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Characterization of bottom ash from municipal solid waste incineration as a possible element in concrete

Investigation of the compressive strength and leaching properties

Master of Science Thesis in the Master Degree Program,
Innovative and Sustainable Chemical Engineering

LINA HANSSON

Department of Chemistry and Chemical Engineering
Research group Nuclear Chemistry and Industrial Materials Recycling
CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER’S THESIS 2017

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Examiner and Supervisor: Britt-Marie Steenari, Industrial Materials Recycling
Supervisor: Rikard Ylmén, Industrial Materials Recycling

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Department of Chemistry and Chemical Engineering
Division of Energy and Materials
Research group Nuclear Chemistry and Industrial Materials Recycling
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: The front of the picture shows bottom ash from incineration of municipal solid waste and the background shows one casted concrete cube with bottom ash.
Photo: Lina Hansson 2017-06-09

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ABSTRACT

There is an increasing need for new areas of application for bottom ash from incineration of municipal solid waste. The reason is that the use of bottom ash in today's applications decreases because the coverage of landfills soon is going to be completed. One possible area of use for the bottom ash may be in concrete. This was the main focus of this project, where the aim was to investigate the opportunity of using bottom ash from municipal solid waste incineration as a potential substitute to cement or aggregate in concrete. The purpose was also to find a pre-treatment method for the bottom ash with a particle size less than 5 mm so the fraction in the ash can be used in concrete.

The used bottom ash was first characterized to evaluate the opportunity of using it in concrete. The characterization was performed by different approaches; sieving, X-ray powder diffraction, isothermal calorimetry, leaching and determination of the concentrations of some selected elements in the bottom ash. The characterization was followed by casting concrete cubes with different amount of bottom ash included as replacement for aggregate.

The result showed that the compressive strength of concrete with added bottom ash decreased compared to the reference, where 100 percent replacement with bottom ash as aggregate gave less than half the strength compared to the reference. It seems that this mostly depends on the extra water that is needed for the concrete mixture with added bottom ash. One of the concrete cubes with added bottom ash was also broken during the hardening time and further investigations are needed to avoid this. The element concentrations in the bottom ash and the amounts released from the bottom ash in a water leaching test were compared with Naturvårdsverket's limits for waste that is intended to be used in construction works. It showed that the concentrations of seven elements and three leached elements were higher than the limit values, which means that the used bottom ash in this study cannot be used in construction works without a permission investigation or further pre-treatments.

Keywords: Bottom ash, Recycling, MSW, MSWI, Concrete, Cement

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CONTENTS

ABBREVIATIONS

BA	Bottom ash
C/A	Cement/aggregate ratio
<DL	Under limit of detection
DS	Dry substance
ICP-MS	Inductive Coupled Plasma with Mass Spectrometry
ICP-OES	Inductive Coupled Plasma with Optical Emission Spectrometry
L/S	Liquid to solid ratio
MSW	Municipal solid waste
MSWI	Municipal solid waste incineration
n.d.	Not detected
w/c	Water cement ratio
XRD	X-ray powder diffraction

1 INTRODUCTION

This project has been dealing with the issue regarding the usage of bottom ash when the need in today's applications decreases. The thesis has investigating the opportunity of trying bottom ash as a possible element in concrete.

1.1 Background

Every year more than 4 million tons of Municipal Solid Waste (MSW) is treated by different waste management methods in Sweden (Avfall Sverige, 2016). The amount of treated MSW 2015 was 4.7 million tons, an increase with 4 percent compared to the year before. This gave an average amount of 478 kg MSW per person. The waste is treated in different ways; by material recovery, biological recovery, energy recovery in the form of incineration or landfilling. In Sweden almost 50 percent of the MSW is treated by incineration, which makes this the most common treatment method. The incineration reduces the volume of the waste by up to 90 percent and the mass by up to 80 percent (Zhang & Zhao, 2014). In Sweden the incineration of MSW is an important part of the district heating system, where 17 TWh was recovered 2015 (Avfall Sverige, 2016). However, the incineration gives by-products, in the form of fly ashes and bottom ashes (BA) (Forteza et al., 2004). For every tonne of waste that is incinerated, around 200-300 kg of ash is formed, where the bottom ash is the major part with 80-95 percent of the total ash amount (Avfall Sverige, 2016; Ginés et al., 2009; Izquierdo et al., 2002).

The incineration generates large amounts of ash that needs to be handled every year (Ginés et al. 2009). The bottom ash that is created from MSW is in Sweden to a large extent used in construction materials on waste facilities, for example as coverage of landfills (Hedenstedt, 2015). However, the need of bottom ash in this type of applications decreases because the covering of landfills is going to be completed in the next few years. Therefore there is a need for new application areas where bottom ash can be used, both from an environmental and a management view. Stena Recycling AB is therefore looking for new alternatives where bottom ash can be used. One possible area to use bottom ash is in concrete, which for example has been studied by Ginés et al. (2009) and Zhang & Zhao (2014).

1.2 Objectives of the project

The aim of the project was to characterize bottom ash from municipal solid waste to understand how it can function as a potential substitute for cement or aggregate in concrete. The intention was also to find a pre-treatment method which treats bottom ash with particle size smaller than 5 mm so that this fraction can be used in concrete.

2 THEORY

2.1 Bottom ash

This part describes how the bottom ash is generated, the characteristics of bottom ash, leaching properties for waste intended to be used in construction works, different available pre-treatment methods existing for bottom ash and how they are used in construction works today.

2.1.1 Incineration

Incineration of municipal solid waste is, as mentioned before, the most common way to handle waste in Sweden (Avfall Sverige, 2016). The combustor type most commonly used for the incineration of waste is grate boilers, because of their simple and robust technology and because they require minimal pre-sorting and reduction of the waste size (Naturvårdsverket, 2005; Karlfeldt Fedje, 2010). A grate boiler consists of a grid of iron rods with open structures which air is flowing through to increase the combustion rate (Naturvårdsverket, 2005; Svensk energy, 2011). The grid can be leaned or the rods can be moveable, so that the waste can be move forward during the incineration and new waste can be supplied to the grate boiler. The fly ash that is generated from the combustion is rising in the flue gas channel, while the created bottom ash is discharged at the end and bottom of the boiler (Thunman, 2016). Most often the bottom ash is collected in a water tank, a so called quenching tank, to cool down the material, but can also be collected dry (Astrup et al., 2016). Tang et al. (2015) reported a water content of 12-25 % in bottom ash that has been quenched. The disadvantage with the quenching is that the particles in the bottom ash agglomerate and form glassy components, which makes the recycling more difficult (Astrup et al. 2016). After combustion the bottom ash is landfilled or processed for further usage, the type of utilization depending on in which country the bottom ash is generated. The processing methods will be described later in the "pre-treatment methods" (paragraph 2.1.4).

2.1.2 Characteristics of bottom ash

Bottom ashes from incineration of waste often have similar characteristics, although the inputs of the waste to the boilers can vary hugely (Astrup et al., 2016). The bottom ash that is generated can be characterized as heterogeneous and consists of particles with different sizes. It contains noncombustible inorganic residuals (glass, minerals, metals and metal alloys), unburned organic materials and melted materials (glasses, silicate minerals and oxide minerals) (Chimenos et al., 1999; Astrup et al., 2016). The melted part of the bottom ash often contains metals impurities, which makes the recycling more difficult. The distribution of the different quantities in the bottom ash are usually 50-75 % minerals, ferrous metals (5-13 % iron and steel), nonferrous metals (mainly aluminum and stainless steel), heavy nonferrous metals (mainly copper and zinc in 2-5 %), 15-30 % relict glass and ceramic particles and 0.2-5 % unburned organic materials (Astrup et al., 2016). The mineral fraction consists mainly of granular material but can also contain large merged lumps and is characterized as partially amorphous. Chimenos et al. (1999) reported that the main crystalline components in the mineral fraction are quartz (SiO_2), calcium carbonates ($CaCO_3$), lime (CaO) and feldspars ($CaO \cdot Al_2O_3 \cdot 2SiO_2$, anorthite). The particle size distribution of the bottom ash has been reported to be equal to the size distribution of sandy gravel, with lower than 5 weight% of particles of a size larger than 40 mm and a low fraction of the finer particles with a size smaller than 63 µm (Izquierdo, Querol & Vazquez, 2011).

The mineral fraction and the metal fraction of the bottom ash have a recycling potential, where the mineral fraction may be used as an aggregate or be inserted in cement, concrete or asphalt (Astrup et al., 2016). These potential applications will be described later, in the part "bottom ash as possible aggregates" (paragraph 2.1.6).

The ash that is generated from the combustion contains most of the elements found in society and they are distributed between the bottom ash and the fly ash. The bottom ash has often a lower concentration of metals compared to the concentrations in the fly ash (Chandler et al., 1997). The inorganic content of the bottom ash depends on the type of waste that is combusted, type of boiler and the conditions during the combustion, but the concentrations of elements are usually in the same range (Astrup et al., 2016). The major inorganic elements in bottom ash are aluminum, calcium, iron, potassium, magnesium, manganese, sodium, phosphorus and silicon. Many of these elements occur often in a range of 1000 mg/kg or higher, up to some 100000 mg/kg has been reported for some of these elements (Allegrini et al., 2014; Morf et al., 2013; Sabbas et al., 2003; Funari et al., 2016). Other elements which are common in bottom ash but in smaller amounts are elements of potential environmental concern, like; arsenic, barium, cadmium, copper, chromium, molybdenum, nickel, lead, tin, titanium, vanadium and zinc. Some other elements, like rare earth elements and precious and critical elements may also follow the bottom ash but often in very small amounts. Chlorides and sulfur are also important inorganic elements existing in the bottom ash (Astrup et al., 2016).

2.1.3 Leaching

The bottom ash contains many elements that are of potential environmental concern, but according to Kosson et al. (2002) the total amount of elements is not the critical part, but the potential of the leaching during usage and storage. It has been shown that the leaching properties and the total amount of inorganic elements do not have any correlation except for soluble salts (Hyks, Astrup & Christensen, 2009). The leaching properties of a substance are measured with a standardized test that has been established on a European level (Astrup et al., 2016). In Sweden both the total content in the material and the content in the leachate are considered in the criteria for use of waste in a construction application. The elements that have been reported to be of largest environmental concern regarding bottom ash are copper, molybdenum, antimony, chloride and sulphates.

In Sweden Naturvårdsverket (the Swedish environmental protection agency) has developed a manual for recovery of waste intended to be used in construction works (Naturvårdsverket, 2010). The handbook handles 13 elements with concentration limits both for the pure material and the leachate from the waste. The limits are shown in Table 1 and refer to levels less than low risk, which represents an insignificant risk.

Table 1. Low risk concentrations for recycled waste intended for construction works (Naturvårdsverket, 2010).

Element	Concentration in mg/kg DS	Leaching L/S = 10 l/kg (mg/kg)
As	10	0.09
Cd	0.2	0.02
Cr total	40	1
Cu	40	0.8
Hg	0.1	0.01
Ni	35	0.4
Pb	20	0.2
Zn	120	4
Cl	-	130
S	-	200
PAH-L	0.6	-
PAH-M	2	-
PAH-H	0.5	-

The concentrations in the waste describe the health risks, for example of possible direct intake of soil, skin absorption or inhalation of dust, but is also used to determine the risk for the terrestrial environment (Naturvårdsverket, 2010). The leached amount from the waste with a liquid to solid ratio of 10 describes the amount of pollutant eventually leached out in the long term. If the levels in the waste exceed some of the limits, it may still be possible to use after a permission investigation but that will be decided from case to case.

2.1.4 Pre-treatment methods

The handling of bottom ash differs between countries in the world; some countries landfill the bottom ash after the combustion without any treatment while others process the ash a lot before use in construction works (Astrup et al., 2016). Even though the handling differs between countries the problems are quite similar for all countries. Different available and possible pre-treatment methods for the bottom ash are for example; dry mechanical separation methods, wet separation in form of extraction and washing and chemical processes in form of natural aging and weathering.

2.1.4.1 Dry and wet separation processing of bottom ash

Dry and wet separation processing involves mechanical separation, integrating scrubbing, and extraction, where the aim is to separate the different parts in the bottom ash for better recycling potential.

Dry mechanical processes are the most applied techniques to separate and recycle the different parts in bottom ash and is used especially in northern Europe (Astrup et al., 2016). Different mechanical separation methods exist to separate clean metals from the bottom ash, like magnetic separation, sieving, eddy current separation, induction sorting system and X-ray sorting (Kahle et al., 2015). The separation increases the recycling potential of bottom ash, because when metals are recovered the remaining fraction, mainly minerals, also obtain higher possibility to be recycled and used for example as aggregate or mineral addition in cement, concrete or asphalt (Astrup et al., 2016).

The quenching tank provides an opportunity for removing a large part of soluble components, mostly chlorides but also a smaller amount of sulfates (Astrup et al., 2016). This so called integrating scrubbing provides a high rate of dissolution of soluble components as the temperature in the quenching tank is about 70 degrees. If extra water is added and the residence time in the tank increased it would be an opportunity to reduce the amount of salts in the ash.

The extraction or washing improves the leaching properties of the bottom ash when it will be applied as aggregate material (Astrup et al., 2016). The simplest process is extraction with water, where soluble substances, like chloride and sulfate, are dissolved in the water and can be removed. The residence time is usually too short in the quenching tank and the L/S ratio too low to achieve equilibrium. Therefore extraction with water can be applied after quenching. One problem that may appear in the water extraction is that the less soluble sulfate minerals may not dissolve completely and the concentrations in the material may not be below limits for usage. Another disadvantage is that the environment in the water extraction is alkaline which means that the solubility of most metal compounds is low. However, Keulen et al. (2016) has reported removal of some heavy metals, organic compounds, unwanted fine particles and unburned particles when washing has been performed on the bottom ash.

The combination of the dry and wet separation processes has in The Netherlands resulted in full scale implementation according to Astrup et al. (2016).

2.1.4.2 Chemical processes due to natural aging and weathering

The chemical processes for the bottom ash includes natural aging and weathering (Astrup et al., 2016). The intention of these processes is to stabilize the bottom ash before use or final disposal. Natural aging is a simple and inexpensive method to stabilize the bottom ash before further use or landfilling. Natural aging includes storage of the ash under atmospheric conditions. In practice, many countries use a natural aging for some weeks or months before further use. During the storage weathering reactions occur when the bottom ash is in contact with atmospheric compounds and the minerals change as a result of for example hydrolysis, hydration, dissolution, carbonation and ion exchange. The reactions occurring during weathering stabilizes the bottom ash. The natural weathering may create a cementitious phase that works as a binder, which gives the bottom ash improved mechanical qualities. The natural weathering has been shown to reduce the release of zinc, copper, lead, chromium, calcium, molybdenum, antimony, barium and nickel (Meima & Comans, 1997; Pfrang-Stotz, Reichelt & Roos, 2000; Arickx, Van Gerven & Vandecasteele, 2006).

2.1.5 Combined sorting systems – wet sieving and wet sorting system

Some countries combined the separation methods into a full-scale process for maximum recovery of the bottom ash. In Belgium wet sieving separation is used today on one facility according to Hedenstedt (2015). The process involves separation of metals for recycling, one fraction of sludge for landfilling, and three different fractions that can be used for construction materials and removal of soluble salts. The process can be seen in Appendix I.

Another example of a modern sorting system is the wet sorting system meant to be introduced in Copenhagen, Denmark 2015 in the AFATEK central bottom ash treatment plant according to Kahle et al. (2015). The system can be seen in Appendix II. The wet sorting system is used in systems where a quenching tank is used at the bottom of the ash discharge. The wet sorting system contains multiple process steps, where the bottom ash first is weathered in one to two months before several sorting steps are performed. The final product is intended to be used in road constructions. The system is made for processing a bottom ash with a water content of 10-15 %. The reason for this is that lower water content makes the sieving easier but with too low water content consideration must be taken for dust handling. In the process a pre-treatment method is applied first, were objects larger than 300 mm are removed and manually sorted. Objects larger than 50 mm are crushed and introduced to the sorting again. Unburned organic material is incinerated one more time to recover more energy. A magnet separates large ferrous substances, which are processed for recycling and the mineral fraction that eventually follows the ferrous substances is mechanically removed and then introduced to the system again. If the content of water in the bottom ash is larger than 15 %, weathering is introduced. The remaining bottom ash is sieved in five different fractions, where a magnet is used for removing ferrous metals in each fraction and the non-ferrous metals are removed by two steps of eddy current separation. The remaining particles with a size larger than 4 mm are going through a step of induction sorting system, where stainless steel is removed. This new wet sorting method is expected to recover 90 % of the metal items in the bottom ash and the remaining part will be used in road construction.

