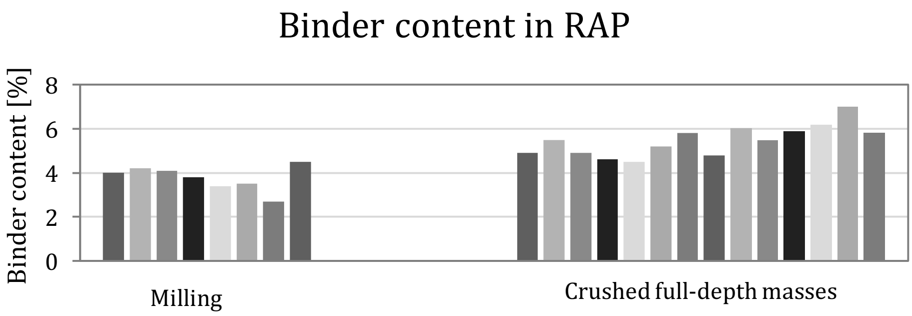

Figure 12 Binder content in RAP (Jacobson, 2002)

Moisture content

The water content in RAP varies between samples. Factors that affect the level is where the material is reclaimed, how long it been stockpiled and weather conditions. In the study by (Jacobson, 2002) the author states that the water content normally varies between 1-3 % in the summer. In the winter, the content was higher and varied between 5-7.5 %. The water content and water absorption of RAP must be considered for use as an aggregate in concrete. This since the w/c ratio could be affected (Berry, Stephens, Bermel, Hagel, & Schroeder, 2013).

Unit weight

The unit weight of RAP material is dependent on the source of the natural aggregate and water content. There is a lack of data on this property, but the unit weight normally varies between 1922 kg/m^3- 2243 kg/m^3 according to (Berry, Stephens, Bermel, Hagel, & Schroeder, 2013). In table 2, a summary of typical values for RAP material is presented:

Table 2 Typical properties values of RAP material (Federal Highway Administration, 2017)

RAP property	Typical range of values
Unit weight	1940-2300 kg/m^3
Moisture content	Normally: up to 5 % Maximum 7-8 %
Binder content	Normally: 4.5-6 % Max range 3-7 %

5 Reclaimed Asphalt Pavement (RAP) in concrete

This chapter will give a further understanding of how RAP can be used in concrete, as an aggregate. There will first be a summary of the Swedish standards concerning recycled aggregate. Second, there will be a study of earlier studies on the subject.

5.1 Regulations of recycled aggregate

In 2015, a new version of the Swedish concrete standard SS137003:2015 (Application of SS-EN 206 in Sweden) was released. In this version, the possibility of using recycled aggregate in concrete has been increased. This due to increased demand from the construction industry (Helsing, 2015).

In the Swedish aggregate standard: SS-EN12620+A1:2008, the components of recycled aggregate are specified. There are no specifications according to reclaimed asphalt pavements, but there are general regulations of recycled aggregates. In the standard, the definition for recycled aggregates is: *"Obtained from the processing of inorganic material previously used for the construction"*. The requirements of what this aggregate can contain are categorised in 7 different components:

Rc – Concrete products and mortar
Ru – Unbound aggregates
Rb – Ceramics
Ra – Bituminous material
Rg - Glass
FL – Liquids
X – Others (Natural soils, gypsum, plastics, metals, wood)

The recycled aggregate is divided into two categories, depending on the components, according to the Swedish standard SS137003:2015. Type A requires - Rc_{90}, Rcu_{95}, Rb_{10}, Ra_{1-}, FL_{2-}, XRg_{1-} and Type B requires – Rc_{50}, Rcu_{70}, Rb_{30-} , Ra_{5-}, FL_{2-}, XRg_{2-}. The requirements for type A and B are explained in table 3.

Table 3 Recycled aggregate component requirements

Category	Type A	Type B	Unit
Rc	≥ 90	≥ 50	%
Rc+u	≥ 95	≥ 70	%
Rb	≤ 10	≤ 30	%
Ra	≤ 1	≤ 5	%
X+Rg	≤ 1	≤ 2	%
FL	≤ 2	≤ 2	cm^3/kg

Recycled aggregate can only be used as coarse aggregate. In addition, it has to meet all the physical and chemical requirements in the aggregate standard. The maximum amount of the coarse aggregate that can consist of recycled aggregate type A and B is regulated in standard SS 137003:2015, see table 4.

Table 4 Largest part of the coarse aggregate mass that could be recycled aggregate

Type	Exposure class			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1, XS1	Other classes
A	50 %	30 %	30 %	0 %[a]
B[b]	50 %	20 %	0 %	0 %
Comments: a: Up to 30 % of reclaimed aggregate Type A can be used, if ensured that its origin from a concrete of same or higher strength. b: Can't be used in strength classes higher than C30/37				

To summarise the recycled aggregate regulations in the standards, there is today no possibility to use RAP aggregate in the concrete production. Type B aggregate allows up to 5 % bituminous material, which the RAP material is normally below, see section 4.4. However, the standard requires that the recycled aggregate contains concrete material, (see table 3) which RAP does not do.

5.2 Earlier studies of RAP in concrete

Several studies have evaluated the properties and feasibility to use RAP in concrete. In this chapter, a summary of results, methods, conclusions and key findings from some of these studies are presented.

Research by Hassan, Brooks and Erdman
Hassan, Brooks and Erdman from the University of Leeds did their research in the year 2000, in Great Britain. The aim of the study was to make an initial investigation of the properties and performance of concrete containing RAP aggregate.

In the study four different mixes were evaluated: One mix with regular aggregate, one mix with regular fine aggregate and coarse RAP aggregate, one mix with regular fine aggregate and coarse RAP aggregate, one mix with 30 % replacement of OPC with FA and a mix with both fine and coarse aggregate from RAP.

The RAP material was collected on a reconstruction work site in Newcastle-upon-Tyne. The fine RAP aggregate had a specific gravity of 2.41 and the coarse RAP 2.56.

Five different properties were tested during the study: Compressive strength, flexural strength, porosity and oxygen permeability. The results showed that RAP aggregate in the concrete mix decreased both flexural and compressive strength. The reduction of compressive strength was about 60 % when only the coarse aggregate was replaced. When both coarse and fine aggregate were replaced, the reduction was almost 80 %.

However, the results showed that there was an improvement of strain and shock absorbent properties. The author concluded that, even though the strength is decreased, RAP concrete has sufficient strength and are suitable to be used in "low-strength and high ductility applications" (Hassan, Brooks, & Erdman, 2000).

Research by Huang, Shu, and Li
Huang, Shu, and Li from the University of Tennessee and Louisiana State University did their research in the year 2005, in the US. The aim of the study was to evaluate the effect on toughness and brittle behaviour of Portland cement concrete when aggregate from RAP was used.

In the study, four different mixes were evaluated. The first mix was a concrete made of a regular aggregate, which was used as a control mix. The second was a mix of coarse RAP aggregate and regular fine aggregate. The third was a mix of regular coarse aggregate and fine RAP aggregate. The last, was a mix containing RAP of both fine and coarse aggregate.

The RAP material was laboratory made material that was made from a fresh aggregate material. The fresh aggregate was coated with about 8 μm of bituminous material. After that the RAP was heated for 12 h, to simulate the normal ageing process of pavements. The specific gravity of the material was 2.8 for the coarse aggregates and 2.6 for the fine aggregate. The absorption was 0.49 % for the coarse and 1.4 % for the fine aggregate. The cement material used in the study was a type I Portland cement.

Five different parameters were tested during the study: Compressive strength, split tensile strength, strain at peak split tensile stress, a slump test and air content.

The results from the study showed that the RAP concrete could be handled and mixed as conventional concrete mixes. The fresh properties showed that the concrete made of either fine or coarse RAP had a lower slump than the control mix. The reason for that could be due to the high viscosity of the binder, the author states. In the mix with both fine and coarse RAP, the slump was higher than for the control mix. The author explains that this might be due to lower absorption of the RAP material which could increase the free water in the mix.

The compressive and split tensile strength was decreased when RAP was used in the concrete. The mix with coarse RAP had a lower strength reduction than the mix with fine RAP. The reduction of the compressive strength was 42.3 % and 50 % respectively. The mix with both fine and coarse RAP had the lowest strength, a reduction of 72.4 %.

However, the tests showed that the toughness increased in the concrete containing RAP. The author states that this is probably due to, that the bituminous material forms a thin film between the aggregate and the cement. This film will absorb energy and prevent cracking, since cracks will rather go around the aggregate, than through it (Huang, Shu, & Li, 2005).

Research by Okafor

Okafor at the University of Nigeria did his research in 2010, in Nigeria. The aim of the study was to evaluate the performance of RAP used as a coarse aggregate in concrete. The performance was evaluated by six different concrete mixes. Three of them had mix proportions by weight of 1:2:3 (cement: sand: coarse RAP) with w/c ratio of 0.5, 0.6 and 0.7. The other three had mix proportions by weight of 1:3:6 with w/c ratio of 0.5, 0.6 and 0.7. In addition, control mixes with regular aggregate were mixed.

The RAP material was collected from a reconstruction of an expressway in Nigeria. The asphalt material was a fine-graded pavement and was crushed and retained on the 4.75 mm sieve, to match the natural gravel. The specific gravity was 2.28, and the absorption was 2.9 % which was lower than the natural gravel. The cement used in the study was a type 1 Portland cement.

During the study, compressive strength, flexural strength and a slump test were evaluated. The results show that the RAP concrete had less workability at all w/c ratio levels and proportions, even though the author state that the RAP concrete was still easy to mix and compress.

The compressive and flexural strength were lower with RAP in the concrete, and the author states that the maximum compressive strength, using coarse RAP aggregate, was 25 MPa. The author recommends that RAP concrete might be a valid option in middle and low strength concrete (Okafor, 2010).