2.1.6 Bottom ash as possible aggregates

The bottom ash has the potential to be used as unbound or bound aggregates in for example road constructions or in concrete or asphalt mixtures (Astrup et al., 2016). The bottom ash has already been used in road constructions in the base layer, as unbound aggregates in some countries, for example Denmark, Belgium and The Netherlands (Astrup et al., 2016; Sahlin, 2013). According to Astrup et al. (2016) the bottom ash has not yet been used as bound aggregates in any country because the technical properties and the product itself might be of concern. It has been reported that cement with added bottom ash may swell and cause the structure to break (Pecqueur, Crignon & Quénée, 2001; Müller &

Rübner, 2006; Pera et al. 1997). The reactions connected to the swelling are oxidation of metallic aluminum, the formation of ettringite (reaction of calcium sulfates, calcium oxides, aluminum oxides and water) and hydration of lime and magnesium oxide. All these reactions results in an increased volume, where the largest problem seems to be the oxidation of metallic aluminum. Natural aging and weathering have been shown to decrease the reactivity of the metallic aluminum (Chimenos et al., 2005). Other disadvantage reported by using bottom ash as aggregates in concrete is lower compressive strength and higher water absorption compared to concrete with natural sand and gravel (Pera et al., 1997; van der Wegen, Hofstra & Speerstra, 2013; Tang et al., 2015). Aside from the swelling problem, the other technical properties often reach the required recommendations.

One other concern of using bottom ash in concrete is the leaching properties, where heavy metals still can be a problem (Cai, Bager & Christensen, 2004). Cai, Bager & Christensen (2004) reported an increased leaching of copper, cadmium, lead and zinc compared to the reference, while no increase could be seen for chromium and nickel. Chlorides and sulfates are problematic because during the life cycle when leaching of the salts occur the porosity of the product increases, which decreases the strength of the concrete (Astrup, et.al., 2016). The salts can also cause aesthetic problems when the salts precipitate to the surface of the construction.

2.2 Concrete

Concrete is a mixture of a binder, often cement mixed with water (called cement paste) and aggregates in form of stones and sand (Ljungkrantz, Möller & Petersons, 1994). According to the Swedish Concrete Association (2017) the distribution of material in concrete is usually around 80 % aggregates, 14 % cement and 6 % water.

2.2.1 Cement

Cement is a hydraulic binder which together with water creates a product that hardens and is resistant against water (Ljungkrantz, Möller & Petersons, 1994). Most cement types contain Portland cement, which is made from limestone ($CaCO_3$) and clay mineral that is milled and exposed to high temperatures (Ljungkrantz, Möller & Petersons, 1994; Taylor, 1990). During the process the particles sinter together and form lumps, called cement clinker. The lumps of cement clinker is mixed with around 5 % gypsum and milled to a powder. The most important chemical compounds in cement are alite ($3CaO \cdot SiO_2$), belite ($2CaO \cdot SiO_2$), aluminate ($3CaO \cdot Al_2O_3$) and ferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$).

The properties of the cement are important for workability, consistency, strength and color of the concrete (Ljungkrantz, Möller & Petersons, 1994). Different types of cement mixtures are defined based on chemical composition, area of use or other typical characteristics. The cement types available in European standard EN197-1 is CEM I, II and III, where the CEM I have a composition of minor constituents of maximum five percent and the rest is Portland cement.

2.2.2 Water

The amount of water that is mixed with cement affects both the compressive strength and the durability of the concrete (Gorse, Johnston & Pritchard, 2012). The ratio between the water and cement is called the *water cement ratio* (w/c) and is calculated from the amount of water in the mixture divided by the amount of cement and any additives in weight (Ljungkrantz, Möller & Petersons, 1994). The absorption of water on the surface of the aggregates material should also be considered to get the right w/c ratio. It has been shown that the w/c ratio correlates to the compressive strength of the concrete; a higher w/c ratio gives a lower compressive strength (Felekoğlu, Türkel & Baradan, 2007; Ysberg, 1979). The *compressive strength* can be defined as the largest normal stress in one direction a body can be affected by before rupture (Ljungkrantz, Möller & Petersons, 1994).

Figure 1 shows the average compressive strength decrease in correlation to w/c ratio reported by Ysberg (1979).

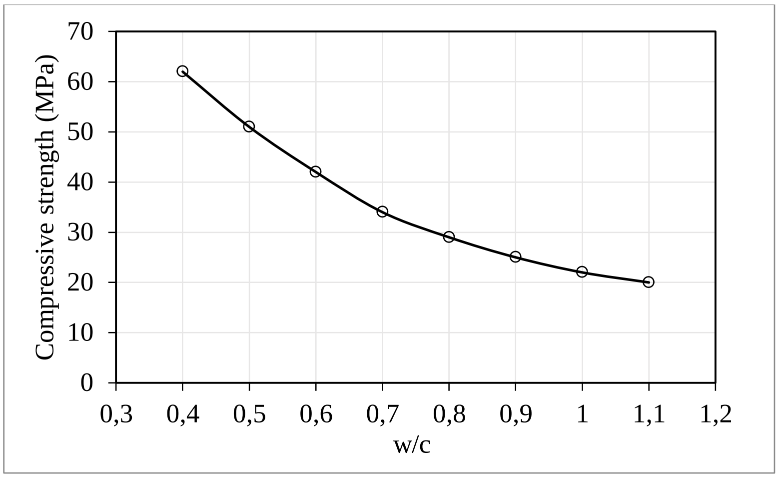

Figure 1. *The correlation between compressive strength of concrete and w/c ratio reported by Ysberg (1979).*

2.2.3 Aggregates

Concrete also contains aggregates in the form of stones, gravel, sand and filler (Ljungkrantz, Möller & Petersons, 1994). The size of the particles decides the type of aggregates; stone has a size higher than 4 mm, gravel has a size equal to or less than 8 mm, sand has a size equal to or less than 4 mm and fillers have a size equal to or less than 0.125 mm. Practically the limit for stone is 8 mm to separate stones and gravel. The distribution of the particle sizes of the aggregates has a large influence on the concrete’s need of water and the workability and stability of the concrete. The characteristics of the aggregates that mainly affects the properties of the concrete is the amount of filler, maximum size of the particles, the form of the particles, the grading and the surface conditions. To get a stable concrete mixture that has a good workability the grading of the sand and gravel is important. The grading curve or the so called sieving curve of the aggregate is determined through a process where the aggregates are dried and then sieved in different sizes. The sieving curve identifies the total amount of material that passes each sieve, normally by weight. Figure 2 shows the higher and lower limits for a suitable sieving curve for aggregate less than 8 mm where the numbers have been obtain from Ljungkrantz, Möller & Petersons (1994).

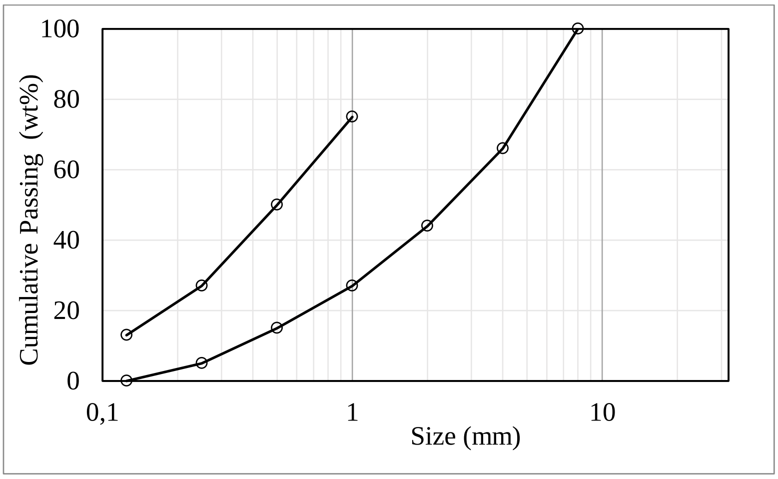

Figure 2. *The higher and lower limits for suitable sieving curve for aggregates less than 8 mm.*

The aggregates can sometimes contain substances that are not suitable in concrete because the substances can damage the concrete (Ljungkrantz, Möller & Petersons, 1994). For example aggregates containing sulfur compounds can expand in the concrete and cause rupture. According to British standards the total content of sulfur calculated as SO_3 in the aggregates is not allowed to exceed 4 % of the cement weight.

2.2.4 Compressive strength

The compressive strength of the concrete can be affected by, as mentioned before, the water amount in the concrete (Gorse, Johnston and Pritchard, 2012; Felekoğlu, Türkel & Baradan, 2007; Ysberg, 1979). The compressive strength depends also on the time of hardening. According to Ljungkrantz, Möller & Petersons (1994), the main compressive strength development occurs in the first week and for Portland cement with 0 % slag reaches the concrete a compressive strength of around 85-90 % of the strength developed after 28 days. According to Felekoğlu, Türkel & Baradan (2007), the compressive strength development is slower for concrete mixtures with higher w/c ratio, when testing concrete samples with w/c ratio of 0.37 to 0.60.

The strength that is needed for the concrete depends on the application. Concrete are divided into different compressive strength levels according to the name system Cxx/xx (for example C20/25), where the first number refers to the compressive strength in MPa after 28 days of a cylinder with a diameter of 150 mm and a height of 300 mm (Projektering.nu , 2017). The second number is the compressive strength in MPa of a cube with a length of 150 mm. The lowest level is C16/20 that exists in Eurokod 2, SS-EN 206, SS 137003 and in construction documentations (Betongindustri, 2017). Concrete used for highways and for tunnels have a strength level of C32/40 – C60/75 (Betongindustri, 2012b), while for example concrete for bus stops and parking lots have a strength level of at least C32/40 (Betongindustri, 2012a).

Concrete has a high compressive strength and can resist high normal stress, but is not so good at resisting shear stress (KTH betongbyggnad, 2012). To increase the resistance against shear stress, reinforcement (a network of steel rods), is often used (Ljungkrantz, Möller & Petersons, 1994; KTH betongbyggnad, 2012). The reinforcement is cured into the concrete and makes the concrete stronger. A high amount of chloride in concrete increases the corrosion rate of reinforcement and to avoid this limits exist for the maximum amount of chlorides that are allowed in the aggregates and the cement (Ljungkrantz, Möller & Petersons, 1994). The allowed limits in Sweden are: 1.0 weight % chlorides of the cement amount for concrete without reinforcement and 0.2 weight % for reinforced concrete (Fagerlund, 2010).

2.2.5 Consistency and concrete slump test

The consistency of the concrete is important to get the right workability and can be tested by the so called concrete slump test (Ljungkrantz, Möller & Petersons, 1997). It is a simple and commonly used test which is performed by filling fresh concrete into a cone with a height of 30 cm and a diameter of 20 cm in the bottom and 10 cm in the top (Figueiredo & Ceccato, 2015; Matern & Odemark, 1944). The cone is then removed and the fresh concrete collapses. The difference between the height of the cone and the concrete mixture state the mixture's slump factor.

3 METHOD

3.1 The properties of the bottom ash

To characterise the bottom ash used for this project several methods were used, such as sieving, X-ray powder diffraction, isothermal calorimetry and determination of the concentration for some selected elements.

3.1.1 The selection of the bottom ash

The bottom ash that was analysed in this study was generated from incineration of municipal solid waste in a grate boiler. The ash has gone through a water bath directly after the combustion and has been collected from a landfill in Lidköping were it has been stored outside for one year and an excavator was needed to break the ash pile. The bottom ash that was collected was; 5 liters of raw bottom ash and 3x10 liters plus 3x5 liters of bottom ash that has gone through an industrial sieve, with a fraction of 0-5 mm. Some larger pieces followed through the sieve because the sieve was old and worn.

For the following experiments the ash samples were taking by turning the bucket with ash upside down to make it as homogenous as possible before the sampling.

3.1.2 Sieving of raw bottom ash and 0-5 mm fraction bottom ash

The raw bottom ash was sieved into the following fractions; smaller than 5.6 mm, 5.6-8 mm, 8-11.2 mm, 11.2-16 mm, 19-22 mm and larger than 22 mm. The particle size fractions were produced by sieving the raw bottom ash sample through a stack of sieves during 15 seconds of shaking in a sieve shaker. The fractions were then stored in plastic jars with tight lids.

To investigate if the particle size distribution of the bottom ash is suitable for use as aggregate in concrete, one bucket (5 liters) of 0-5 mm bottom ash was first dried in 105 degrees during 24 hours and then sieved with amplitude 1.5 mm/”g” during 1 minute in Retsch AS200 in different fractions. The fractions were: smaller than 250 µm, 250-500 µm, 500-1000 µm, 1-2 mm, 2-4 mm, 4-8 mm and larger than 8 mm. The different fractions were weighted and a particle distribution curve was created. The particle curve that was created from this sieving was later used for the distribution of the size of the sand particles in the reference concrete cubes that were casted.

To get an average particle distribution of the analysed bottom ash, three samples of 400 gram bottom ash were dried in 105 degrees for 24 hours and then sieved in the same way as describe above. The weight of each fraction was determined to get a particle distribution curve.

Quartz sand, that was going to be used for the concrete cubes, was also sieved according to the above description.

The 0-5 mm fraction of bottom ash was also sieved to less than 1 mm for the determination of the element concentrations in the bottom ash. 100 gram of the fraction was obtained.

3.1.3 X-ray powder diffraction (XRD)

Two fractions, with particle sizes smaller than 5.6 mm and 8-11.2 mm respectively, of the raw bottom ash was analysed by X-ray powder diffraction (XRD) to identify crystalline compounds in the bottom ash. The X-ray diffractometer used is a Siemens D5000 diffractometer using Cu K radiation wavelength (1.54 Ångström) and a scintillation detector. The 2Θ range 10-70 degrees was covered. Crystalline compounds were identified by comparison with the database JCPDS-ICCD. This method makes it possible to identify crystalline compounds occurring in concentrations of at least 3 % by weight in the sample. Amorphous materials, such as melted and solidified ash compounds cannot be identified. Some grams of the fractions of the raw bottom ash were first grinded into a powder with a pestle and mortar. Then a thin layer was placed on a sample holder before it was placed in the X-ray diffractometer.

3.1.4 Isothermal Calorimetry

The reactivity of the bottom ash towards water was tested using isothermal calorimetry. This analysis was made to investigate if the ash could be used as a replacement of the cement, i.e. if it had similar reactivity as cement, or if it should be used as aggregate in concrete. 5 gram of the 0-5 mm bottom ash was mixed with 5 gram of water in an insulated vessel. The vessel was placed in a sample holder in an isolated container with constant temperature (20 °C) for 7 days and the result from the testing was recorded. The sample holder is in contact with a heat-flow sensor positioned on a heat sink. The temperature was held constant by a thermostat that was controlled by a thermoelectric air-air heater/cooler (AA-100-24-22, SuperCool AB, Gothenburg, Sweden).

3.1.5 Determination of the element concentrations in the bottom ash

The determination of element concentrations was performed by Eurofins Environment Testing Sweden AB in Lidköping, Sweden. Samples consisting of 100 grams respectively of the 0-5 mm fraction of the bottom ash and the sieved 0-5 mm bottom ash with a particle size smaller than 1 mm were analysed by ICP-OES or ICP-MS after homogenisation and total dissolution according to standard methods.

The concentrations of the following elements were determined: chlorine, sulphur, aluminium, phosphorus, iron, cadmium, calcium, potassium, silicon, magnesium, manganese, sodium, titanium, arsenic, antimony, barium, beryllium, lead, cobalt, copper, chromium, molybdenum, nickel, tin, vanadium, zinc, boron and quicksilver. The amounts of moisture and unburned material were also determined.

3.1.6 Washing the bottom ash

The analysis results of the bottom ash showed high concentrations of some salts and therefore it was decided to examine if it was possible to remove all the salts by washing the ash several times. Three samples consisting of 20 gram of the 0-5 mm fraction of the bottom ash was first dried in 105 ºC during 24 hours. After the drying the samples were mixed with deionized water in L/S (liquid to solid ratio) 10. The mixture was stirred with a magnetic stirrer (750 rpm) for one hour before the ash and water was separated by vacuum filtration with a 0.45 µm hydrophilic polypropylene filter on a Büchner funnel. The water was saved for later analysis. The samples were then washed five more times in the same way.

3.1.7 Ion chromatography from the washed bottom ash

The content of anions in the washing water samples was analysed with ion chromatography. The ion chromatograph used was a Dionex DX-100 and the results were analysed by the program IC MagIC Net. 2.0. Standard curves were created in the range 10-100 µM for the anions chloride, fluoride, nitrate, phosphate and sulphate. The washing water from the first three ash washing steps were diluted 100 times with milliQ-water and the last three washing waters were diluted 10 times with milliQ-water, to measure the concentration of salts that has been washed out from the bottom ash. The amounts of salts that were left in the bottom ash after each washing step and the limit of detection for the anions were calculated with linear regression with the least squares method.

3.1.8 Leaching test of the bottom ash

The method used to study the leaching properties of the bottom ash and to compare it with the leaching properties of the concrete samples with added bottom ash was the following:

Three samples of 65-69 gram bottom ash, sieved to less than 4 mm particle size, were dried in 105 degrees for 24 hours. The weight was noted before and after the drying to calculate the w/c ratio of the concrete samples with added bottom ash.

Eight grams of each sample was then leached for 24 hours with 80 gram deionized water, i.e. at L/S 10. The leaching was performed with magnetic stirring (rate 4). A cap was used to avoid evaporation during the leaching. After 24 hours the mixtures were separated by vacuum filtration with a 0.45 µm hydrophilic polypropylene filter on a Büchner funnel. The water was saved for later analysis by ion chromatography, Inductive Coupled Plasma with Optical Emission Spectrometry (ICP-OES) and Inductive Coupled Plasma with Mass Spectrometry (ICP-MS).

3.2 Casting of concrete with added bottom ash

This part describes the procedure for casting concrete cubes with added bottom ash and how the leaching tests of the concrete were performed.

3.2.1 Possible amount of bottom ash as replacement for cement in concrete

After the characteristics of the bottom ash had been established, the next part of the project was to investigate the possibility of using the bottom ash in concrete. However, a series of experiments were made to study how the bottom ash affected the hardening of the cement and water mix and how much of the cement that can be replaced by bottom ash. No aggregate in the form of sand was used for this experiment. For this investigation, only one test per mixture of ash and cement was made. The ash fraction used in all tests was the 0-5 mm fraction. A reference sample was first made with 30 gram base cement, EN 197-1-1CEM II/A-V 52.5 N, and 15 gram deionized water. Eleven mixtures were then prepared with different amount of ash (from 10 up to 90 mass percent of the amount of bottom ash and cement) and the same base cement as for the reference sample, with a total weight of 30 gram. The samples were then mixed in beakers with deionized water. The water amount was adjusted according to the mass of cement and the amount of bottom ash, where a higher amount of bottom ash increased the need of water relative the mass of cement (increased the w/c ratio). The aim was to get a suitable viscosity of the cement-ash-water mix. The samples were cast in plastic jars with lids. After one week the samples were demoulded and the strength of the hardened samples was estimated by pressing by hand. These tests gave indications of possible mixing ratios for fine bottom ash/cement mixture that could be used for further investigations.

3.2.2 Slump test of concrete with parts of the aggregate (sand) replaced by bottom ash

The isothermal calorimetry showed no enthalpy changes indicating reactions between the bottom ash and the water so the bottom ash was therefore used as aggregate replacement in this study. From the particle distribution curve of the bottom ash (paragraph 3.1.2) the decision was taken that only the particle fraction smaller than 4 mm of the bottom ash was going to be used for the casting of the concrete cubes with parts of the aggregate (sand) replaced by bottom ash. Since the bottom ash absorbs some water, it was necessary to investigate the amount of water that was needed for the concrete cubes to get the right consistency. This was done with a simplified slump test.

For the slump test only one experiment per cement/ash/sand mixture was made. The reference mixture was made with a cement aggregate ratio (C/A) of 1:3 and with a water cement ratio (w/c) of 0.5 according to Swedish standard SS-EN 196-1. 100 gram base cement, EN 197-1-1CEM II/A-V 52.5 N, was mixed with 50 gram deionized water and 300 gram sand, where different amounts of the particle fractions were added to the mixture, see Table 2. A small cone, with a height of 6.9 cm and an internal diameter of 4.6 cm at the top and of 5.9 cm at the bottom, was filled with the mixture and was put upside down on a flat surface and the cone was then removed. The decrease of the height of the reference sample concrete "cone" was noted as it gradually lost its cone form. The same method was carried out for the mixture with bottom ash with particle size less than 4 mm, instead of sand, but this mixture was tested with different amounts of water. Two tests were carried out for the BA; with a w/c of 0.5 and 0.65. The extra water (10 gram) for the second mixture, with a w/c 0.65, was added to the bottom ash before it was added to the cement, because aggregate that absorbs water can be mixed with water before addition to the cement and water mixture to get the "right" w/c. This procedure, with adding extra water to the bottom ash before mixing with cement and water, was also implemented in the casting experiments of the concrete cubes with added bottom ash.

Table 2. The particle distribution of sand in the reference concrete cone test.

Particle size (mm)	**Weight (g)**
<0.25	37.55
0.5-1	74.65
1-2	78.19
2-4	109.33

3.2.3 Washing the bottom ash used as aggregate replacement in the concrete cubes

To analyse the difference in strength and leaching between concrete made with part of the aggregate replaced by washed bottom ash or unwashed bottom ash, 1.5 kg of dried and sieved (less than 4 mm) bottom ash was prepared by washing. The washing step for the bottom ash used for the concrete cubes could not be performed in the exact same way as has been described in paragraph 3.1.6. The reason for this was that the amount of bottom ash that was needed for the casting was too large for that method. The ash was divided into two parts, 750 gram ash per part, and each part was washed in a large bucket with 7.5 kg deionized water in L/S 10 in a shaking machine (Köttermänn). The bucket was taped to the shaking machine and the lid was placed on the bucket. The rate of the shaking machine was set at medium. After one hour the solution was filtered through a filter funnel without filter paper to remove the largest particles in the bottom ash. Then the washing water, where the smallest particle still remained, was filtered one more time through a MUNKTELL analytical filter (quality 3).

The washing water was saved for later analysis with ion chromatography to compare with the results from the earlier washing experiments and to calculate the amount of salts that has been removed from the bottom ash that was going to be used in the concrete samples.

To calculate the w/c ratio of the concrete samples with washed bottom ash, three samples with 81 gram of the washed bottom ash were dried for 24 hours in 105 degrees to calculate the amount of water in the concrete cubes with added washed bottom ash.

Three dried washed bottom ash samples of 8 gram each were then taken for leaching tests during 24 hours in 80 gram deionized water (L/S 10) to be able to compare the leaching of the washed bottom ash with that of the hardened concrete cubes. The leaching was performed during magnetic stirring and a cap was used to avoid evaporation. After 24 hours the mixtures were vacuum filtrated with a 0.45 µm hydrophilic polypropylene filter on a Büchner funnel. The water was saved for later analysis with ion chromatography, ICP-OES and ICP-MS.

3.2.4 Casting of concrete cubes with added bottom ash as aggregate

The concrete mixtures that were created for this study was mixed according to Svensk Standard SS-EN 196-1. This standard method was developed to test the strength of cement but was in this study implemented on the concrete mixtures with added bottom ash. This standard is based on C/A 1:3 and w/c 0.5.

Four different batches were prepared for the casting of the concrete cubes. The batches were named according to the aggregate composition; one reference batch with 100 percent quartz sand (REF), one with 100 percent bottom ash (BA100), one with 50 percent bottom ash and 50 percent quartz (BA50-50) and one with 100 percent washed bottom ash (WashedBA). For the batches made with bottom ash, sieved bottom ash with particle size less than 4 mm was used. That decision was made based on the particle size distribution of the bottom ash (paragraph 3.1.2) and comparisons with limits according to Ljungkrantz, Möller & Petersons (1994).

The REF batch was first prepared and six reference cubes were created. The moulds that were used for the casting had a size of 5x5x5 cm and had been 3D-printed at the division of Product Development at Chalmers University of Technology. A thin film of oil was first applied to the surface of the moulds. 450 gram of base cement, EN 197-1-1CEM II/A-V 52.5 N, 225 gram of deionized water and 1350 gram quartz sand were weighed. The particle size distribution of the sand is shown in Table 3. The water was poured into the bowl of the mixer (The Mortar Mixer (ELE International) 39-0031) that was used for the mixing of the concrete. The cement was also added to the bowl and the time was noted. The mixer was started according to programme 1 at low speed, with a rotation of 140 ± 5 min^{-1} and a planetary movement of 62 ± 5 min^{-1}. After 30 seconds the sand was added steadily during 30 seconds. The mixer switched to high speed, with a rotation of 285 ± 10 min^{-1} and a planetary movement of 125 ± 10 min^{-1} and the mixing continued for 30 seconds. Then the mixer stopped for 1 minute and 30 seconds. During this time a rubber scraper was used to move mortar adhering to the wall of the bowl to the middle of the bowl. The mixing continued for 60 seconds at high speed. When the program stopped the bowl was removed. The moulds were filled to 1/3 with the concrete mixture and then vibrated for 10 seconds on a jolting table, FD A24-G, with 50-60 Hz. Further 1/3 of the moulds were filled with the mixture and again vibrated for 10 seconds. The rest of the moulds were filled with the mixture and again vibrated for 10 seconds. Excess of mortar was removed with a metal straightedge. The surface was also smoothed by holding the same straightedge flat. Each mould was put in a plastic bag that contained wet paper to prevent the concrete cubes from drying too fast and eventually crack. The plastic bags were closed carefully. The samples were placed on a horizontal surface for 24 hours, where the time was taken from the cement and water was mixed. After 24 hours the samples were taken out of the moulds and placed in a water bath. The water bath contained around 35 litres tap water and was saturated with 80 gram of calcium hydroxide. The temperature of the water bath was controlled by a thermostat and held at a temperature of 25 °C. A plastic film was used to cover the water bath to avoid evaporation. The samples were placed on the bottom of the water bath with at least 5 mm space between the cubes and at least 5 mm away from the walls. The samples were kept in the water bath until the compressive strength was tested.

Table 3. The amount of different sand particles added to the REF batch.

Particle size (mm)	**Weight (g)**
< 0.25	101.47
0.25-0.5	133.99
0.5-1	269.89
1-2	352.63
2-4	492.02

The three other batches; BA100, BA50-50 and WashedBA, were prepared according to the same method as described above, but with different water amount and aggregate composition. From these batches seven cubes from each batch were prepared. In the BA100 batch, where 1350 gram sieved bottom ash less than 4 mm was used instead of quartz, 67.5 gram extra deionized water was added to the bottom ash before it was mixed with the cement and water mixture. This procedure was chosen based on the earlier experiment with the concrete slump test, paragraph 3.2.2. In the BA50-50 batch 675 gram of sieved bottom ash less than 4 mm and 675 gram of sand was used as aggregate. The particle size distribution of the sand can be seen in Table 4. In this batch 33.7 gram of water was added to the bottom ash before the sand and the bottom ash was mixed with the cement and water mixture. To the WashedBA batch 1350 gram of sieved washed bottom ash was used and no extra water was added.

Table 4. The particle size distribution of the sand in the BA50-50 batch.

Particle size (mm)	**Weight (g)**
< 0.25	50.73
0.25-0.5	66.99
0.5-1	134.94
1-2	176.31
2-4	246.03

3.2.5 Compressive strength test

After 9-11 days three concrete cubes of each batch (REF, BA100, BA50-50 and WashedBA) were exposed to compressive strength test. The BA50-50 cubes were tested after 9 days, the BA100 plus the reference cubes were tested after 10 days and the WashedBA cubes were tested after 11 days, because the device used for the test was only available for certain times. The cubes were put in a bucket with water about one hour before the compressive strength tests were performed. The cubes were then placed in plastic bags, to collect the splitter from the cubes generated during the tests and to save the cubes for further investigations. The tests were performed by Instron 400RD 2MN at the division of Product Development at Chalmers University of Technology. The crushed concrete cubes were saved for later leaching analysis. Three cubes from each batch; REF, BA100 and BA50-50 were also tested after 26 and 27 days in the same way that just has been described (26 days for BA50-50 and 27 days for REF and BA100).

3.2.6 Leaching testing of the concrete cubes

To study the leaching properties of the concrete cubes that were compressive strength tested after 9-11 days, the samples were first sieved to particle size less than 4 mm and then dried during 24 hours in 105 degrees. 8 gram of each cube sample was then leached during 24 hours in 80 gram deionized water (L/S 10) during magnetic stirring (rate 4). A cap was used to avoid evaporation during the leaching. The mixture was then separated by vacuum filtration with a 0.45 µm hydrophilic polypropylene filter on a Büchner funnel. The water was saved for later analysis with ion chromatography, ICP-OES and ICP-MS.

3.2.7 ICP-OES for analysis of leachates

The leaching water was analysed in Inductive Coupled Plasma with Optical Emission Spectrometry (ICP-OES). For the analysis in the ICP-OES standard curves were prepared using standard samples with concentrations 40.0 mg/dm^3, 20.0 mg/dm^3, 10.0 mg/dm^3, 5.0 mg/dm^3 and 2.5 mg/dm^3 for the elements; As, Pb, Cd, Cu, Cr, Hg, Ni, Zn and Sb. The leaching samples were diluted 10, 100 and 1000 times in 0.1 M HNO_3. The samples that were analysed were leached bottom ash, leached washed bottom ash and leached concrete cubes; REF, BA100, BA50-50 and WashedBA that were compressive strength tested after 9-11 days.

3.2.8 ICP-MS for analysis of leachates

The ICP-OES showed low concentrations of the analysed metals, so further investigation of the amount of the metals in the leached water were performed by Inductive Coupled Plasma with Mass Spectrometry (ICP-MS). The leaching samples with 10 times dilution were analysed. For the analysis a standard curve was created with the concentrations 50.0 µg/dm^3, 25.0 µg/dm^3, 12.5 µg/dm^3, 6.3 µg/dm^3 and 3.1 µg/dm^3 for the same elements as for ICP-OES. The standard curves for zinc and copper were not reliable and the values for zinc and copper from the ICP-MS could therefore not be used. The values for these two elements were instead used from the ICP-OES.

3.2.9 Ion chromatography for analysis of leachates

All the leaching samples and three samples of washing water, from when the bottom ash for the concrete was washed, were also analysed in ion chromatography, Dionex. DX-100. The samples were first diluted 100 times with milliQ-water and a standard curve was prepared with concentrations of 10, 50 and 100 µM for chloride and sulfate. The results from the leaching water of REF, BA50-50 and WashedBA showed values under the limit of detection, so they were diluted 20 times with milliQ-water and were analysed one more time.

4 RESULTS

4.1 The properties of the bottom ash

This part describes the determined characteristics of the bottom ash used in this project in form of particle size, crystalline compounds, reactivity and concentrations of some selected elements.

4.1.1 The selection and particle distribution curve of the bottom ash

The bottom ash that was selected for the project was a heterogeneous material with different particle sizes. The larger particles consisted of agglomerated particles and pieces of glass and metals.

The raw bottom ash contained 45.5 percent particles with a size less than 5.6 mm and 11.7 percent of particles with a size larger than 22 mm. The distribution curve of the raw bottom ash can be seen in Figure 3 and is represented by the red line. The total amount and proportion of each fraction can be seen in Appendix III. The black lines in Figure 3 represent the upper and lower limits for appropriate sizes of aggregate smaller than 8 mm in concrete (Ljungkrantz, Möller & Petersons, 1997).