Research by Hossiney, Tia and Bergin

Hossiney, Tia and Bergin from the University of Florida in the US, did their study in 2010. The aim of the study was to evaluate the feasibility to use RAP in concrete for concrete pavements.

In the study, 14 different concrete mixes were produced and tested. The mixes used were different combinations of 10, 20 and 40 % of RAP (both fine and coarse), w/c ratio between 0.48-0.53 and two different RAP samples.

The RAP material in the study was obtained at an asphalt plant stockpile in Gainesville, Florida and was separated to fine and coarse aggregate at a 4.75 mm sieve. A porous limestone was used as fresh coarse aggregate and a silica sand, as a fine aggregate. The specific gravity (SSD) varied between 2.23-2.31 for the coarse RAP and 2.18-2.32 for the fine RAP. The absorption for the coarse RAP was between 2.08 %-2.20 % and 2.84 %-1.77 % for the fine RAP.

The concrete was tested according to the US standards. The tests that were performed were compressive strength, modulus of elasticity, splitting tensile strength, flexural strength, shrinkage and thermal expansion.

The fresh properties of the concrete showed a small increase of the slump, with an increased amount of RAP. The results from the hardened properties indicated that compressive strength, modulus of elasticity, splitting tensile strength and flexural strength decreased when the percentage of RAP increased in the concrete. The compressive strength reduction was 18, 28 and 58 % for the mixes with 10, 20 and 40 % RAP receptivity. The shrinkage test and the thermal expansion test showed no clear effect on the concrete that contained RAP material.

The properties found in the studies were used in a finite element model (FEM). The model was used to evaluate the performance of the RAP concrete as a typical concrete pavement in Florida. The FEM analysed all the 14 mixes and indicated that an increased RAP content, gave a lower stress ratio, which is desirable since it will withstand a larger amount of stress cycles until failure. This result indicated that the RAP concrete could perform better than the regular concrete for concrete pavements (Hossiney, Tia, & Bergin, 2010).

Research by Khodair and Raza

Khodair and Raza from the Bradley University in the US did their research in 2016. The goal of the study was to investigate the effect on different properties as hardening process, durability and strength when adding RAP to self-consolidating concrete (SCC).

The properties were evaluated by 16 concrete mixtures. The mixtures were mixed with a replacement of natural aggregate, with 0, 15, 30 and 50 % RAP aggregate. In addition, the cement was combined with fly ash and slag according to: 100-25 % cement, 0-75 % fly ash and 0-75 % slag.

The coarse RAP material used in the study had a specific gravity of 2.62 (SSD) and an absorption of 1 %.

During the test, compressive strength, tensile strength, unstrained shrinkage, chloride permeability and slump flow test were performed. The fresh properties of the concrete showed that with increased amount of RAP in the mixture, the workability decreased. The reason for that was probably due to a higher viscosity of the binder and a more angular shape on the RAP aggregate.

The results showed that the compressive and tensile strength decreased with an increased level of RAP. The compressive strength decreased with 16, 28.9 and 34.8 % compared to the reference mix with 100 % cement. The author explained this due to a decreased bonding between the asphalt mortar and the aggregate, compared to natural aggregate.

The SCC mixtures containing slag and fly-ash had a better resistance to chloride penetration than the mixtures of 100 % Portland cement. The test also showed that higher levels of RAP increased the resistance to chloride penetration (Khodair & Raza, 2016).

Research by Brand and Roesler

Brand and Roesler from the University of Illinois in the US did their study in 2016. Their study aimed to investigate the poor bonding between RAP and cement paste. This is believed to be the main reason for the impaired properties of RAP concrete. During the study, 12 different mixes were evaluated. Three different RAP samples were used, and 0-50 % RAP was added to the aggregate.

In the study, the bonding between the RAP and cement was evaluated trough an investigation of the interfacial transition zone (ITZ). This is the 50 μm thick region around the aggregate that is referred as the "weak link in the failure of concrete". In the study, the ITZ was evaluated trough microscopy, to evaluate the effect of the RAP material.

The results of the study indicate that the long-term properties of the ITZ are worse in the RAP concrete. The ITZ area had a higher porosity, larger width and more CH (calcium hydroxide) levels. Which is likely the reason for the decreased performance of the RAP concrete compared to conventional aggregate concrete (Brand & Roesler, 2016).

5.3 Summary of earlier studies

When summarizing previous studies of Using RAP in concrete, there are a couple of key findings:

1) Compressive strength, tensile strength, modulus of elasticity and flexural strength will decrease with a higher amount of RAP material in the concrete mix.

2) According to one study, chloride penetration decreases with an increased amount of RAP in the concrete mix.

3) Shock absorption and strain is increased with more RAP in the concrete mix.

4) RAP concrete is most suitable for medium and low strength concrete.

5) RAP concrete could perform better than regular concrete as a concrete pavement.

6) The bonding between RAP and the cement paste is less than between regular aggregate and cement paste.

7) The workability is less (lower slump), in most of the studies, when RAP aggregate was added to the mix.

8) The specific gravity of RAP varied between 2.2 and 2.6 (SSD) and was less than the natural aggregate.

9) The absorption of the RAP aggregate was both lower and higher, compared to the fresh aggregates.

6 Materials used in the laboratory tests

In this chapter, the materials used in the study are presented. The source and basic properties of each material will also be described.

6.1 Cement

In the study, two types of cement were used. One Portland cement used for general constructions and one for civil engineering structures.

The cement used for general constructions was a CEM II from the fabric Cementa, manufactured in Degerhamn. The specifications of this cement are presented table 5 (Cementa AB, 2017).

Table 5 Specifications of Portland cement designed for general constructions

Property	Guideline value	Range	Unit
Blaine fineness	480	±30	m^2/kg
Setting time	150	±30	min
Compressive strength 1d	22	±3	MPa
Compressive strength 2d	34	±3	MPa
Compressive strength 7d	-	±4	MPa
Compressive strength 28d	56	±4	MPa
Compact density	3000	±20	kg/m^3
Bulk density	1250	±250	kg/m^3
Brightness	26	±1	%

The civil engineering cement was a CEM I from the fabric Cementa, manufactured in Skövde. The specifications of the civil engineering cement presented in table 6 (Cementa AB, 2017).

Table 6 Specifications of Portland cement designed for civil engineering structures

Property	Guideline value	Range	Unit
Blaine fineness	310	±30	m^2/kg
Setting time	150	±30	min
Compressive strength 1d	10	±3	MPa
Compressive strength 2d	20	±3	MPa
Compressive strength 7d	35	±4	MPa
Compressive strength 28d	54	±4	MPa
Compact density	3200	±20	kg/m^3
Bulk density	1250	±250	kg/m^3
Brightness	21	±1	%

6.2 Aggregate

In this section, the properties of fresh aggregate and RAP material used in the study are presented. During the study, the 0/8 mm material will be called fine aggregate (FA), and the 8/16 mm material will be called coarse aggregate. Even though the limit for fine and coarse aggregate normally refers to the 4 mm.

6.2.1 Basic properties of fresh aggregate

In the study, two types of fresh aggregates were used. The fine aggregate was a 0/8 mm natural gravel produced in Hol, near Alingsås. The coarse aggregate was an 8/16 mm crushed stone produced in Ale, north of Gothenburg.

The properties (unless moisture content) of the fresh aggregate was provided by the supplier. The moisture content was measured at the concrete lab at Chalmers according to standard. The properties of the fresh aggregate are presented in table 7, 8 and 9.

Table 7 Properties fresh 0/8 mm aggregate

Fine fresh aggregate 0/8 mm		
Property	**value**	**unit**
Specific gravity (OD)	2.65	-
Specific gravity (SSD)	2.66	-
Density (OD)	2650	kg/m^3
Density (SSD)	2660	kg/m^3
Water absorption	0.3	%
Moisture content	0.1	%

Table 8 Properties fresh 8/16 mm aggregate

Coarse fresh aggregate 8/16 mm		
Property	**value**	**unit**
Specific gravity (OD)	2.71	-
Specific gravity (SSD)	2.72	-
Density (OD)	2710	kg/m^3
Density (SSD)	2720	kg/m^3
Water absorption	0.3	%
Moisture content	0.2	%

Table 9 Gradation fresh aggregate

	Fine fresh aggregate 0/8 mm	Coarse fresh aggregate 8/16 mm
Sieve size [mm]	**Passed [%]**	**Passed [%]**
31.5	100	100
22.4	100	100
16	100	93
11.2	100	50
8	96	13
5.6	94	6
4	92	1
2	88	1
1	79	1
0.5	60	1
0.25	29	1
0.125	6	1
0.063	1.3	0.5

6.2.2 Basic properties of reclaimed asphalt pavements (RAP)

The RAP used in the study was a mixed RAP material from the asphalt plant Vikan, in Gothenburg operated by Skanska. The RAP was a 0/16 mm material that is reclaimed trough full-depth pavement demolition and contained about 4.49 % bitumen. After the reclaiming process the material has been crushed and stockpiled.

Before using it in this study, the RAP material was sorted into two fractions to match the original fractions of the fresh aggregate material. The fractions were 0/8 mm and 8/16 mm.

The density, specific gravity, water absorption, and moisture content were evaluated according to standards at the concrete lab at Chalmers. Gradation and binder content were evaluated with help from the technical lab for road engineering in Gunnilse, operated by Skanska. The properties of the RAP materials are presented in table 10-12.

Table 10 Properties RAP 0/8 mm aggregate

Fine RAP 0/8 mm		
Property	**value**	**unit**
Specific gravity (OD)	2.44	-
Specific gravity (SSD)	2.45	-
Apparent specific gravity	2.47	-
Density (OD)	2440	kg/m^3
Density (SSD)	2450	kg/m^3
Water absorption	0.4	%
Moisture content	4	%
Bitumen content	4.55	%

Table 11 Properties RAP 8/16 mm aggregate

Coarse RAP 8/16 mm		
Property	**value**	**unit**
Specific gravity (OD)	2.57	-
Specific gravity (SSD)	2.59	-
Apparent specific gravity	2.61	-
Density (OD)	2570	kg/m^3
Density (SSD)	2590	kg/m^3
Water absorption	0.5	%
Moisture content	1.2	%
Bitumen content	2.57	%

Table 12 Gradation RAP aggregate

	Fine RAP 0/8 mm	**Coarse RAP 8/16 mm**	**RAP 0/16 mm**
Sieve size [mm]	**Passed [%]**	**Passed [%]**	**Passed [%]**
31.5	100	100	100
22.4	100	100	100
16	100	100	100
11.2	100	69	85
8	100	4	70
5.6	-	4	59
4	60	0	50
2	34	0	38
1	18	0	30
0.5	8	0	24
0.25	3	0	19
0.125	1	0	14
0.063	0	0	10.2

6.2.3 Aggregate gradation

In figure 13, the gradation of the fine aggregates is presented in a gradation chart. In figure 14, a picture of the aggregates is presented. The fresh 0/8 mm aggregate is to the left, and the RAP 0/8 mm aggregate is to the right.

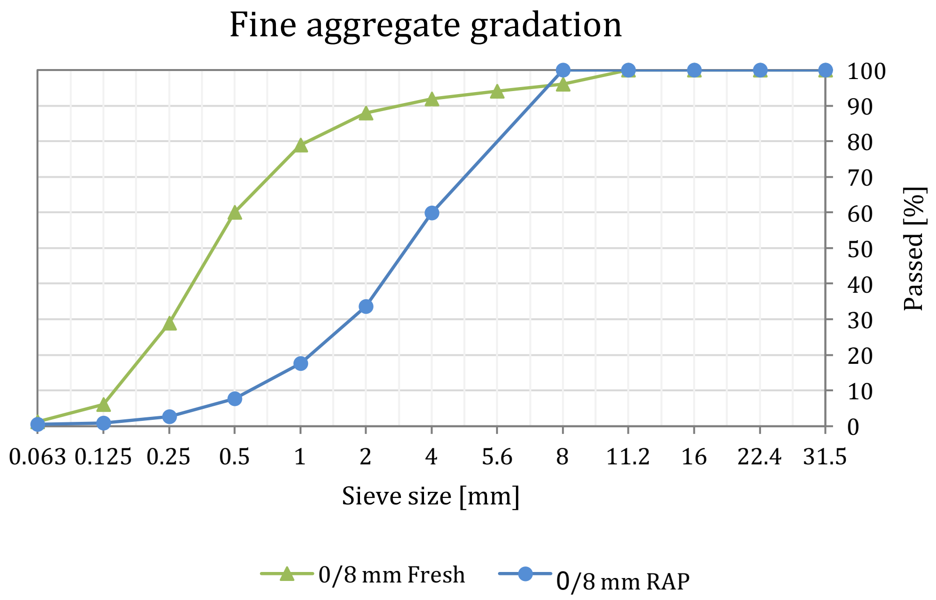

Figure 13 Fine aggregate gradation

Figure 14 Fresh 0/8 mm aggregate and RAP 0/8 mm aggregate

In figure 15, the gradation of the coarse aggregates is presented in a gradation chart. In figure 16, a picture of the aggregates is presented. The fresh 8/16 mm aggregate is to the left, and the RAP 8/16 mm aggregate is to the right.

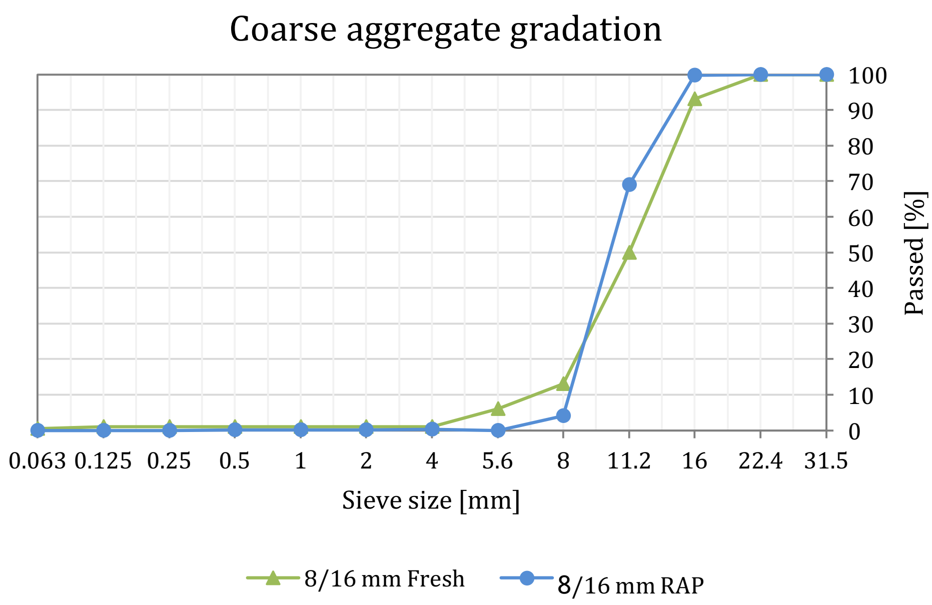

Figure 15 Coarse aggregate gradation

Figure 16 Fresh 8/16 mm aggregate and RAP 8/16 mm aggregate

7 Concrete mixtures used in the study

In the study, 14 different concrete mixes were evaluated. In seven of them, a Portland cement for general constructions was used. In the other seven, a Portland cement for civil engineering structures was used. In each cement type, a control mixture was made. The rest were mixes with RAP blended with fresh aggregate.

The reference mixes for both cement types were based on commercial concretes used in Skanska's production. The concrete mix based on civil engineering cement was a C32/40 recipe with a w/c ratio of 0.45. The cement for general constructions was used in a recipe for a C28/35 concrete with a w/c ratio of 0.6 made for house construction

In both mixes, superplasticizers admixture was used. In the civil engineering concrete, 0.8 % of the cement weight was used. In the housing concrete, 1 % of the cement weight was added. In addition to this, air-entrainment was added to the civil engineering concrete to achieve around 4.5 % air in the mix.

There was also a correction of moisture content in each mix to keep a constant amount of free water. This since the RAP materials were moist and therefore adds water to the mix, which will affect the w/c ratio and workability. The water correction was calculated at the day for mixing. A total declaration of the mixes used in the study, before correction for moisture content, is presented in table 13 and table 14. A cross section of each concrete mix is presented on the next page, see figure 17 and 18.

7.1 Concrete for house constructions

In the house concrete mixes, the replacement of fresh aggregate to RAP material was made by weight, see list below. The recipe of the mixes is presented in table 13.

1. Reference mix
2. 25 % CA RAP
3. 50 % CA RAP
4. 25 % FA RAP
5. 50 % FA RAP
6. 25 % CA RAP, 25 % FA RAP
7. 50 % CA RAP, 50 % FA RAP

Table 13 Laboratory mix proportions, concrete for housing constructions [kg/m^3]

Concrete for house constructions							
Mix	**0/8 Fresh**	**0/8 RAP**	**8/16 Fresh**	**8/16 RAP**	**Water**	**Cement**	**Superplasticizers**
1	1524	-	269	-	212	354	3.5
2	1524	-	201.75	67.25	212	354	3.5
3	1524	-	134.5	134.5	212	354	3.5
4	1143	381	269	-	212	354	3.5
5	762	762	269	-	212	354	3.5
6	1143	381	201.75	67.25	212	354	3.5
7	762	762	134.5	134.5	212	354	3.5

7.2 Concrete for civil engineering constructions

In the civil engineering concrete mixes, the replacement of fresh aggregate to RAP material was made by volume instead of weight. This was done to make the results more trustworthy since the lower density of the RAP aggregate could affect the workability.

The replacement of fresh aggregate to RAP material was made by volume, see list below. The recipe of the mixes is presented in table 14.

1. Reference mix
2. 25 % CA RAP
3. 50 % CA RAP
4. 25 % FA RAP
5. 50 % FA RAP
6. 25 % CA RAP, 25 % FA RAP
7. 50 % CA RAP, 50 % FA RAP

Table 14 Laboratory mix proportions, concrete for civil engineering constructions[kg/m^3]

Concrete for civil engineering constructions								
Mix	**0/8 Fresh**	**0/8 RAP**	**8/16 Fresh**	**8/16 RAP**	**Water**	**Cement**	**Super plasticizers**	**Air**
8	938	0	866	0	184.5	410	3.4	1.3
9	938	0	649.5	205.5	184.5	410	3.4	1.3
10	938	0	433	410.5	184.5	410	3.4	1.3
11	703.5	216	866	0	184.5	410	3.4	1.3
12	469	432	866	0	184.5	410	3.4	1.3
13	703.5	216	649.5	205.5	184.5	410	3.4	1.3
14	469	432	433	410.5	184.5	410	3.4	1.3

Figure 17 Cross section mix 1-7

Figure 18 Cross section mix 8-14

8 Test methods used in the study

In this chapter, the laboratory tests during the study are described.

8.1 Concrete preparation

During the mixing of concrete, a 100 litres drum mixer was used to produce the concrete. All tests were performed at the concrete laboratory at Chalmers Technical University, Gothenburg. The following procedure was used for all mixes.

1. Water, aggregate, admixture and cement were weighted and corrected for the moisture content according to the recipes in chapter 7.1. For each mix, 20 litres of concrete were prepared for casting.
2. Aggregate and cement were mixed in the drum mixer for 1 minutes.
3. Water and admixture were added, and the concrete was mixed for 2 minutes
4. Slump tests were performed at 5, 30 and 60 minutes. On the reference mix, superplasticizer was added to reach an S4 consistency at the first slump test at 5 minutes. When S4 was reached, the superplasticizer was held at a constant value for the rest of the mixes.
5. A plastic cover was used to cover the drum between the slump tests. This to simulate the environment in a concrete truck during transportation.