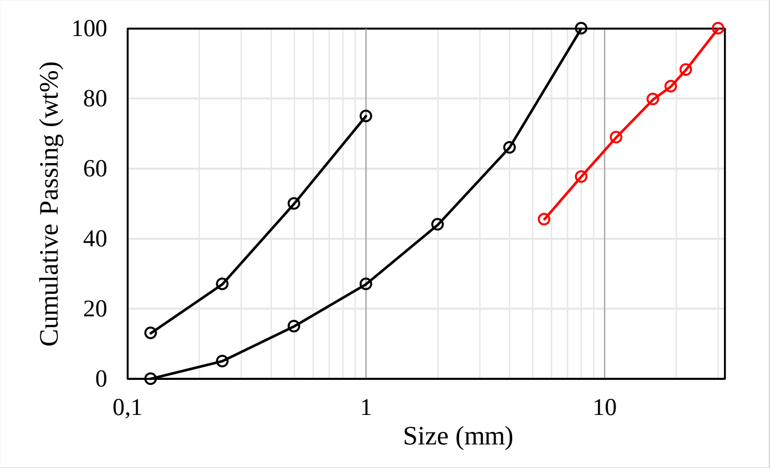

Figure 3. *The particle distribution curve of the raw bottom ash is represented by the red line and the limits for appropriate size of aggregate smaller than 8 mm (Ljungkrantz, Möller & Petersons, 1997) by the black lines.*

The distribution curve from the sieving of one bucket (5 liters) of the 0-5 mm bottom ash can be seen in Figure 4. The figure shows that the particle size distribution curve of the bottom ash is larger than the upper limit. When fractions larger than 4 mm not were taken into account the distribution curve was located between the limits, which also can be seen in Figure 4. This particle distribution curve was used for the amount of sand particles that were used for REF and BA50-50 concrete cubes. The amounts from the sieving can be seen in Appendix IV.

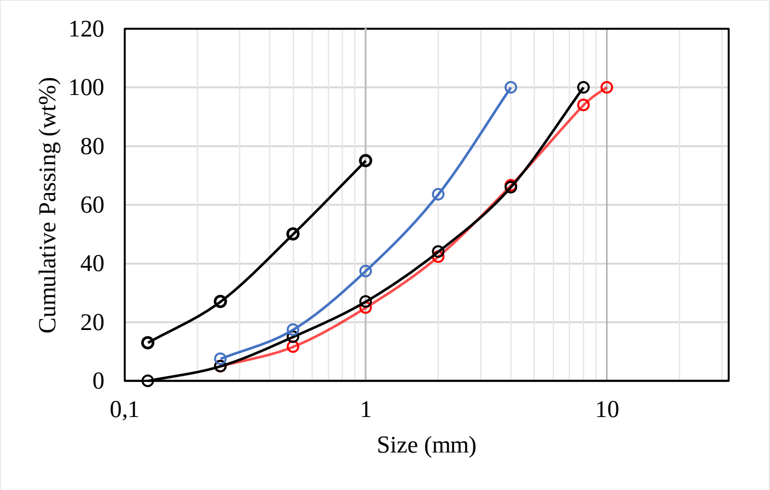

Figure 4. *The red line in the figure is the particle size distribution curve of one sieved bucket with 0-5 mm bottom ash. The black lines represent the limits for appropriate size of aggregate smaller than 8 mm (Ljungkrantz, Möller & Petersons, 1997). The blue line is the particle size distribution when the fractions larger than 4 mm not were taken into account. This distribution curve (blue line) was used for the amount of sand particles in the REF and BA50-50 concrete cubes.*

The average particle distribution from sieving three samples with 0-5 mm bottom ash can be seen in Figure 5. The average distribution curve for the 0-5 mm bottom ash was larger than the suitable limits for aggregate smaller than 8 mm. When fractions larger than 4 mm not were considered the particle distribution curve was between the suitable limits. All the values from the sieving can be seen in Appendix IV.

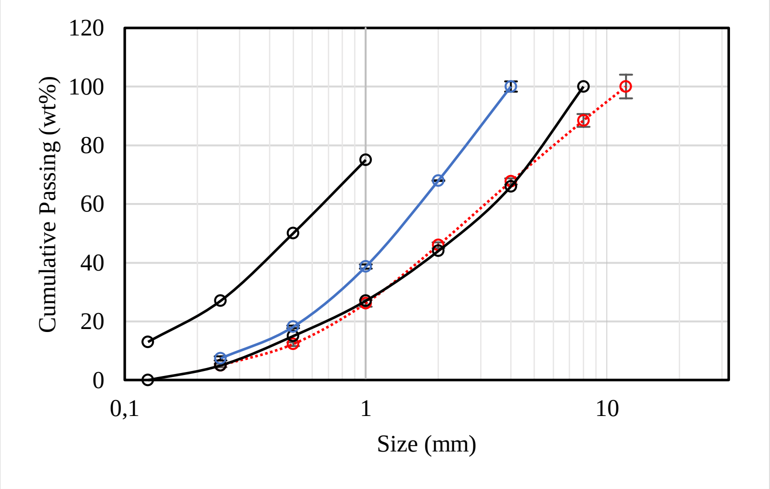

Figure 5. *The average particle size distribution curve of the 0-5 mm bottom ash is represented by the red line, with added standard deviations. The blue line is the distribution curve when the 0-5 mm bottom ash has been sieved smaller than 4 mm. The black lines represent the lower and upper limits for suitable distribution curves of aggregates with a size less than 8 mm (Ljungkrantz, Möller & Petersons, 1997).*

4.1.2 X-ray powder diffraction (XRD)

The result from XRD can be seen in Figure 6 and Figure 7. Figure 6 shows the analysis of crystalline compounds in the raw bottom ash in the fraction that was smaller than 5.6 mm. Figure 7 shows the analysis of the bottom ash in the fraction 8-11 mm of the raw bottom ash. Both results showed presence of calcite and quartz. The fraction with particles smaller than 5.6 mm (Figure 6) also showed the presence of gehlenite, labradorite, gypsum and bassanite. The fraction with particle size 8-11 mm (Figure 7) shows the presence of cristobalite, albite, anorthite, akermanite aluminian and magnetite.

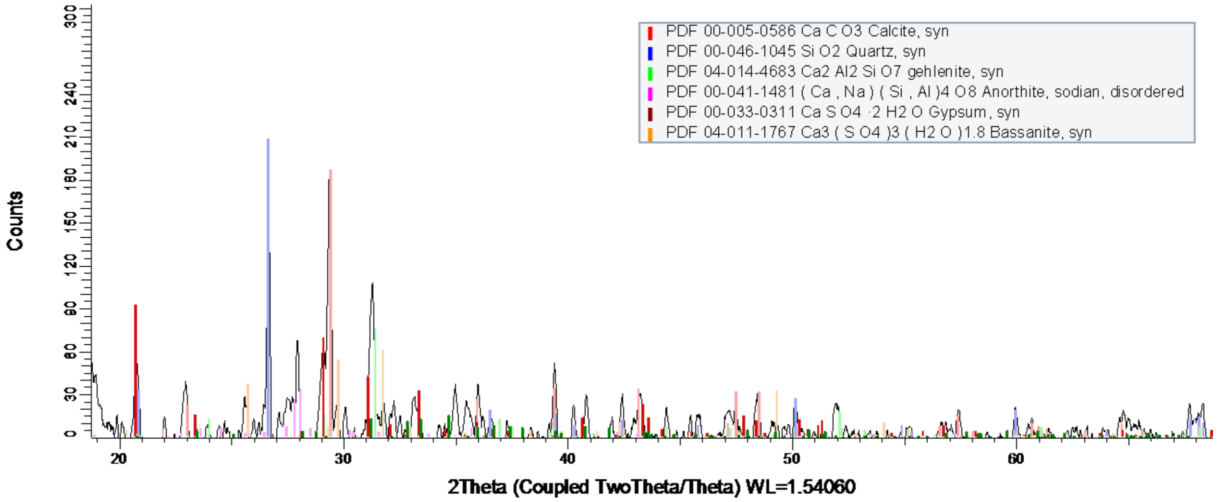

Figure 6. *XRD analysis of the raw bottom ash fraction smaller than 5.6 mm, where the found phases can be seen in the box above the graph.*

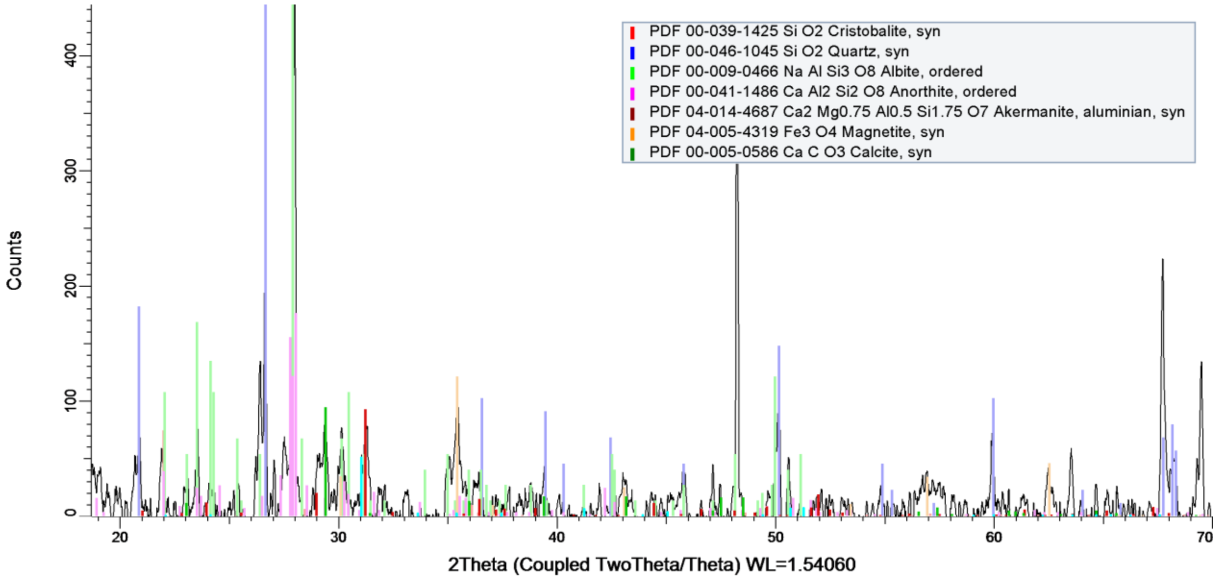

Figure 7. *The XRD result from the 8-11 mm fraction of raw bottom ash and the founded components can be seen in the box above the graph.*

4.1.3 Isothermal calorimetry

The results from the isothermal calorimetry when the 0-5 mm bottom ash was mixed with water did not show any enthalpy changes during the recorded seven days. This means that the bottom ash did not react with the water, alternatively that the reaction was so slow or the energy difference was so small that the calorimetry device could not measure so small amount of energy.

4.1.4 Determination of the element concentrations in the bottom ash

The results from the analysis of the 0-5 mm bottom ash and the fraction less than 1 mm that was sieved from 0-5 mm bottom ash fraction showed quite similar results, where the concentrations of elements were in the same range for both samples. All the concentrations of the elements can be seen in Appendix V. For the further investigations the concentrations of the elements from the 0-5 mm bottom ash were used to compare how much chloride and sulfate that had been removed during the washing and how much of the substances that were leached out during the leaching tests. The elements used for this approach can be seen in Table 5, where DS means dry substance. The amount of unburned parts in the 0-5 mm bottom ash was less than 0.1 percent of the DS and the bottom ash had a moisture content of 16.8 percent.

Table 5. The concentration of the elements in the bottom ash used for the further investigations.

Elements	Bottom ash 0-5 mm	Unit
As	32	mg/kg DS
Cd	3.5	mg/kg DS
Cr	1500	mg/kg DS
Cu	5000	mg/kg DS
Hg	0.093	mg/kg DS
Ni	630	mg/kg DS
Pb	1300	mg/kg DS
Zn	7800	mg/kg DS
Sb	160	mg/kg DS
Cl	0.26	% of DS
S	1.5	% of DS

4.1.5 Washing the bottom ash

During washing of the ash, no bubbles were observed, which indicates that no hydrogen was formed from reactions between metallic aluminium and water. However, the ash created a gel of the smallest particles which clogged the filter to some extent. This became a problem when the process was scaled up for the washing of the bottom ash that was used in the concrete.

4.1.6 Ion chromatography results of the bottom ash washing tests

The results from the ion chromatography of the wash waters showed high amounts of both chlorides and sulfates after the first wash. None of the other analyzed anions were detected. After this wash, the wash water contained lower amount of both chlorides and sulfates and the amounts were quite stable after the third wash. The average amount of chlorides and sulfates (in mg/kg dry weight of the ash) in the wash water of the three samples can be seen in Figure 8 and in Figure 9. The amount of chlorides and sulfates for each sample can be seen in Appendix VI. The lower limit of detection was calculated with linear regression with the least squares method to 5.09 µM for chloride and 5.27 µM for the sulfate. This means that all the values for the sulfate concentrations are reliable but for the chloride concentrations the values for the third washing step is not reliable due to that the results are lower than the limit of detection for all three samples. For the third sample the results for the second washing water is also under the limit of detection for chloride, so the average value for the second washing can thereby differ from the real value. Table 6 shows how much chloride and sulfate that have been removed during each washing step. During the first washing step were 65 % of the chlorides removed and 25 % of the sulfates. After the sixth washing had 80 % of the chlorides been removed and 44 % of the sulfates. The calculations can be seen in Appendix VII.

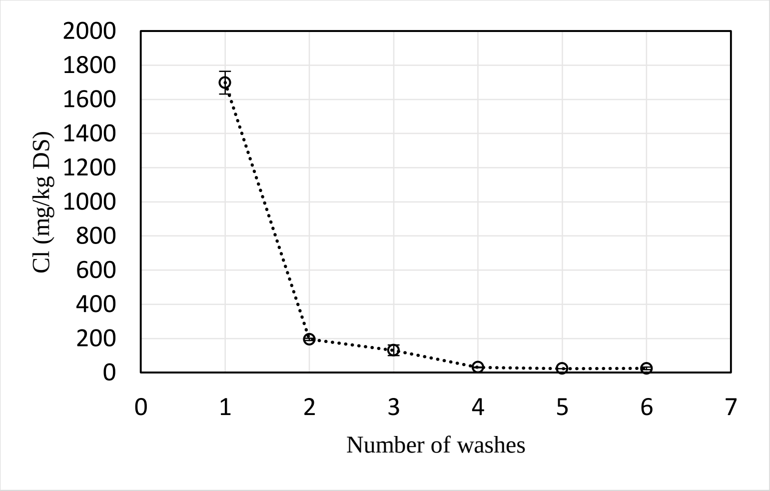

Figure 8. Shows the average amount of chloride in the washing water after each washing step.

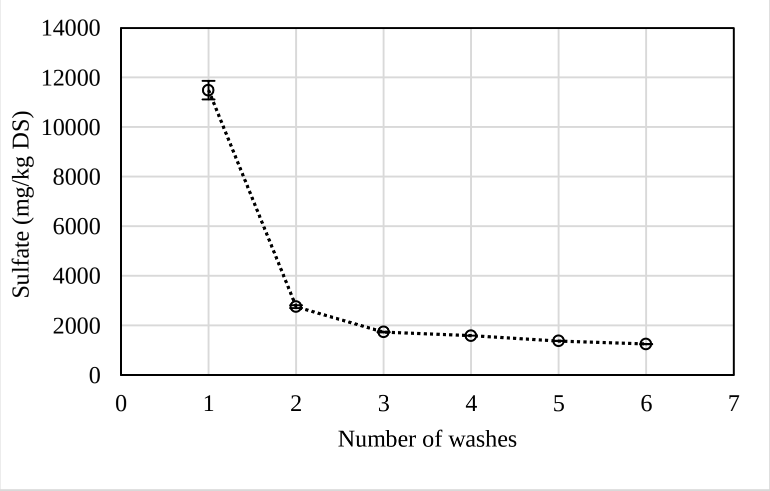

Figure 9. *The average concentration of sulfates in the washing water after each washing step.*

Table 6. Average removed amount of chloride and sulfate after each washing step from the washed bottom ash.

Wash nr	Chloride (removed amount of total amount (%))	Sulfate (removed amount of total amount (%))
1	65.3 ± 2.5	25.6 ± 1.5
2	72.8 ± 4.2	31.7 ± 1.7
3	77.8 ± 4.0	35.6 ± 1.7
4	79.0 ± 4.0	39.1 ± 1.7
5	79.9 ± 4.0	42.1 ± 1.7
6	80.8 ± 4.2	44.9 ± 1.7

The average concentration of chloride and sulphate from the washing water from the bottom ash used for the concrete cubes can be seen in Table 7. The removed amounts were calculated from the concentrations in the washing water and converted to mg/kg dry substance. The remaining concentrations in the washed bottom ash used for the concrete cubes were calculated to 1509 mg chloride/kg dry substance and 11050 mg sulphate/kg dry substance.

Table 7. The average removed amount of sulfate and chloride in the washing water of the bottom ash used for the concrete cubes. The percentage of the removed amount and remaining concentration left in the bottom ash can also be seen.