Figure 19 Drum mixer

Figure 20 Preparation before mixing

8.2 Specimen preparation

After the last slump test, the concrete mixes were used to cast cubes and prisms according to standards SS 12390-1 and SS 12390-2:

1. Molds were filled halfway and vibrated for about 20 seconds.
2. Molds were filled and vibrated an additional 20 seconds.
3. The specimens were covered by plastic for 24 h to avoid excessive loss of moisture.
4. Specimens were removed from molds and were marked with mix number and the day of the cast.
5. Specimens were cured in a water tank until strength test.

Figure 21 Cube casting

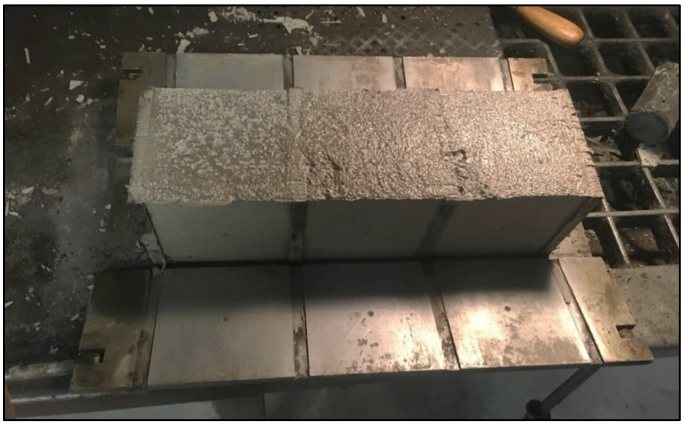

Figure 22 Removing cubes from molds

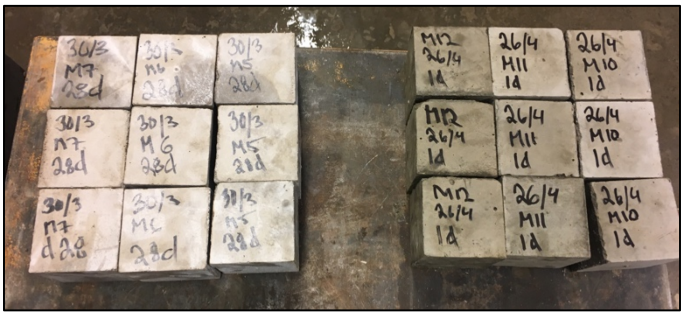

Figure 23 Concrete cubes

8.3 Fresh concrete

In this section, the test methods used to evaluate the fresh concrete is described.

8.3.1 Workability test

To evaluate the workability of the concrete mixes, a slump test was performed. Since the workability is difficult to measure, the slump test is evaluating the consistency which is related to workability.

The test aims to create a concrete cone and measure the height it will lose when the slump cone is ablated. A high slump value is indicating a looser and more workable mix. A lower slump value indicates a stiffer and less workable mix. The slump test is used in the interval 10-210 mm and shouldn't be used when aggregate larger than 40 mm is used. The test was carried out according to the latest SS-EN 12350-2 standard.

Equipment's
To evaluate the slump test, following equipment's were used:

- Slump cone
- Slump baseplate
- Slump rod
- Ruler
- Scoop
- Timer

Procedure
1. The slump cone was moisturized and was set on the baseplate
2. The slump cone was filled by three layers. Each layer was a third of the height. Each layer was tamped by the slump rod 25 times.
3. The cone was carefully removed.
4. The slump was measured. The slump is the distance between the top of the slumped concrete and the top level of the slump cone. The test was performed at 5, 30 and 60 minutes after the mixing of the concrete.

Figure 24 Slump test equipment's

Figure 25 Slump test

8.4 Hardened concrete

In this section, the test methods used to evaluate the hardened concrete is described.

8.4.1 Compressive strength test

To evaluate the strength of the concrete mixes with RAP, a compressive strength test was performed. The test is performed on a cube or cylinder. The aim of the test is to apply a continues load on the specimen until it fails. The test was managed and performed according to the latest SS-EN 12390-3 standard.

Equipment's
To evaluate the strength, following equipment was used:

- Concrete test cubes (100x100x100 mm)
- Compression testing machine

Procedure
1. Nine concrete cubes of each mix in chapter 7, were prepared according to standard.
2. The compressive strength was tested after 1, 7 and 28 days. Three cubes from each mix were tested.
3. Maximum load at failure was recorded, and the mean values for each mix were calculated. In addition strength correction due to the size of the cubes were applied according to standard SS 13 72 07.

Figure 26 Cubes before test

Figure 27 Compression testing machine

Figure 28 Cubes after compression test

8.4.2 Flexural strength test

To evaluate the flexural strength of the concrete mixes with RAP, a flexural strength test was performed on mix 8-14. The aim of the test is to put a continues load on concrete prisms according to a "three-point loading method" until fracture. The test was performed according to standard SS-EN 196-1. This standard is normally used to determine the strength of cement. Therefore, the result might not be accurate.

Equipment's

- Concrete test prisms (40x40x160 mm)
- Compression testing machine

Procedure

1. Six concrete prisms of each mix in chapter 7, were prepared according to standard.
2. The flexural strength was tested after 7 and 28 days. Three prisms from each mix 8-14 were tested.
3. Maximum load at failure was recorded, and the mean values for each mix were calculated.

Figure 29 Flexural strength tester

Figure 30 Concrete prisms before and after test

9 Test results

In this chapter, the test results from the laboratory tests will be presented and explained. A discussion about the result will be presented in chapter 10.

9.1 Fresh concrete

This section will present the results of the workability test for all the mixes.

9.1.1 Workability test mix 1-7 (House constructions concrete)

The slump tests for mix 1-7 showed a small increase of the slump (higher workability) when the amount of RAP as an aggregate was increased. The reference mix was at the lowest limit for an S4, 160 mm at 5 minutes. The mix 7 which has the largest amount of RAP, had a slump on the highest limit for S4, 210 mm.

The results also show that the fine and coarse RAP seems to affect the workability in the same way. Over time the slump follows the same pattern for all mixes. There was a big drop in slump and workability, between 5 and 30 minutes. Between 30 and 60 minutes, there is a smaller drop on all mixes.

During the mixing of mix 3, the amount of superplasticizer was probably measured wrong. Therefore, the slump test for this mix is not valid to compare to the other mixes where the amount was kept constant.

Table 15 Slump test mix 1-7 [mm]

Mix	RAP in the mix	Time (min)		
		5	30	60
1	reference mix	160	80	60
2	25 % CA RAP	160	80	60
3	50 % CA RAP	300*	150*	60*
4	25 % FA RAP	160	80	60
5	50 % FA RAP	180	80	70
6	25 % CA/FA RAP	170	90	80
7	50 % CA/FA RAP	210	130	100

**Not valid data, due to the wrong amount of superplasticizer was used*

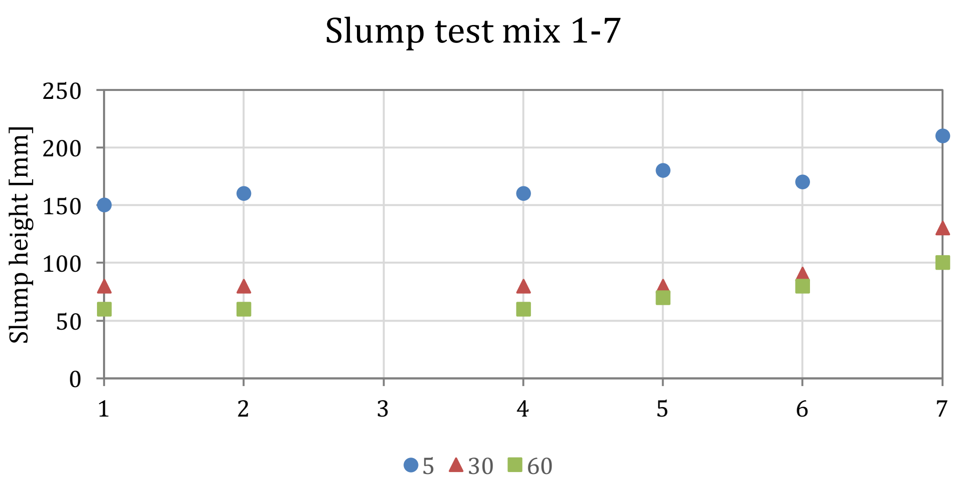

Figure 31 Slump test mix 1-7

9.1.2 Workability test mix 8-14 (Civil engineering concrete)

The slump test for mix 8-14 showed a decrease of the slump (lower workability) when the amount of RAP as an aggregate was increased. The reference mix was close to the highest limit for an S4 slump, 190 mm at 5 minutes. The mix 7 which had the largest amount of RAP, had a slump on the highest limit for S2, 90 mm.

The results indicate that the slump decreased more when fine RAP was mixed in, compared to coarse RAP. The development of the workability over time followed the same pattern for mix 10-14, where there was a big drop in workability between 5 and 30 minutes. Between 30 and 60 minutes, there was a smaller drop of workability.

However, mix 8 and 9 showed a different pattern, where there was a small change in workability between 5 and 30 minutes, and a large change between 30 and 60 minutes.

Table 16 Slump test mix 8-14 [mm]

Mix	**RAP in the mix**	**Time (min)**		
		5	30	60
8	reference mix	190	170	60
9	25 % CA RAP	180	160	70
10	50 % CA RAP	120	50	50
11	25 % FA RAP	150	70	50
12	50 % FA RAP	110	60	40
13	25 % CA/FA RAP	100	40	40
14	50 % CA/FA RAP	90	60	30

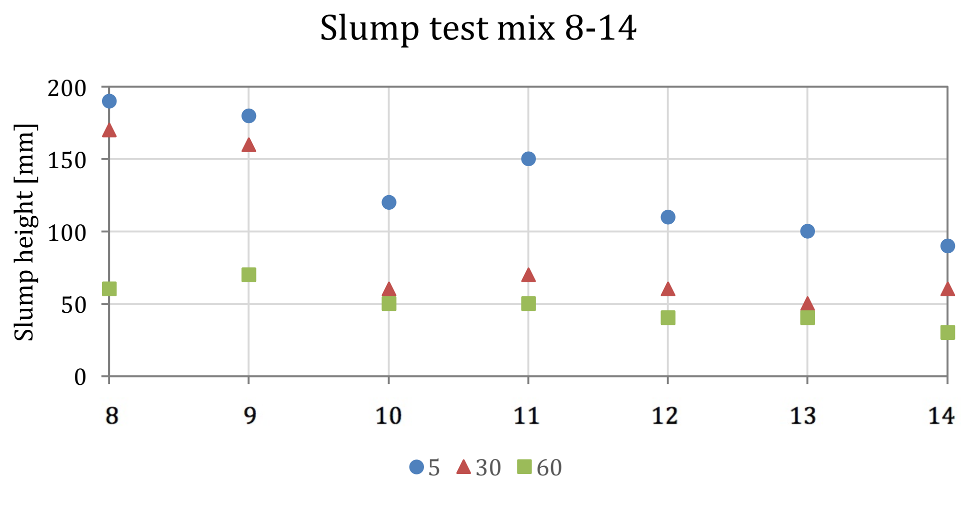

Figure 32 Slump test mix 8-14

9.2 Hardened concrete

In this section, the test results from the laboratory tests of the hardened concrete will be presented.

9.2.1 Compressive strength mix 1-7 (House construction concrete)

The results of the compressive strength tests of mix 1-7, showed that the reference mix had the strength of 43.37 MPa after 28 days, which was the highest of all mixes. On mix 2, containing 25 % coarse RAP, there was no clear change in compressive strength, compared to the reference mix. On the other mixes, there were clear indications that the compressive strength decreased when the amount of RAP increased in the concrete mix.

The fine RAP material gave a larger decrease in compressive strength, compared to the coarse RAP. The lowest compressive strength was reached in mix 7, that had 50 % of both coarse and fine aggregate was replaced with RAP, see table 17 and figure 33.

There were two mixes, in addition to the reference mix, which reached the specified compressive strength class C28/35. These were the two mixes where the coarse aggregate was replaced by 25 and 50 %, which were mix 2 and mix 3.

The strength development follows the same pattern for all mixes. There was a large development the first 24 h for all mixes, where about 50 % of the strength was reached. The development to 7 and 28 days followed almost linear increase in strength for all mixes, see figure 34.

The reduction of compressive strength, compared to the reference mix, varies between 0.3 % (mix 2) to 66.6 % (mix 7). The reductions in percentage compared to the reference mix seemed to be constant between 1,7 and 28 days, for most of the mixes. However, there is an indication on mix 7, that the early development of strength was decreased, see figure 35.

Table 17 Compressive strength mix 1-7 [MPa]

Mix	**RAP in the mix**	**Age (days)**		
		1	**7**	**28**
1	reference mix	17.68	34.03	43.37
2	25 % CA RAP	20.06	33.97	43.22
3	50 % CA RAP	13.97	27.97	35.56
4	25 % FA RAP	10.10	21.05	26.51
5	50 % FA RAP	7.52	15.05	18.29
6	25 % CA/FA RAP	8.48	17.75	22.98
7	50 % CA/FA RAP	4.60	11.75	14.48

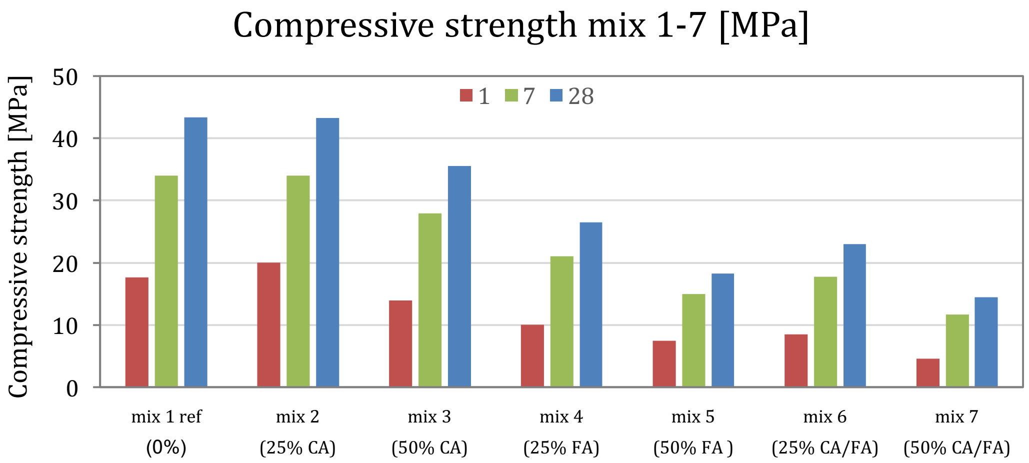

Figure 33 Compressive strength mix 1-7, (%) indicates the amount of RAP in the mix

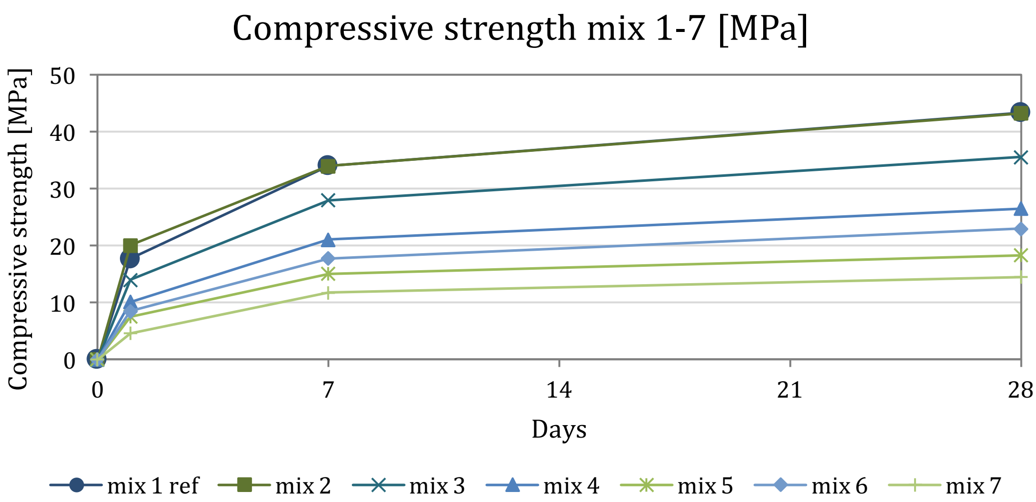

Figure 34 Compressive strength mix 1-7

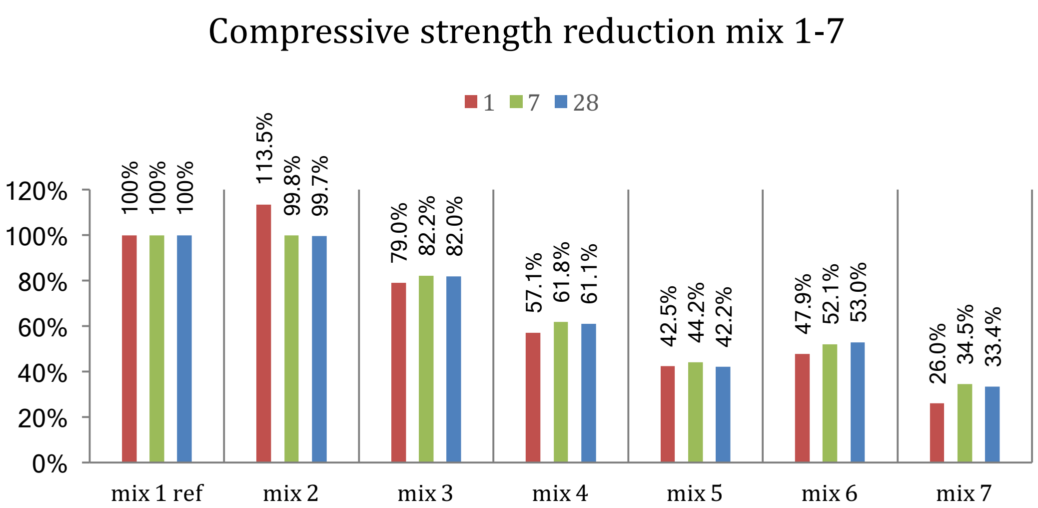

Figure 35 Compressive strength compared to reference mix in %, mix 1-7

9.2.2 Compressive strength mix 8-14 (Civil engineering concrete)

The results of the compressive strength test of mix 8-14, showed that the reference mix achieved a compressive strength of 62.35 MPa after 28 days, which was the highest of all mixes in the study. The compressive strength of the other mixes, decreased when the amount of RAP aggregate in the mix was increased, see table 18.

In this concrete type, the difference in compressive strength, when fine or coarse aggregate was replaced, was less clear than the previous concrete type. The compressive strength that was reached when 25 % of the aggregate was replaced with either coarse RAP and fine RAP were similar. The same applies to the replacement of the aggregate with either 50 % coarse and fine RAP. However, both results indicated a marginal larger decrease of compressive strength, when FA was replaced, see table 18 and figure 36.

There were five mixes, in addition to the reference mix, which reached the specified compressive strength class C32/40. The only mix that didn't reach the requirements was mix 14, which was the mix where both the fine and coarse aggregate were replaced with RAP.

The strength development followed the same pattern for all mixes. During the first 24 h, about 25 % of the compressive strength was reached. After seven days, about 80 % of the final strength was reached, see figure 37.