Compound	Removed amount (mg/kg DS)	Removed amount (% of total amount of the compound)	Left in the washed bottom ash (mg/kg DS)
Chloride	1092 ± 44	42.0 ± 1.7	1509 ± 44
Sulfate /Sulfur	11830 ± 380	26.3 ± 0.8	11050 ± 130

The drying of the washed bottom ash showed that the moisture content was on average 23.6 percent. This number was used in the calculation of the w/c ratio in the concrete cubes with added washed bottom ash. All the data from the drying can be seen in Appendix VIII.

4.1.7 Leaching properties of the bottom ash

Before the leaching test started the bottom ash was sieved to a size smaller than 4 mm and dried in 105 degrees. This gave an average moisture content of 17.8 percent, which was used for calculating the w/c ratio for the concrete cubes with added bottom ash. All the values from the drying can be seen in Appendix VIII. The results from the leaching test of the sieved bottom ash are presented in paragraph 4.2.5 about the leaching with the concrete samples.

4.2 Casting of concrete with added bottom ash

This section focus on the results of the compressive strength test performed on the concrete cubes with added bottom ash and its leaching properties.

4.2.1 Possible amount of bottom ash used as cement replacement in concrete

The investigation of how large amount of bottom ash that is possible to use for the casting experiments showed that all the samples hardened. The samples had no added aggregate in the form of sand. All the samples, except the sample with 90 percent added bottom ash, manage the strength by pressing by hand.

4.2.2 Concrete slump test

The concrete slump test was used for investigating the consistency of the concrete mixtures. It showed a 3 mm decrease of the height in the reference mixture. The diameter of the reference mixture also spread out and increased with 4 mm at the bottom. The mixture with w/c 0.5 and added bottom ash showed no decrease of the height or increase of the diameter, instead the height of the sample increased with 2 mm and the diameter decreased in the top when the cone where removed, because the concrete mixture got stuck in the cone and followed the cone a bit when it was removed. When the w/c ratio increased to 0.65 in the mixture with added bottom ash, the concrete slump test showed the same decrease of the height and increase of the diameter as for the reference mixture.

4.2.3 Casting of concrete cubes with added bottom ash as aggregate replacement

When the demoulding of the concrete cubes from the batches; REF, BA100, BA50-50 and WashedBA, took place the appearance of the cubes were noted. The REF samples had just small air bubbles. The BA100 cubes had some larger air bubbles and one of the BA100 cubes that were casted cracked in the water bath. This indicates that there may be some gas formation from ash components after all. The BA50-50 and WashedBA concrete cubes were quite similar to the REF concrete cubes and had only small air bubbles. All these cubes were intact.

4.2.4 Compressive strength test

The average compressive strength after 9-11 days of the four batches; REF, BA50-50, BA100 and WashedBA can be seen in Table 8. It can be seen that with a larger fraction of the sand replaced with bottom ash in the concrete cubes, the lower the compressive strength becomes. All the values from the measurement can be seen in Appendix IX.

Table 8. The average compressive strength of the four batches.

Sample	Compressive strength (MPa)	Tested after X days
REF	43.13 ± 3.10	10
BA50-50	26.40 ± 1.14	9
BA100	19.13 ± 0.35	10
WashedBA	15.94 ± 0.08	11

The average compressive strength of REF, BA100, BA50-50 and WashedBA relative the amount of bottom ash is plotted with standard deviations in Figure 10, where the red square is WashedBA and the blue dots are REF, BA50-50 and BA100 from left to right. From the figure it does not seem like the compressive strength decreases linearly with increasing amount of bottom ash in the concrete when comparing the concrete samples with not washed bottom ash. The BA100 and WashedBA contained the same amount of bottom ash but the compressive strength of the WashedBA was little lower compared to BA100.

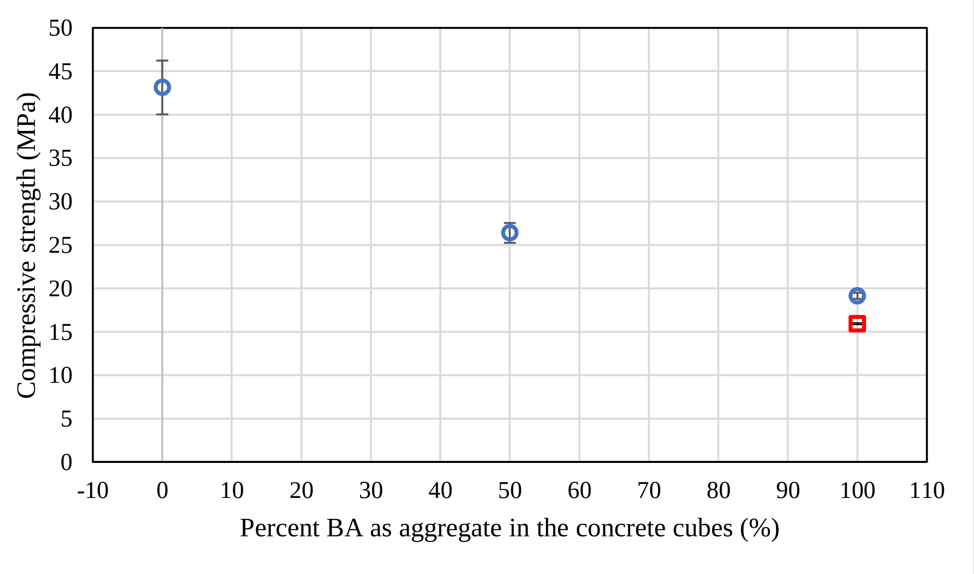

Figure 10. The average compressive strength relative the amount of bottom ash in the concrete samples. The blue dots from left to right: REF, BA50-50 and BA100 and the red dot is the WashedBA.

The results from the compressive strength determination done after 26-27 days of the REF, BA50-50 and BA100 can be seen in Table 9, where the average strength and the standard deviations are shown. A small increase of the compressive strength compared to the results obtained after 9-11 days could be seen. Three cubes of each mixture were tested. All the values from the test can be seen in Appendix IX.

Table 9. The average compressive strength after 26-27 days for the REF, BA100 and BA50-50 cubes.

Sample	Compressive strength (MPa)	Tested after X days
REF	47.76 ± 3.39	27
BA50-50	28.44 ± 0.40	26
BA100	21.72 ± 1.32	27

The compressive strength data was plotted against the fraction of bottom ash in the aggregate part and can be seen in Figure 11. The compressive strength seems to not decrease linearly with increasing amount of bottom ash in the concrete cubes.

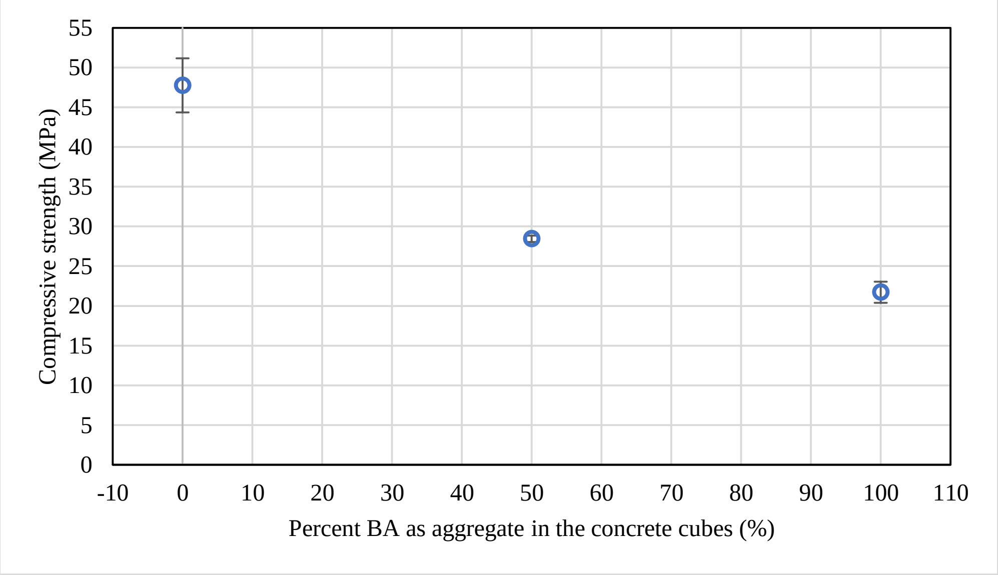

Figure 11. *The compressive strength after 26-27 days relative the amount of added bottom ash as aggregate in the concrete cubes. From left to right: REF, BA50-50 and BA100.*

4.2.5 Results from the leaching test

The results from the leaching performed on the bottom ash, the washed bottom ash and the concrete cubes compressive strength tested after 9-11 days; REF, BA50-50, BA100 and WashedBA, are divided into two subparts; the results from the ICP-OES and ICP-MS giving the amounts of cat-ions in the leachates and the results from the ion chromatography giving the amounts of an-ions.

4.2.5.1 ICP-OES and ICP-MS

The results from the ICP-OES and ICP-MS were calculated from concentrations in the leachates to mg of element/kg dry substance and were then compared with Naturvårdsverket's handbook 2010 (Naturvårdsverket, 2010). The limits in the handbook are valid for leached bottom ash, but are also used for the concrete cubes in this report to compare the concrete with the leached bottom ash. The average values for concentrations of the investigated elements in the 24 hours leaching tests can be seen in Table 10 and Table 11. The values in the tables are shown in mg of the element per kg of dry substance. Table 10 shows the amount of the elements that have leached out from the bottom ash as such and the washed bottom ash. In Table 11 the average values from the leaching of the concrete samples can be seen. The values for copper and zinc was used from the analysis in the ICP-OES due to that the standard curve in the ICP-MS was not reliable for these elements, but all data for the other elements where from the ICP-MS measurements. However the concentrations for copper and zinc were so low so these values are not reliable. All the leached concentrations for cadmium and the data for mercury leached from concrete were also low so these values are not reliable. All the concentrations from the leached bottom ash, washed bottom ash and concrete samples can be seen in Appendix X.

Table 10. Elements in mg/kg of dry substance leached out from bottom ash and washed bottom ash. The red highlighted elements correspond to elements that have leached out in higher amounts from the bottom ash leachates compare to the concrete leachates. The green highlighted element corresponds to lower concentration in the leachate with the bottom ash compared to the leachates with concrete.

Element	**Bottom Ash (mg/kg DS)**	**Washed Bottom Ash (mg/kg DS)**
As	0.040 ± 0.003	0.026 ± 0.003
Cd	0.003 ± 0.000	0.002 ± 0.000
Cr	0.327 ± 0.197	0.483 ± 0.114
Cu	1.295 ± 0.129	0.965 ± 0.179
Hg	0.060 ± 0.014	0.036 ± 0.005
Ni	0.078 ± 0.001	0.142 ± 0.118
Pb	0.039 ± 0.006	0.033 ± 0.003
Sb	0.101 ± 0.017	0.208 ± 0.025
Zn	0.599 ± 0.312	0.289 ± 0.076

Table 11. Elements leached out from concrete cubes that were the strength tested after 9-11 days. The red highlighted elements correspond to elements that have leached out in higher amount from the bottom ash leachates compared to the concrete leachates. The green highlighted element corresponds to lower concentration in the leachate with the bottom ash compared to the leachates with concrete.

Element	**REF (mg/kg DS)**	**BA100 (mg/kg DS)**	**BA50-50 (mg/kg DS)**	**WashedBA (mg/kg DS)**
As	0.021 ± 0.001	0.022 ± 0.002	0.022 ± 0.002	0.020 ± 0.003
Cd	0.003 ± 0.003	0.002 ± 0.000	0.002 ± 0.000	0.002 ± 0.001
Cr	0.098 ± 0.016	0.178 ± 0.015	0.120 ± 0.008	0.198 ± 0.098
Cu	1.049 ± 0.266	0.810 ± 0.164	0.923 ± 0.245	1.034 ± 0.486
Hg	0.008 ± 0.001	0.008 ± 0.001	0.006 ± 0.001	0.005 ± 0.000
Ni	0.112 ± 0.014	0.098 ± 0.002	0.108 ± 0.011	0.149 ± 0.056
Pb	0.447 ± 0.207	3.539 ± 2.885	1.130 ± 0.089	1.599 ± 0.607
Sb	0.032 ± 0.003	0.050 ± 0.003	0.050 ± 0.010	0.068 ± 0.019
Zn	1.833 ± 1.852	0.651 ± 0.122	0.519 ± 0.059	0.480 ± 0.043

The concentration of chromium in the leachate of washed bottom ash was higher compared to the concentration in the leachate of the concrete samples, between the other samples no larger differences could be seen for the concentration of chromium. For nickel, cadmium, zinc and copper no larger differences between the leachates could be seen, even though the concentrations for cadmium, zinc and copper are not reliable. The amount of arsenic from the leachate with bottom ash was little higher compared to the other samples, which had similar concentrations in the leachates. The concentration for antimony was higher for the leachate of washed bottom ash compared to the not washed bottom ash and both leachates had higher concentrations compared to the leachates from the concrete samples. The amount of leached mercury was higher for the bottom ash compared to the washed bottom ash and both these samples had a higher concentration compared to the leachate from concrete, however the concentration of mercury in the leachate from concrete samples are not reliable. For lead was the concentration in the leachate with ashes lower compared to the leachate with concrete samples.

4.2.5.2 Ion chromatography

The results from the ion chromatography were calculated from concentrations in the leachates to mg of element/kg dry substance. The average concentration of sulfate and chloride in the leachate from concrete samples and bottom ash samples can be seen in Table 12. The results were compared with Naturvårdsverket's handbook 2010 (Naturvårdsverket, 2010).

Table 12. The average concentrations of chloride and sulfate in the leachates from the bottom ash and concrete samples, reported as mg/kg dry substance.

Elements	Sulfate (mg/kg DS)	Chloride (mg/kg DS)
Bottom Ash	< DL	1160 ± 103
Washed Bottom Ash	< DL	118 ± 24
REF	47.2 ± 18.3	49.2 ± 1.3
BA100	53.0 ± 4.5	199 ± 8
BA50-50	<DL	203 ± 3
WashedBA	<DL	161 ± 5

The concentration of sulfate in the leachate was under the calculated limit of detection for all the samples without the REF and BA100 concrete samples had an average release of 47.19 mg/kg DS respectively 53.00 mg/kg DS. The amounts of chlorides in the leachate were highest for the bottom ash and lowest for the REF concrete sample. All the concentrations from the ion chromatography can be seen in Appendix XI.

5 DISCUSSION

The aim with this project was to characterize one MSWI bottom ash to understand how it can function in concrete, both as replacement for the cement and as replacement for the aggregate, and also find a pre-treatment method for the bottom ash that could make it suitable for use in concrete. The investigation of the reactivity of bottom ash towards water by calorimetry measurements showed that the bottom ash did not react with the water, which was not unexpected since the bottom ash has gone through a water bath and has been stored outside for one year. This kind of weathering has been shown to stabilize the bottom ash to some extent after some weeks or a few months (Astrup, et.al., 2016). Possible reactivity of the bottom ash towards water can have existed before the quenching and the weathering. This implies that the bottom ash in this case should be used as a replacement for the aggregate in concrete and not as a replacement for the cement since it has lost the cementitious properties that it may have had. One possible option could also be to use the bottom ash as filler in cement. The bottom ash would in that case be grinded, but this can eventually make the bottom ash reactive. To examine the possibility of using the bottom ash as filler in cement a separate study would be needed.

The concentrations of the elements in the bottom ash were compared with Naturvårdsverket’s limits for waste intended to be used in construction works. The limits can be seen in Table 1 in the introduction part, paragraph 2.1.3. All the concentrations in the bottom ash for these elements are higher than the limits except that of mercury. According to Naturvårdsverket a notification is needed if the limit is exceeded regarding usage in construction works, which will be determined after a permission investigation or more pre-treatment steps needed. To lower the concentration of the non-ferrous metals and possibly be below the limit for these metals, eddy current separation could for example be used as a pre-treatment step. Stainless steel in the bottom ash could be removed by using induction sorting as a pre-treatment step.

The amount of chlorides in the bottom ash can be compared with the limit that is allowed in concrete. The amount of chlorides in the bottom ash relative the amount of cement mass was calculated to 0.6 % when all the aggregate in the concrete is replaced by bottom ash, which is lower than the allowed limit for concrete without reinforcement but not for concrete with reinforcement. So even without any washing the concentration of chlorides is below the limit for concrete without reinforcement. When the bottom ash is washed one time the concentration of the chlorides is 0.4 % of the cement amount, which still is too high compared to the allowed limit in Sweden for concrete with reinforcement according to Fagerlund (2010).