The reduction of compressive strength after 28 days, compared to the reference mix varies between 15.1 % (mix 2) and 44.1 % (mix 14). The reduction in percentage between 1, 7 and 28 days, was about the same for most of the mixes. However, mix 12 and mix 14 indicated a larger decrease in compressive strength, after one day compared to the reference mix. This indicated a lower strength development during the first days of these mixes, see figure 38.

Table 18 Compressive strength mix 8-14 [MPa]

Mix	**RAP in the mix**	**Age (days)**		
		1	**7**	**28**
8	reference mix	17.05	49.59	62.35
9	25 % CA RAP	14.25	42.25	52.92
10	50 % CA RAP	14.70	36.32	44.79
11	25 % FA RAP	13.30	40.41	50.54
12	50 % FA RAP	8.63	33.94	42.76
13	25 % CA/FA RAP	11.71	35.52	43.75
14	50 % CA/FA RAP	7.59	28.16	34.83

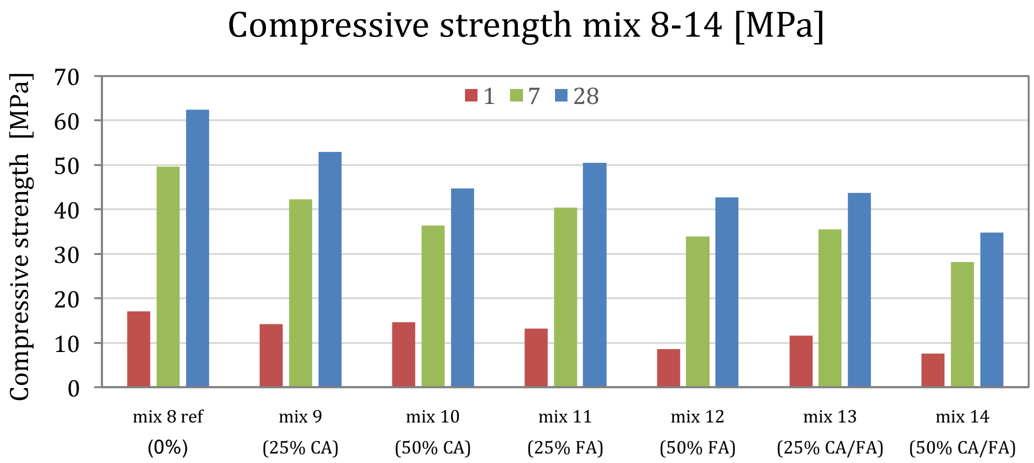

Figure 36 Compressive strength mix 8-14, (%) indicates the amount of RAP in the mix

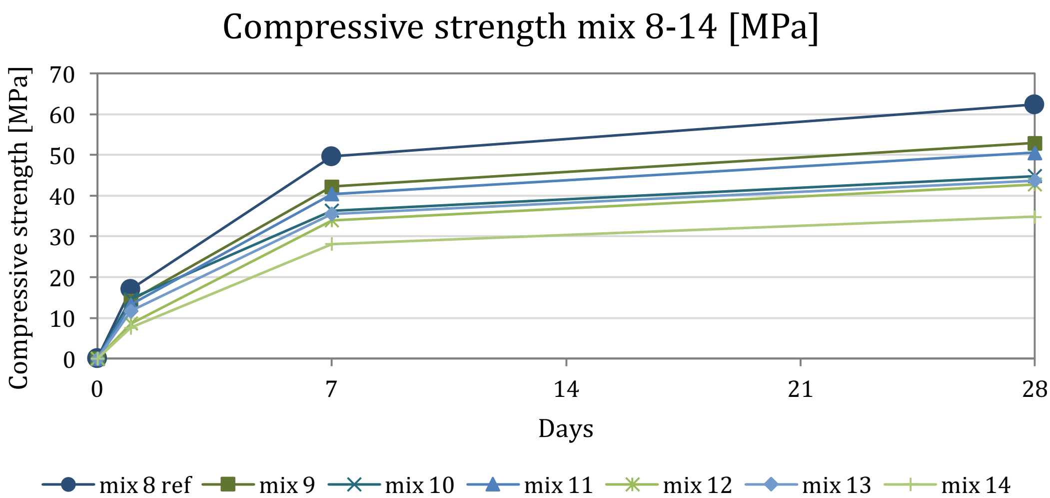

Figure 37 Compressive strength mix 8-14

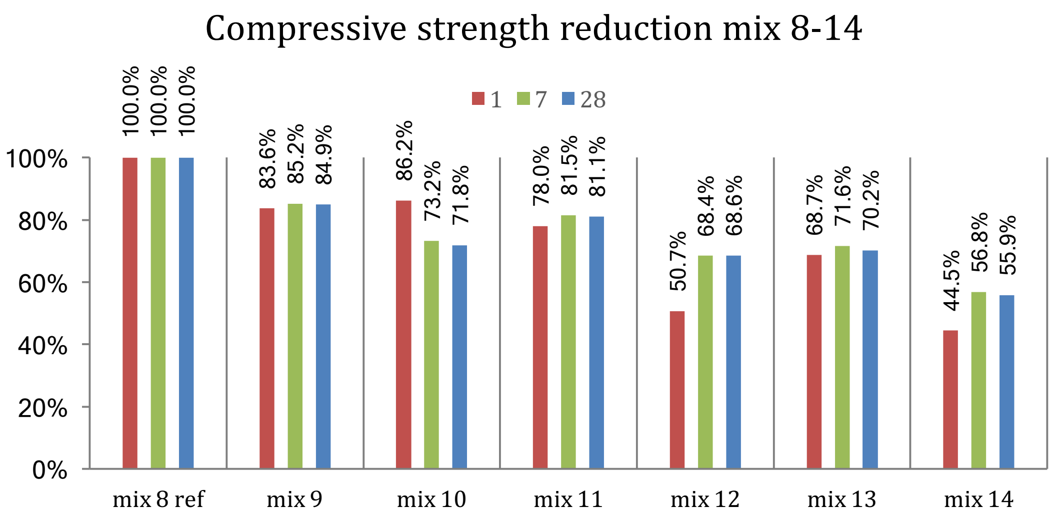

Figure 38 Compressive strength compared to reference mix in %, mix 8-14

9.2.3 Flexural strength mix 8-14 (Civil engineering concrete)

The flexural strength test for mix 8-14, showed that the reference mix had the highest strength after 28 days, that was 8.8 MPa. Mix 9 that had 25 % of the CA replaced with RAP, showed the same flexural strength as the reference mix. The rest of the mixes showed a decreased strength when the amount of RAP was increased.

The fine RAP indicated a larger decrease in flexural strength, than the coarse RAP. The largest reduction in strength was in the mix with both 50 % fine and coarse RAP material, which was mix 14, see table 19 and figure 39.

The strength development followed the same pattern for all mixes. At day seven, 80-90 % of the final flexural strength was reached, see figure 40.

The reduction of flexural strength at 28 days, compared to the reference mix, varied between 0 % (mix 9) and 21 % (mix 14). The reduction in percentage, compared to the reference mix, was lower during day 7, compared to the day 28. This indicated a lower early flexural strength development on the mixes that contained RAP aggregate, see figure 41.

Table 19 Flexural strength mix 8-14 [MPa]

Mix	**RAP in the mix**	**Age (days)**	
		7	**28**
8	reference mix	7.9	8.8
9	25 % CA RAP	6.4	8.8
10	50 % CA RAP	6.5	8.4
11	25 % FA RAP	7.0	8.0
12	50 % FA RAP	6.4	7.9
13	25 % CA/FA RAP	7.0	7.7
14	50 % CA/FA RAP	5.4	6.9

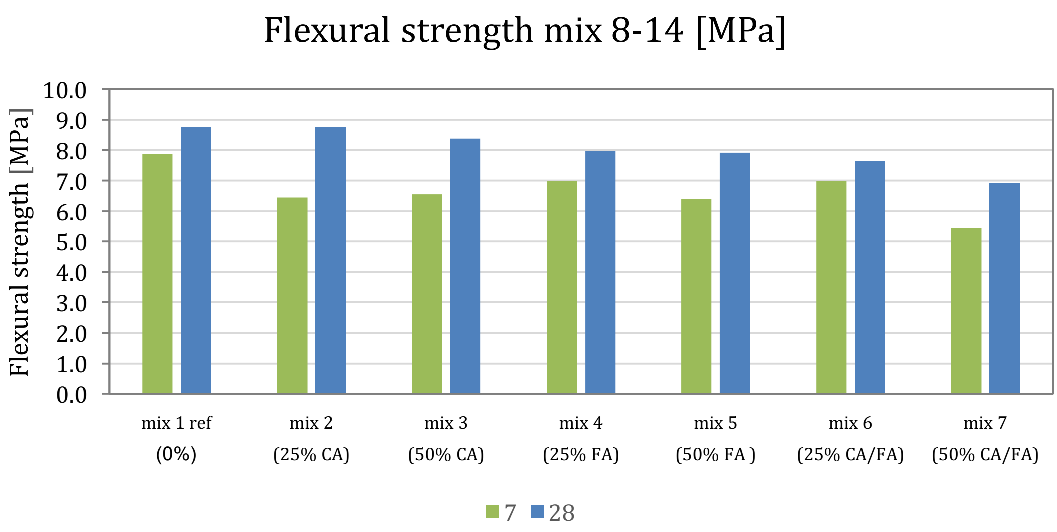

Figure 39 Flexural strength mix 8-14, (%) indicates the amount of RAP in the mix

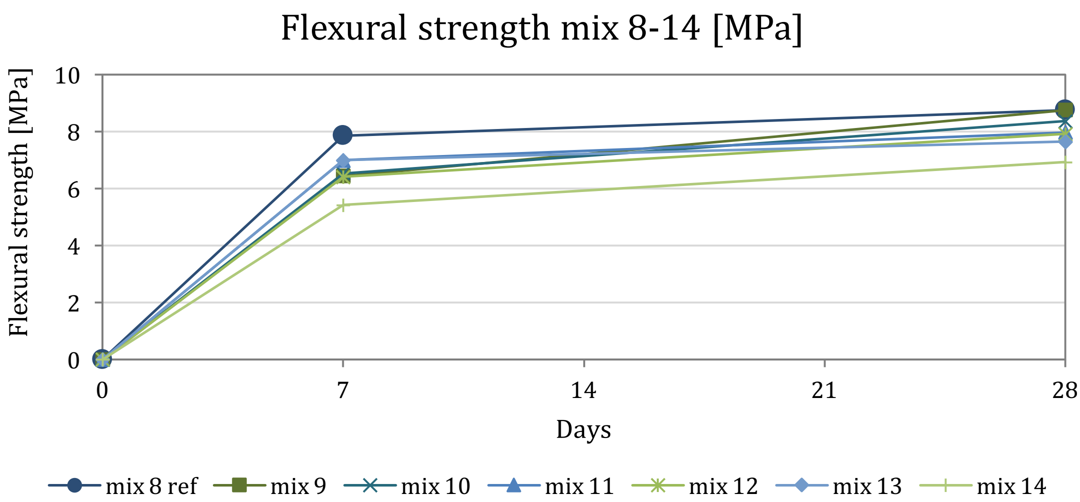

Figure 40 Flexural strength mix 8-14

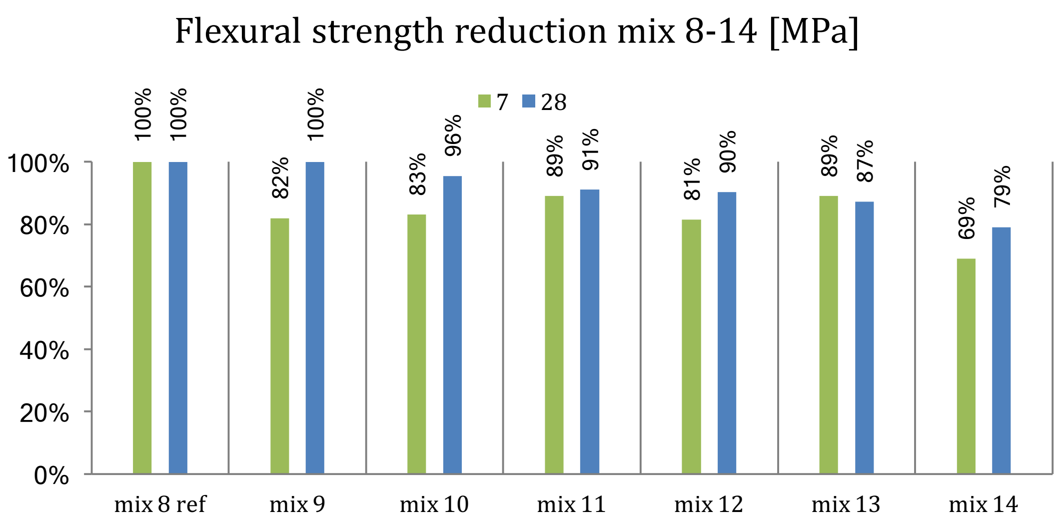

Figure 41 Flexural strength compared to reference mix in %, mix 8-14

10 Discussion of test results

During the study, different aspects of the RAP aggregate were evaluated. First of all, the properties of the RAP material were investigated. Just like concrete aggregate, aggregate in asphalt pavements is made from a stone material with high strength and good quality. Therefore, the strength of the rock is not a factor when evaluating how concrete is affected when using RAP as an aggregate.

However, as the review of earlier studies indicated, the binder content is affecting the strength of the concrete since it decreases the bonding between the aggregate and the cement paste. The RAP material used during my study had binder content of 4.55 % and 2.57 % for the fine RAP and coarse RAP respectively. This is in line with earlier studies of binder content of Swedish RAP material.

The gradation of the RAP aggregates showed that the RAP material is well graded and contain most of the fractions. The coarse RAP was similar to the coarse fresh aggregate. The fine RAP less similar to the fresh material and contained less amount of fine material.

Absorption is an important property during mixing and casting of concrete. The RAP sample used in the study had an absorption of 0.4 % for the fine RAP and 0.5 % for the coarse RAP. This is low and similar the fresh aggregate that had 0.3 % absorption for both fractions. The small difference indicates that absorption, would not be an issue if RAP aggregate was used in concrete.

However, the RAP used in the study was only from one RAP sample, which originated from full-depth masses from the Gothenburg region. Whether properties like binder content, strength, absorption, gradation, etc. differ between different pavements, areas and samples is not further investigated which could affect the results.

During the study, concrete mixes that contained RAP aggregate were cast. The mixing and casting of these mixes were easy to perform, and there were no difficulties, to handle RAP aggregate compared to the fresh aggregate.

A slump test was performed on all mixes to evaluate the workability of the concrete. The results for mix 1-7 showed a small increase of the slump (increased workability) when the amount of RAP in the mix was increased. There was no clear difference in workability, between coarse and fine replacement.

During workability test of mix 8-14, there was in contrast to mix 1-7, a small decrease in workability when more RAP was added to the mix. The result also showed that the fine aggregate affected the workability more. The reason for the different results, between the two concrete types, could be related to many factors. One could be, that the replacement of fresh aggregate with RAP was done by weight in the first concrete mix. In the second, the replacement was done by volume, to eliminate one source of error.

The different results could also be due to a uniform moisture content in the RAP aggregate. The moisture content that was used was a mean value measured on a couple of samples, but they might not be representative of all material used in the study. One way to improve the results could be too dry all the aggregate material to oven-dry state, before mixing.

However, most of the earlier studies, have shown a decrease in workability, with an increased amount of RAP in the mix, which means that the results from the second concrete mix are most trustworthy.

In the study, the compressive strength of nine cubes of each concrete mix was tested. In the concrete for house constructions, mix 2 that had 25 % CA RAP, didn't show any reduction in strength. The rest of the mixes indicated a clear reduction in strength when the amount of RAP was increased in the mix. The reduction of strength was expected, since earlier studies explained a decreased bonding between the stone and the cement, due to the binder content.

The replacement with fine RAP had a larger effect on the strength than the coarse RAP. However, since the recipe contained 85 % FA and the 15 % CA by weight, the amount of RAP that was added was not the same. Therefore, the source of the difference in reduction is not clear from these results.

The compressive strength results for mix 8-14, showed the same pattern as the previous concrete type. Which was a lower compressive strength, with a larger amount of RAP content in the mix. The difference between replacing fine or coarse aggregate was less in these mixes. The reason for this is probably due to the recipe contains almost the same amount of fine and coarse aggregate.

The strength development followed the same pattern for most of the mixes, where the strength in percentage, compared to the reference mix, was steady. However, there was an indication on both mix 7, 12 and 14, that the strength development at 24 h was lower. All these mixes contained 50 % fine RAP and this could be an indication of that the fine aggregate decreased the early development of strength.

The strength reduction, compared to the reference mix, showed a larger decrease in the first concrete mix. The largest reduction, of 66.5 %, was found in mix 7 that contained 50 % fine and coarse RAP. In the second concrete type, the reduction was also largest at the mix with 50 % fine and coarse RAP, mix 14. But the reduction was only 44.1 %. This, data confirmed the finding that fine RAP gave a larger reduction in strength since the housing concrete had a larger part FA.

When looking at the compressive strength classes, that the concrete recipes were aiming for, both reference mixes showed a large margin to the limit. The concrete for house constructions was a C28/35 concrete, and the reference mix reached a strength of 43.37 MPa after 28 days. The civil engineering concrete was a C32/40 concrete, and the reference mix reached a strength of 62.35 MPa after 28 days. The large margin and the less reduction in strength led to that the civil engineering concrete reached the desired strength on all mixes unless mix 14. For the housing concrete, there were only the two mixes with 25 and 50 % coarse RAP aggregate, that reached the desired level of strength. To counteract the reduced strength, when RAP is used in concrete, the w/c ratio or the amount of RAP in the mixed could be adjusted to achieve the desired strength.

In the study, a flexural strength test was also performed. The test method is normally not used for concrete but gave an indication of how the flexural strength is affected by RAP. The results of the tests indicated a similar reduction in strength as the compressive strength tests. The strength decreased when more RAP was added to the mix. There was also an indication that the fine RAP decreased the flexural strength more than coarse RAP.

As described in the report, the aggregate is a limited resource that needs to be used in a sustainable way. Whether RAP aggregate in concrete is a sustainable option is depending on many factors. In my opinion, the best use of RAP is within new asphalt pavements. This since both the stone material and the binder is reused within the new construction. However, other options should be evaluated during periods when there is a low demand for asphalt pavements or periods when large masses are reclaimed. This since putting RAP on landfill is both unstainable according to the waste management hierarchy and could also be costly due to charges.

Another point that could be a benefit of using RAP in concrete is synergies between the concrete and asphalt pavements production. In Gothenburg, Skanska's asphalt and concrete plant are situated at the same site, and this is the situation in many other places. This enables an easier cooperation between the two production units in terms of recycled aggregate.

To summarise my study, using RAP as an aggregate in concrete, is possible according to compressive strength, workability and the properties of the aggregate. All these properties vary from regular aggregate and concrete. But if they are known, the concrete mix could be adjusted, so the desired quality could be reached.

However, in the Swedish standard, there is no possibility to use RAP material as a recycled aggregate today. In the standards, there is a possibility to use recycled aggregate that contains up to 5 % bituminous material, see chapter 5. This means that the RAP material can be used in this aspect. But, there is also requirements that recycled aggregate needs to contain recycled concrete material which means that there is not possible to use RAP aggregate or other unbound recycled aggregates alone. This should in my opinion be reviewed in the standards, to see if there are possibilities to broaden the options to use recycled aggregates from different sources.