The high amount of chlorides and sulfates in the first washing step were expected due to that after the ash has fallen down in the quenching tank, both the ash and water are placed on the landfill and all the soluble salts that have leached out in the water bath follows the ash to the landfill. The calculations, see Appendix VII, showed that around two thirds of the chlorides in the bottom ash were removed after the first wash and one fourth of the sulfur. After the sixth washing had 80 % of the chlorides been removed and 44 % of the sulfates.

The concentration of chlorides in the leachates from the bottom ash was higher than the limit from Naturvårdverket. This was not the case in the leachate from the washed bottom ash. The concentration of chlorides in the first washing water and the water from the leached bottom ash was almost the same, which means that with introducing one washing step the concentration can be lower than the limit. This washing can maybe be implemented in the quenching tank, in that case called integrating scrubbing which also has been suggested by Astrup et.al. (2016) as a possible option to remove soluble components.

Even though the bottom ash contains a lot of sulfate, which also was washed out during the washing steps, the results from the leaching where no sulfate was detected in the leachate from the bottom ash and washed bottom ash can depend on that the sulfate has reacted and form insoluble products, like for example calcium sulfate. To investigate the concentration of sulfate from the bottom ash compared to Naturvårsverket's limit for sulfur, the concentration in the washing water was used for this approach. The concentration in the washing water was approximately 12000 mg sulfate per kg dry substance, which corresponds to approximately 3000 mg sulfur per kg dry substance. From this point of view it seems that six washing steps not is enough to reach below the limit (200 mg/kg dry substance). Therefor more pre-treatment processes are needed or a notification before further use in construction works. The solubility of sulfates has been reported to increase by using sodium bicarbonate ($NaHCO_3$) or carbon dioxide in the washing solution (Astrup, 2007).

The concentrations in the leachate from the bottom ash and washed bottom ash were compared with the concentrations in the bottom ash to investigate how much of the elements that have leached out during 24 hours. These values can be seen in Table 13.

Table 13. The percent of leached elements during 24 hours from the bottom ash and washed bottom ash.

Element	Bottom Ash (% leached out)	Washed Bottom Ash (% leached out)
As	0.13	0.09
Cd	0.09	0.06
Cr	0.02	0.03
Cu	0.03	0.02
Hg	64.5	43.0
Ni	0.01	0.02
Pb	0.01	0.01
Sb	0.06	0.13
Zn	0.01	0.01

Table 13 shows that less than 1 percent of the elements leached out during the leaching test except mercury where 64 percent leached out from the bottom ash and 43 percent from the washed bottom ash. This means that some of the mercury can be removed from the bottom ash by introducing one washing step.

The leaching tests showed that chromium, mercury and antimony leached out in higher amount from the bottom ash and washed bottom ash compared to from the concrete, while the opposite occurred for lead that leached out in higher amount from the concrete compared to from the bottom ash. This can depend on that cement may contain lead which sometimes follows in the product from the production.

The concentrations in the leachate from bottom ash and washed bottom ash were compared with Naturvårdsverket's limits (2010). The leaching test showed that arsenic, cadmium, chromium, nickel, lead and zinc leached out in lower concentrations from the bottom ash and washed bottom ash compared to the limits. The concentrations for mercury and copper in the leachate from the bottom ash and washed bottom ash were higher compared to the limit. This implies that some further pre-treatment methods are necessary to lower the concentrations of these elements.

The limits from Naturvårdsverket (2010) are valid for the concentrations in the leachate from the waste but were also compared with the leachate from the concrete. The comparison showed that the concentrations of arsenic, cadmium, chromium, mercury, nickel and zinc in the concrete leachates were lower than the limits. The concentration of mercury in the leachate with concrete was though too low to be reliable. For copper and lead were the concentrations in the leachates higher compared to the limits.

The concentration of copper in all the leachates was higher compared to Naturvårdsverket's limit. However the values for copper are not reliable due to very low detected concentrations so further investigations are needed to examine the amount of leached copper. If these values still show too high concentrations further pre-treatments are needed to lower the amount of leached copper in the bottom ash.

It should also be mentioned that the values for cadmium and zinc were so low for all the leachates and are therefore not reliable so further investigations are needed to be sure that the leached concentrations are lower than Naturvårdsverket's (2010) limits. For antimony was no limit available in the manual from Naturvårdsverket.

The decrease of the compressive strength in the concrete samples with bottom ash added as aggregate replacement compared to the reference can for example depend on the added water amount in the concrete. The concrete mixture with added bottom ash needed more water which has been shown to decrease the compressive strength for concrete. To examine this, the w/c ratio for each batch was calculated from the amount of water that was added to the cement and the bottom ash plus the water amount in the bottom ash, see Appendix IX for the calculations. The compressive strength relative the w/c ratio of each batch can be seen in Figure 12, where the red dots show data for the concrete tested after 26-27 days; REF, BA50-50 and BA100 from left to right. The blue dots represent the cubes testes after 9-11 days, REF, BA50-50, BA100 and WashedBA from left to right. The correlation looks similar to the described correlation between w/c ratio and compressive strength in the theory (paragraph 2.2.2).

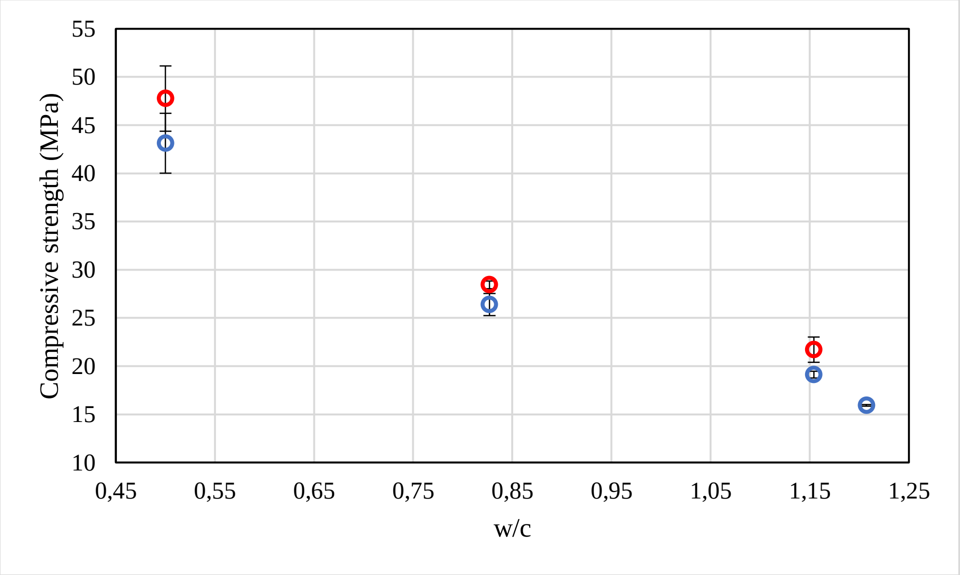

Figure 12. *The w/c ratio versus the compressive strength of the concrete cubes, where the red dots represent the cubes tested after 26-27 days from left to right: REF, BA50-50 and BA100. The blue dots represent the concrete cubes tested after 9-11 days, from left to right: REF, BA50-50, BA100 and WashedBA.*

The decrease of the compressive strength can also depend on reactions like; oxidation of aluminum, formation of ettringite and hydration of lime and magnesium oxide from the bottom ash. They may explain why one of the BA100 cubes got a rupture during the hardening period. Ruptures in concrete mixture with added bottom ash has also been seen in other work (Pecqueur, Crignon & Quénée, 2001; Müller & Rübner, 2006; Pera, et.al, 1997). At the same time it has also been shown that natural weathering decreases the reactivity of metallic aluminum in bottom ash (Chimenos, et.al., 2005). Another factor which can affect the compressive strength is the amount of the salts in the bottom ash, because when the salts leach out from the concrete the porosity of the cubes increases and the strength decreases according to Astrup et.al. (2016). Even though the concrete cubes with added bottom ash had a lower compressive strength compared to the reference, it may have an opportunity in the future to be used in some of the lower compressive strength levels from a mechanical view if not considering the rupture in one concrete cube. The tested concrete samples are not designed according to standard testing, so before clear conclusions can be made according to the technical properties standard test is needed.

6 CONCLUSIONS

In this study bottom ash from incineration of municipal solid waste has been investigated to understand its ability to be used in concrete. The conclusions are that the compressive strength of concrete with added bottom ash to replace aggregate is lower, less than half the compressive strength when all the aggregate is replaced by bottom ash, compared to the reference. It seems that a large influence to this is because of the extra water that is needed for the concrete with added bottom ash. The concentrations of the elements in the bottom ash; arsenic, cadmium, chromium, copper, nickel, lead and zinc, and the leached elements; chloride, sulfate and mercury, showed that further pre-treatment methods are required to decrease the concentration below Naturvårdsverket’s limits in order to use the bottom ash in construction works without a permission investigation.

7 FUTURE WORK

The investigations of concrete with bottom ash used as partial or total replacement for the natural sand aggregates normally used in this study have only considered the short term effects, so future works need to investigate the long time effects of how the bottom ash works in the concrete. It is also needed to examine how to avoid rupture in concrete with added bottom ash. This can maybe be done through more comparison of concrete with added washed bottom ash and not washed bottom ash, to investigate if the concentrations of easily dissolved elements are one of the largest problems that create rupture in the concrete. The main reason for the decrease in the compressive strength in concrete with added bottom ash seems to be the amount of extra water that is needed. It is therefore important to study why the bottom ash absorbs so much water and examine the effects of the compressive strength of using super plasticizer in the concrete with added bottom ash. Further investigations need to perform standard test on concrete samples with added bottom ash to ensure that the compressive strength have similar strength received in this study.

Future studies need also to investigate how to lower the concentrations and the leaching of the mentioned elements in the conclusion below Naturvårdsverket's limit values in order to make it possible to use the bottom ash without any permission investigations. Studies must also explore how the concentrations in the solid phase and the leaching of elements from the bottom ash are affected by other pre-treatment methods or pre-treatment systems and how this affects the compressive strength of concrete with added bottom ash.

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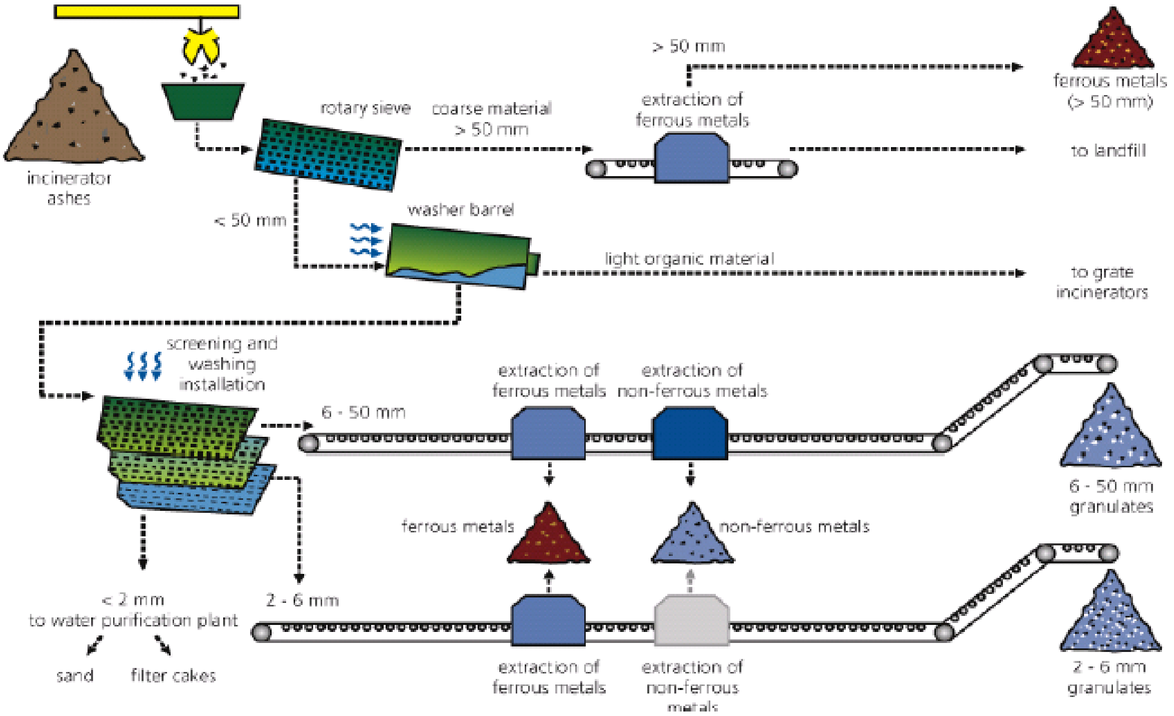
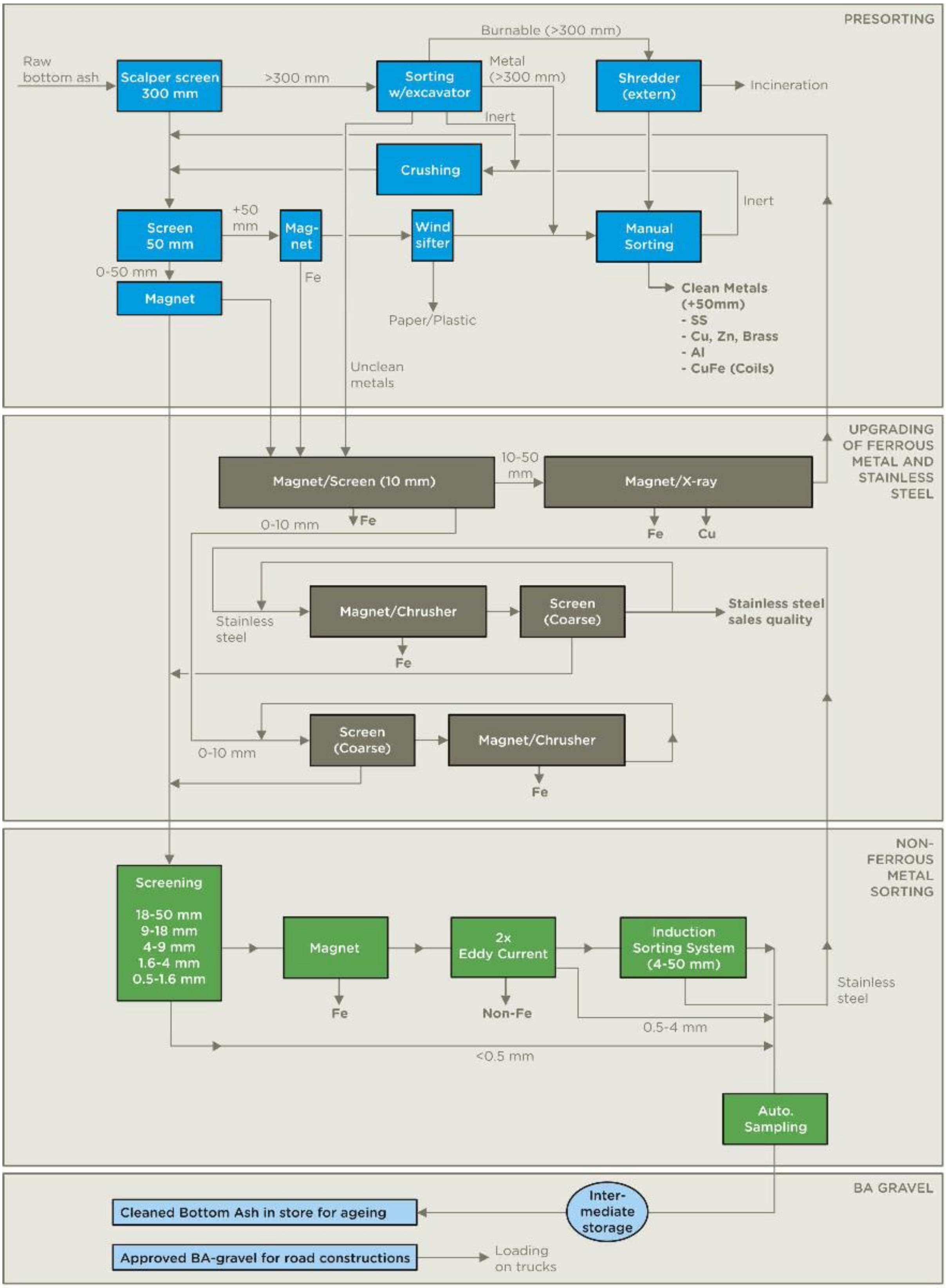
APPENDIX I

The wet sieving separation on one facility in Belgium according to Hedenstedt (2015).



APPENDIX II

The wet sorting system, meant to be introduced in Denmark 2015 according to Kahle et al. (2015).



APPENDIX III

Table 14 shows the weight and the proportion of the different fractions of the sieved raw bottom ash.

Table 14. Weight and proportion of the different fractions in the raw bottom ash.

Fraction (mm)	Weight (g)	Proportion (%)
<5.6	2651.8	45.5
5.6	710.1	12.2
8	652.4	11.2
11.2	634.1	10.9
16	213.3	3.7
19	281.2	4.8
>22	683.6	11.7
Total	5826.5	100.0

APPENDIX IV

Table 15 shows the amount from the different fractions in the bucket of sieved bottom ash. Table 16 shows the amount from sieving 0-5 mm bottom ash for determination of the average particle distribution curve. In Table 17 is the average amount of sieved bottom ash.

Table 15. The weight of the different fractions in one bucket of bottom ash

Particle size (mm)	Weight (g)	Percent of total (%)	Passing (%)
<0.25	456.73	5.01	5.01
0.25-0.5	603.09	6.61	11.62
0.5-1	1214.77	13.32	24.94
1-2	1587.17	17.40	42.34
2-4	2214.51	24.28	66.62
4-8	2492.32	27.32	93.94
>8	552.83	6.06	100.00
Total	9121.42	100.00	100.00

Table 16. The amount of different fractions in the three sieved samples of bottom ash.

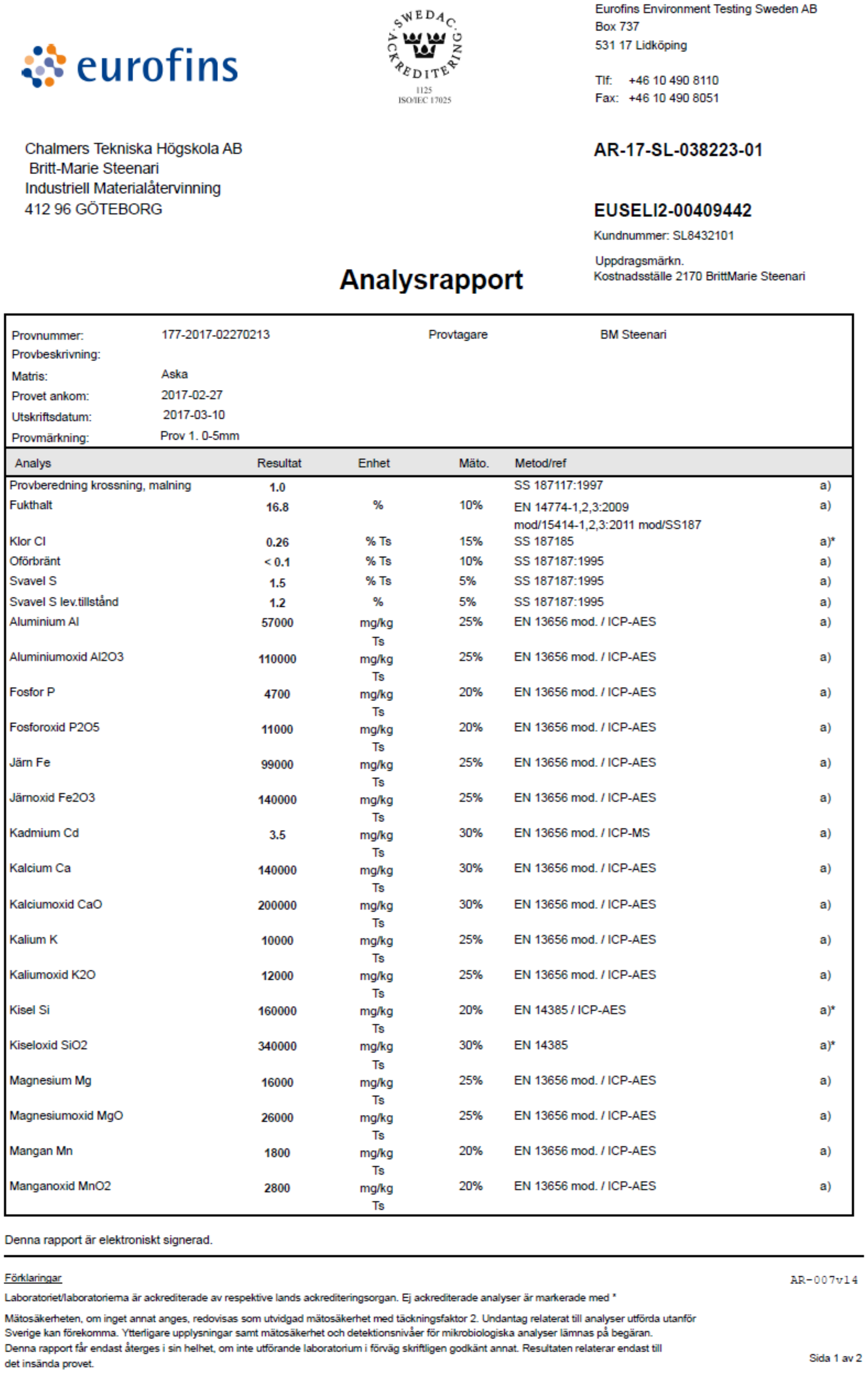
Particle size (mm)	Sample 1 (g)	Sample 2 (g)	Sample 3 (g)
<0.25	18.69	17.49	14.65
0.25-0.5	25.45	26.19	22.17
0.5-1	48.05	50.03	42.82
1-2	67.06	70.22	63.86
2-4	69.78	76.57	73.72
4-8	61.64	73.94	75.38
>8	47.39	23.43	46.38
Total	338.06	337.87	338.98

Table 17. The average amount of the three sieved samples of bottom ash.

Particle size (mm)	Average (g)	Percent of total (%)	Passing (%)
<0.25	16.95 ± 2.08	5.01	5.01
0.25-0.5	24.60 ± 0.98	7.27	12.28
0.5-1	46.97 ± 4.45	13.88	26.16
1-2	67.05 ± 1.02	19.82	45.98
2-4	73.36 ± 3.57	21.68	67.67
4-8	70.32 ± 4.91	20.79	88.45
>8	39.07 ± 18.24	11.55	100.00
Total	338.31 ± 0.59	100.00	100.00

APPENDIX V

The two following pages show the concentrations in the 0-5 mm bottom ash.



1125
ISO/IEC 17025

Eurofins Environment Testing Sweden AB
Box 737
531 17 Lidköping

Tlf: +46 10 490 8110
Fax: +46 10 490 8051

Chalmers Tekniska Högskola AB
Britt-Marie Steenari
Industriell Materialåtervinning
412 96 GÖTEBORG

AR-17-SL-038223-01

EUSELI2-00409442

Kundnummer: SL8432101

Uppdragsmärkn.
Kostnadsställe 2170 BrittMarie Steenari

Analysrapport

Provnummer:	177-2017-02270213	Provtagare	BM Steenari
Provbeskrivning:			
Matris:	Aska		
Provet ankom:	2017-02-27		
Utskriftsdatum:	2017-03-10		
Provmärkning:	Prov 1. 0-5mm		

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Provberedning krossning, malning	**1.0**			SS 187117:1997	a)
Fukthalt	**16.8**	%	10%	EN 14774-1,2,3:2009 mod/15414-1,2,3:2011 mod/SS187	a)
Klor Cl	**0.26**	% Ts	15%	SS 187185	a)*
Oförbränt	**< 0.1**	% Ts	10%	SS 187187:1995	a)
Svavel S	**1.5**	% Ts	5%	SS 187187:1995	a)
Svavel S lev.tillstånd	**1.2**	%	5%	SS 187187:1995	a)
Aluminium Al	**57000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Aluminiumoxid Al2O3	**110000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Fosfor P	**4700**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Fosforoxid P2O5	**11000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Järn Fe	**99000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Järnoxid Fe2O3	**140000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Kadmium Cd	**3.5**	mg/kg Ts	30%	EN 13656 mod. / ICP-MS	a)
Kalcium Ca	**140000**	mg/kg Ts	30%	EN 13656 mod. / ICP-AES	a)
Kalciumoxid CaO	**200000**	mg/kg Ts	30%	EN 13656 mod. / ICP-AES	a)
Kalium K	**10000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Kaliumoxid K2O	**12000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Kisel Si	**160000**	mg/kg Ts	20%	EN 14385 / ICP-AES	a)*
Kiseloxid SiO2	**340000**	mg/kg Ts	30%	EN 14385	a)*
Magnesium Mg	**16000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Magnesiumoxid MgO	**26000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Mangan Mn	**1800**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Manganoxid MnO2	**2800**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)

Denna rapport är elektroniskt signerad.

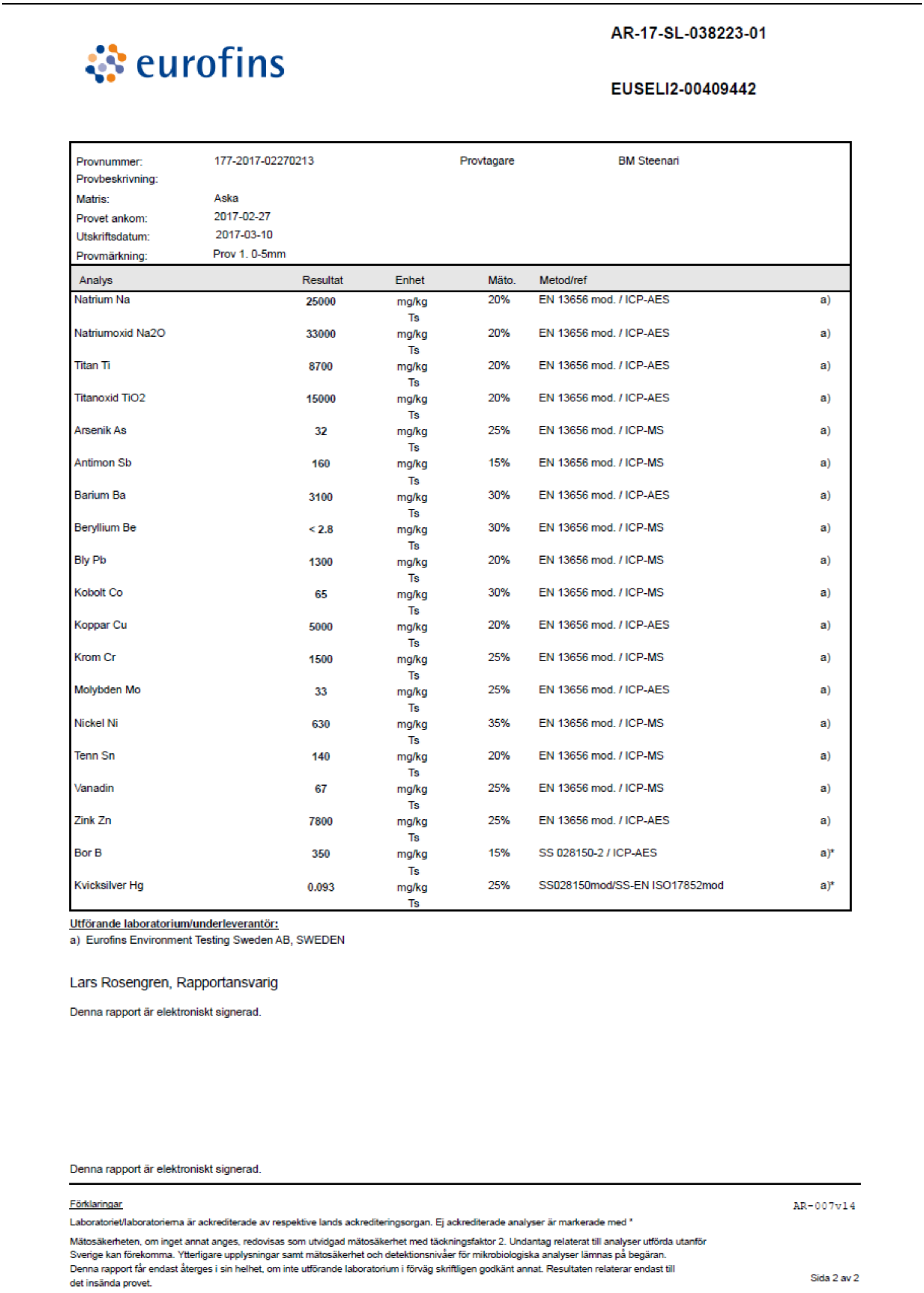
Förklaringar

AR-007v14

Laboratoriet/laboratorierna är ackrediterade av respektive lands ackrediteringsorgan. Ej ackrediterade analyser är markerade med *

Mätosäkerheten, om inget annat anges, redovisas som utvidgad mätosäkerhet med täckningsfaktor 2. Undantag relaterat till analyser utförda utanför Sverige kan förekomma. Ytterligare upplysningar samt mätosäkerhet och detektionsnivåer för mikrobiologiska analyser lämnas på begäran.
Denna rapport får endast återges i sin helhet, om inte utförande laboratorium i förväg skriftligen godkänt annat. Resultaten relaterar endast till det insända provet.

Sida 1 av 2



AR-17-SL-038223-01

EUSELI2-00409442

Provnummer:	177-2017-02270213	Provtagare	BM Steenari
Provbeskrivning:			
Matris:	Aska		
Provet ankom:	2017-02-27		
Utskriftsdatum:	2017-03-10		
Provmärkning:	Prov 1. 0-5mm		

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Natrium Na	**25000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Natriumoxid Na2O	**33000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Titan Ti	**8700**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Titanoxid TiO2	**15000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Arsenik As	**32**	mg/kg Ts	25%	EN 13656 mod. / ICP-MS	a)
Antimon Sb	**160**	mg/kg Ts	15%	EN 13656 mod. / ICP-MS	a)
Barium Ba	**3100**	mg/kg Ts	30%	EN 13656 mod. / ICP-AES	a)
Beryllium Be	**< 2.8**	mg/kg Ts	30%	EN 13656 mod. / ICP-MS	a)
Bly Pb	**1300**	mg/kg Ts	20%	EN 13656 mod. / ICP-MS	a)
Kobolt Co	**65**	mg/kg Ts	30%	EN 13656 mod. / ICP-MS	a)
Koppar Cu	**5000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Krom Cr	**1500**	mg/kg Ts	25%	EN 13656 mod. / ICP-MS	a)
Molybden Mo	**33**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Nickel Ni	**630**	mg/kg Ts	35%	EN 13656 mod. / ICP-MS	a)
Tenn Sn	**140**	mg/kg Ts	20%	EN 13656 mod. / ICP-MS	a)
Vanadin	**67**	mg/kg Ts	25%	EN 13656 mod. / ICP-MS	a)
Zink Zn	**7800**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Bor B	**350**	mg/kg Ts	15%	SS 028150-2 / ICP-AES	a)*
Kvicksilver Hg	**0.093**	mg/kg Ts	25%	SS028150mod/SS-EN ISO17852mod	a)*

Utförande laboratorium/underleverantör:

a) Eurofins Environment Testing Sweden AB, SWEDEN

Lars Rosengren, Rapportansvarig

Denna rapport är elektroniskt signerad.