However, before that is possible, there are physical and chemical requirements that need to be fulfilled for aggregates. These requirements have not been evaluated on RAP aggregate in this report. There is a need to investigate these requirements and how other concrete properties are changed when RAP is used as an aggregate.

11 Conclusion and future recommendations

During the study, there were some key findings that could be used for further studies on the subject. Some of them confirm earlier studies on the subject, and some are specific findings for this study.

1. RAP material is similar to fresh aggregate in many aspects. The material is well graded, has similar unit weight and has low water absorption.
2. RAP aggregate can be mixed in the same way as fresh aggregate, and there were no difficulties during casting and testing of the concrete.
3. The compressive strength decreases when the amount of RAP aggregate is increased in the mix. Adding fine RAP aggregate to the mix decreases the compressive strength more than the coarse RAP aggregate.
4. In the concrete recipe for house constructions, that was evaluated in this study, 25 % coarse RAP could be used, with no effect on the compressive strength. In addition, 50 % coarse RAP could be added to the concrete mix, and still be within the compressive strength class C28/35.
5. In the concrete recipe for civil engineering construction, that was evaluated in this study, 50 % coarse RAP or 50 % fine RAP or 25 % coarse and fine RAP could be added to the concrete mix, and still be within the compressive strength class C32/40.
6. There are indications of that fine RAP aggregate decreases the early development of compressive strength.
7. The flexural strength decreases when the amount of RAP in the concrete mix is increased. The fine RAP aggregate affects the strength more than the coarse RAP aggregate.
8. Using RAP in concrete is a sustainable option compared to landfill in terms of the waste hierarchy management model.
9. There is possible to use recycled aggregate in concrete according to the latest aggregate standard in Sweden. However, the standard is not enabling recycled aggregates from RAP.

This study was an initial study of this subject, and there is a need to broaden the knowledge. My recommendation for the future is that the recycled aggregate from RAP should be studied further. This to see how the material meets the physical and chemical requirements in the national aggregate standards, but also how RAP properties can vary between samples. The studies could enable a change in the standards, concerning recycled aggregate, and broaden the possibility to use unbound recycled aggregates.

This knowledge will enable the use of RAP in concrete in the future, which has many benefits. First of all, this will increase the sustainability of the aggregate industry. Second, reusing construction materials within construction projects is requested. National regulations intend to reuse 70 % of the construction materials in 2020. In addition, environmental assessment and ratings of constructions projects, encourage reuse of materials. Third, even though the best use of RAP is within new asphalt pavement, options is needed. This to enable a more efficient and more sustainable aggregate industry.

12 Suggestions for future studies

During my research, only some of the properties of concrete and RAP aggregate were evaluated. Additional studies of the RAP material in Sweden would be interesting. In this study, the properties of the material could be investigated and which of these that affect the feasibility as an aggregate in concrete.

The feasibility to use RAP in concrete is dependent on what the option is. There would be interesting to compare the use of RAP in new asphalt pavements and concrete in aspects of cost, environmental impact, transportation needs, etc. This to find out when RAP in concrete is a good option or not.

There is also a need to evaluate the RAP concrete further and see how different concrete recipes are affected by the RAP aggregate. This, along with earlier studies, would enable a deeper understanding how concrete recipes needs to be adjusted to meet the strength requirements, workability requirements, etc.

13 References

Agardh, S. (2016). *Road engineering - Introduction of course VMT060.* Göteborg.

Asphalt Recycling and Reclaiming Association. (2001). *Basic asphalt recycling manual.* -: Federal Highway Administration.

Berry, M., Stephens, J., Bermel, B., Hagel, A., & Schroeder, D. (2013). *FEASIBILITY OF RECLAIMED ASPHALT PAVEMENT AS AGGREGATE IN PORTLAND CEMENT CONCRETE.* Montana: Montana State University.

Bleischwitz, R., & Bahn-Walkowiak, B. (2006). Sustainable Development in the European aggregates industry. Berlin.

Brand, A. S., & Roesler, J. R. (2016). Bonding in cementitious materials with asphalt-coated particles: Part I – The interfacial transition zone. *Construction and Building Materials*. Urbana, USA.

Brand, A. S., & Roesler, J. R. (2016, 6 28). Bonding in cementitious materials with asphalt-coated particles: Part I – The interfacial transition zone. *Construction and building materials*.

Burström, P. G. (2006). *Byggnadsmaterial.* Lund: Studentlitteratur AB.

Cementa AB. (2017). *Cementa*. Retrieved from Our products: http://www.cementa.se/en/Products

de Brito, J., & Saikia, N. (2013). *Recycled Aggregate in Concrete - Use of Industrial, Construction and Demolition Waste.* Lisbon: Springer.

European aggregates association. (2016). *A Sustainable Industry for a Sustainable Europe - An annual review 2015-2016.* Brussels.

European asphalt pavement association. (2017). *Asphalt in figures.* Retrieved from EAPA: http://www.eapa.org/userfiles/2/Asphalt%20in%20Figures/2016/AIF_2015_v6.pdf

European asphalt pavement association. (2017). *What is asphalt*. Retrieved from http://www.eapa.org/promo.php?c=173

Eurostat. (2016). *Material flow accounts - flows in raw material equivalents*. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Material_flow_accounts_-_flows_in_raw_material_equivalents

Federal Highway Administration. (2017). User Guidelines for Waste and Byproduct Materials in Pavement Construction.

Gröndahl, F., & Svanström, M. (2011). *Hållbar utveckling - en introduktion för ingenjörer och andra problemlösare.* Stockholm: Liber AB.

Hassan, K. E., Brooks, J., & Erdman, M. (2000). *The use of reclaimed asphalt pavement (RAP) aggregates in concrete.* Leeds: Elsevier Science Ltd.

Helsing, E. (2015). Större möjligheter att använda återvunna material i betong med nya SS 137003. *CBI nytt*(nr 2).

Hossiney, N., Tia, M., & Bergin, M. J. (2010). *Concrete containing RAP for use in concrete pevements.* Gainsville.

Huang, B., Shu, X., & Li, G. (2005). Laboratory investigation of Portland cement concrete containing recycled asphalt pavements.

Jacobson, T. (2002). *Återvinning av krossad asfalt som bär- och förstärkningslager, Del 1.* Linköping: Väg- och transportforskningsinstitutet.

Khatib, J. M. (2016). *Sustainability of construction materials.* Woodhead Publishing.

Khodair, Y., & Raza, M. (2016, 6 8). Sustainable self-consolidating concrete using recycled asphalt pavement and high volume supplementary cementitious materials. *Construction and building materials*.

Miljöförvaltningen Göteborgs Stad. (2017). *Miljöförvaltningen.* Retrieved from Faktablad: https://goteborg.se/wps/wcm/connect/804bd979-44fc-4c72-bc87-5dfd0d128b25/Faktablad_miljo_HanteraAsfaltOchTjarasfalt.pdf?MOD=AJPERES

Miljömål.se. (2016). *Sveriges miljömål.* Retrieved from Miljömålen: http://www.miljomal.se/sv/Miljomalen/

Neuwald, A. D. (2008). *Water-to-Cement Ratio and Aggregate Moisture Corrections.* Retrieved from National precast concrete association: http://precast.org/2010/05/water-to-cement-ratio-and-aggregate-moisture-corrections/

Nordisk vägforum. (2017). *nvfnorden*. Retrieved from nvfnorden: http://www.nvfnorden.org/library/Files/Utskott-och-tema/Belaggning/Brosjyre/NVF_se.pdf

Okafor, F. O. (2010). *Performance of recycled asphalt pavements as coarse aggregate in concrete.*

Palm, D., Sundqvist, J.-O., Jensen, C., Tekie, H., Fråne, A., & Ljunggren Söderman, M. (2015). *Analys av lämpliga åtgärder för att öka återanvändning och återvinning av bygg- och rivningsavfall.* Bromma: Naturvårdsverket.

SGU. (2017, 02 13). *Swedish aggregates production*. Retrieved from Geological Survey of Sweden: http://www.sgu.se/en/physical-planning/rock-materials-for-construction/swedish-aggregates-production/

Swedish environmental protection agency. (2012). *http://www.swedishepa.se.* Retrieved from http://www.swedishepa.se: http://www.swedishepa.se/Documents/publikationer6400/978-91-620-8620-6.pdf

Swedish environmental protection agency. (2016). *Lagar och regler om avfall*. Retrieved from Stöd i miljöarbetet: http://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Avfall/Lagar-och-regler-om-avfall/

Svensk Byggtjänst. (2017). *Betonghandbok material del 1.* Stockholm : Svensk Byggtjänst AB.

Svenska Betong. (2016). *Betongindikatorn.* Retrieved from Betongindikatorn: http://www.svenskbetong.se/images/Betongindikatorn/2016/Betongindikatorn_jan-dec_2016.pdf

Svenska Kommunförbundet. (2004). *På väg igen - Vägen tillbaka för återvunnen asfalt.* Stockholm: Svenska Kommunförbundet.

The Swedish Transport Administration. (2015). Bitumenbundna lager.

Thomas, M. (2007). *Optimizing the Use of Fly Ash in Concrete.* Retrieved from http://www.cement.org: http://www.cement.org/docs/default-source/fc_concrete_technology/is548-optimizing-the-use-of-fly-ash-concrete.pdf

Trafikverket. (2015, 12 31). *Gröna koncept inom asfaltbeläggningar.* Retrieved from https://trafikverket.ineko.se/Files/sv-SE/11696/RelatedFiles/2015_276_grona_koncept_inom_asfaltbelaggningar.pdf

World Business Council for Sustainable Development. (2009). Recycling Concrete Executive summary. Conches-Geneva, Switzerland.