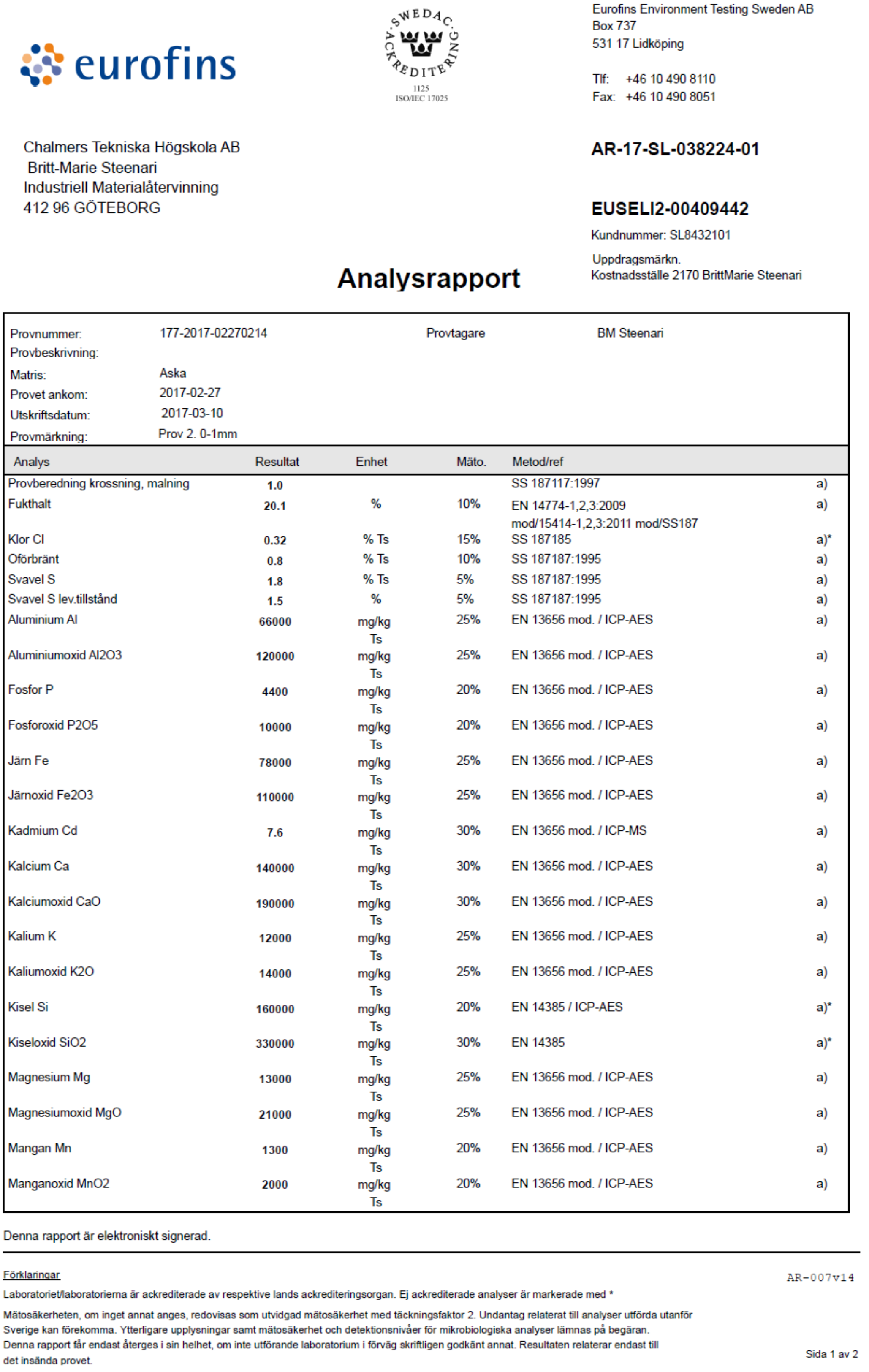
Denna rapport är elektroniskt signerad.

Förklaringar

Laboratoriet/laboratorierna är ackrediterade av respektive lands ackrediteringsorgan. Ej ackrediterade analyser är markerade med *

Mätosäkerheten, om inget annat anges, redovisas som utvidgad mätosäkerhet med täckningsfaktor 2. Undantag relaterat till analyser utförda utanför Sverige kan förekomma. Ytterligare upplysningar samt mätosäkerhet och detektionsnivåer för mikrobiologiska analyser lämnas på begäran.
Denna rapport får endast återges i sin helhet, om inte utförande laboratorium i förväg skriftligen godkänt annat. Resultaten relaterar endast till det insända provet.

The two following pages represent the concentrations of sieved 0-5 mm bottom ash smaller than 1 mm.



eurofins

1125
ISO/IEC 17025

Eurofins Environment Testing Sweden AB
Box 737
531 17 Lidköping

Tlf: +46 10 490 8110
Fax: +46 10 490 8051

Chalmers Tekniska Högskola AB
Britt-Marie Steenari
Industriell Materialåtervinning
412 96 GÖTEBORG

AR-17-SL-038224-01

EUSELI2-00409442

Kundnummer: SL8432101

Uppdragsmärkn.
Kostnadsställe 2170 BrittMarie Steenari

Analysrapport

Provnummer: 177-2017-02270214 Provtagare BM Steenari
Provbeskrivning:
Matris: Aska
Provet ankom: 2017-02-27
Utskriftsdatum: 2017-03-10
Provmärkning: Prov 2. 0-1mm

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Provberedning krossning, malning	**1.0**			SS 187117:1997	a)
Fukthalt	**20.1**	%	10%	EN 14774-1,2,3:2009 mod/15414-1,2,3:2011 mod/SS187	a)
Klor Cl	**0.32**	% Ts	15%	SS 187185	a)*
Oförbränt	**0.8**	% Ts	10%	SS 187187:1995	a)
Svavel S	**1.8**	% Ts	5%	SS 187187:1995	a)
Svavel S lev.tillstånd	**1.5**	%	5%	SS 187187:1995	a)
Aluminium Al	**66000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Aluminiumoxid Al2O3	**120000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Fosfor P	**4400**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Fosforoxid P2O5	**10000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Järn Fe	**78000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Järnoxid Fe2O3	**110000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Kadmium Cd	**7.6**	mg/kg Ts	30%	EN 13656 mod. / ICP-MS	a)
Kalcium Ca	**140000**	mg/kg Ts	30%	EN 13656 mod. / ICP-AES	a)
Kalciumoxid CaO	**190000**	mg/kg Ts	30%	EN 13656 mod. / ICP-AES	a)
Kalium K	**12000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Kaliumoxid K2O	**14000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Kisel Si	**160000**	mg/kg Ts	20%	EN 14385 / ICP-AES	a)*
Kiseloxid SiO2	**330000**	mg/kg Ts	30%	EN 14385	a)*
Magnesium Mg	**13000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Magnesiumoxid MgO	**21000**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Mangan Mn	**1300**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Manganoxid MnO2	**2000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)

Denna rapport är elektroniskt signerad.

Förklaringar

AR-007v14

Laboratoriet/laboratorierna är ackrediterade av respektive lands ackrediteringsorgan. Ej ackrediterade analyser är markerade med *

Mätosäkerheten, om inget annat anges, redovisas som utvidgad mätosäkerhet med täckningsfaktor 2. Undantag relaterat till analyser utförda utanför Sverige kan förekomma. Ytterligare upplysningar samt mätosäkerhet och detektionsnivåer för mikrobiologiska analyser lämnas på begäran.
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Sida 1 av 2

Provnummer:	177-2017-02270214	Provtagare	BM Steenari
Provbeskrivning:			
Matris:	Aska		
Provet ankom:	2017-02-27		
Utskriftsdatum:	2017-03-10		
Provmärkning:	Prov 2. 0-1mm		

Analys	Resultat	Enhet	Måto.	Metod/ref	
Natrium Na	**19000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Natriumoxid Na2O	**26000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Titan Ti	**7700**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Titanoxid TiO2	**13000**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Arsenik As	**33**	mg/kg Ts	25%	EN 13656 mod. / ICP-MS	a)
Antimon Sb	**190**	mg/kg Ts	15%	EN 13656 mod. / ICP-MS	a)
Barium Ba	**3200**	mg/kg Ts	30%	EN 13656 mod. / ICP-AES	a)
Beryllium Be	**< 2.8**	mg/kg Ts	30%	EN 13656 mod. / ICP-MS	a)
Bly Pb	**3100**	mg/kg Ts	20%	EN 13656 mod. / ICP-MS	a)
Kobolt Co	**64**	mg/kg Ts	30%	EN 13656 mod. / ICP-MS	a)
Koppar Cu	**6800**	mg/kg Ts	20%	EN 13656 mod. / ICP-AES	a)
Krom Cr	**610**	mg/kg Ts	25%	EN 13656 mod. / ICP-MS	a)
Molybden Mo	**24**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Nickel Ni	**430**	mg/kg Ts	35%	EN 13656 mod. / ICP-MS	a)
Tenn Sn	**230**	mg/kg Ts	20%	EN 13656 mod. / ICP-MS	a)
Vanadin	**47**	mg/kg Ts	25%	EN 13656 mod. / ICP-MS	a)
Zink Zn	**9100**	mg/kg Ts	25%	EN 13656 mod. / ICP-AES	a)
Bor B	**300**	mg/kg Ts	15%	SS 028150-2 / ICP-AES	a)*
Kvicksilver Hg	**< 0.050**	mg/kg Ts	25%	SS028150mod/SS-EN ISO17852mod	a)*

Utförande laboratorium/underleverantör:
a) Eurofins Environment Testing Sweden AB, SWEDEN

Lars Rosengren, Rapportansvarig

Denna rapport är elektroniskt signerad.

Denna rapport är elektroniskt signerad.

Förklaringar

Laboratoriet/laboratorierna är ackrediterade av respektive lands ackrediteringsorgan. Ej ackrediterade analyser är markerade med *

Mätosäkerheten, om inget annat anges, redovisas som utvidgad mätosäkerhet med täckningsfaktor 2. Undantag relaterat till analyser utförda utanför Sverige kan förekomma. Ytterligare upplysningar samt mätosäkerhet och detektionsnivåer för mikrobiologiska analyser lämnas på begäran.
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APPENDIX VI

Table 18 shows the values for the standard curve for chloride and sulfate in the ion chromatography used for the several washing steps. Figure 13 shows the standard curve for chloride and Figure 14 shows the standard curve for sulfate.

Table 18. The values from the standard

Standard	**Chloride (mVxmin)** **first / second sampling**	**Sulfate (mVxmin)** **first / second sampling**
10 µM	6.104 / 6.507	8.341 / 8.072
50 µM	29.133 / 30.342	50.932 / 51.383
100 µM	47.029 / 46.636	82.708 / 80.901

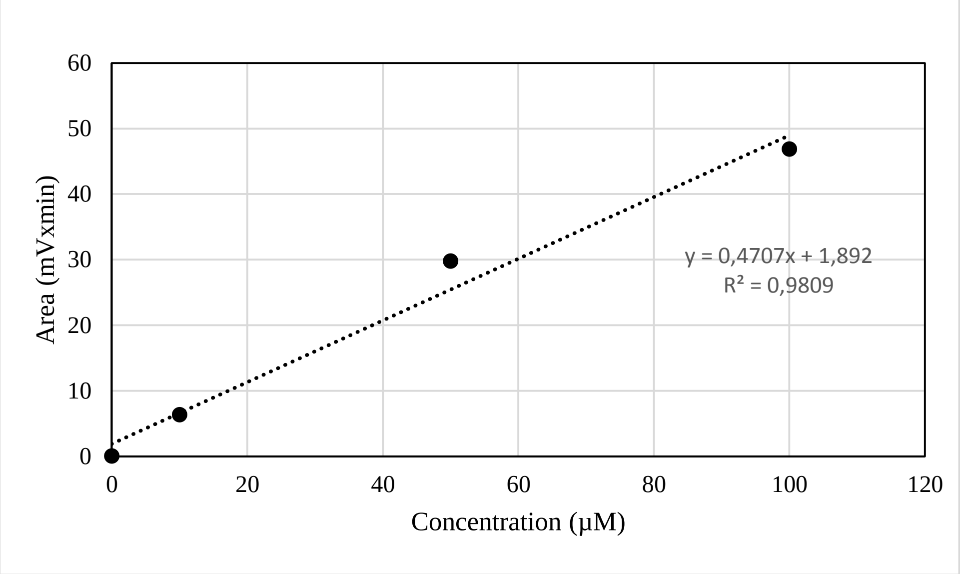

***Figure 13**. The standard curve for chloride*

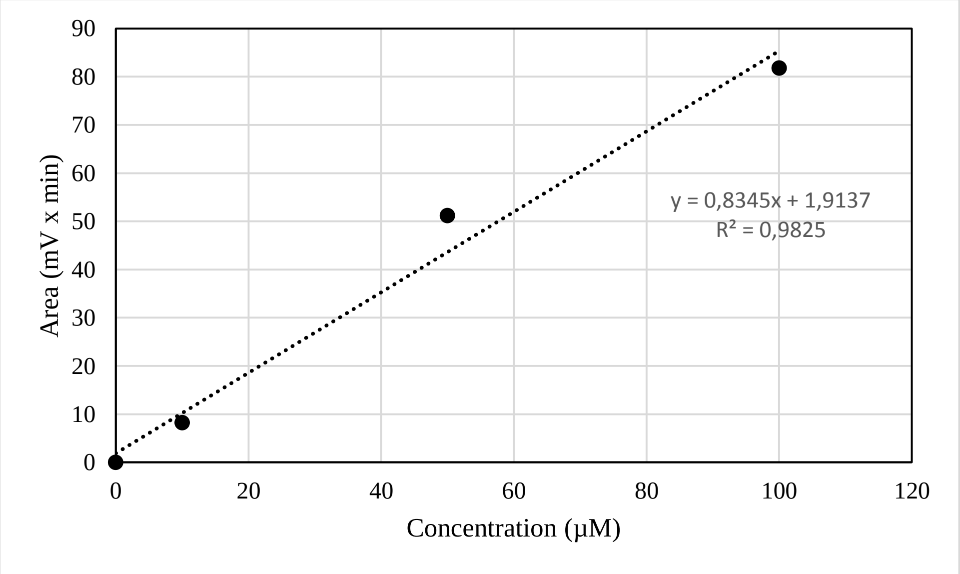

***Figure 14.** The standard curve for sulfate.*

Table 19 shows the chloride result from the ion chromatography and Table 20 show the sulfate results. The first three washing step in each sample have been diluted 100 times and the last three washing step have been diluted 10 times. Table 21 shows the calculated concentrations of chloride in the washed water from the bottom ash. Table 22 shows the calculated concentrations of sulfate in the washed water from the bottom ash.

Table 19. The results for the chloride in the three washing samples.

Washing step	Sample 1 (mVxmin) first/second sampling	Sample 2 (mVxmin) first/second sampling	Sample 3 (mVxmin) first/second sampling
1	25.530 / 24.913	24.347 / 24.717	24.077 / 23.714
2	5.099 / 4.886	4.584 / 5.008	3.627 / 4.046
3	3.204 / 3.305	3.840 / 4.322	3.263 / 3.889
4	5.501 / 6.101	6.038 / 6.098	6.556 / 6.062
5	4.710 / 5.138	5.172 / 5.001	4.954 / 5.233
6	6.344 / 6.385	4.820 / 4.846	4.043 / 4.910

Table 20. The results for the sulfate in the three washing samples.

Washing step	Sample 1 (mVxmin) first/second sampling	Sample 2 (mVxmin) first/second sampling	Sample 3 (mVxmin) first/second sampling
1	107.847 / 107.334	101.200 / 99.892	98.800 / 98.141
2	27.577 / 27.903	25.346 / 25.427	25.873 / 26.165
3	17.114 / 17.160	16.495 / 17.224	17.779 / 16.514
4	142.217 / 140.431	143.351 / 143.181	145.280 / 143.343
5	123.049 / 125.547	121.737 / 123.586	123.795 / 126.895
6	113.125 / 111.420	114.245 / 113.893	115.872 / 113.324

Table 21. The calculated chloride values in each sample from the washing steps.

Sample	Washing step	Average (µM)	Dilution	Total (mM)	Water (dm^3)	Ash (kg)	Chloride (mg/kg DS)
1	1	49.566	100.680	4.990	0.165	0.0165	1765.53
	2	6.587	96.615	0.636	0.165		225.31
	3	2.895	100.169	0.290	0.165		102.56
	4	8.305	9.897	0.082	0.165		29.07
	5	6.442	9.808	0.063	0.165		22.35
	6	9.502	9.723	0.092	0.165		32.68
2	1	48.101	99.530	4.788	0.166	0.0166	1695.83
	2	6.170	98.864	0.610	0.166		216.14
	3	4.651	98.885	0.460	0.166		162.87
	4	8.872	9.782	0.087	0.166		30.74
	5	6.787	9.804	0.067	0.166		23.57
	6	6.248	9.755	0.061	0.166		21.59
3	1	46.749	98.817	4.620	0.168	0.0169	1633.38
	2	4.131	98.440	0.407	0.168		143.76
	3	3.578	99.767	0.357	0.168		126.19
	4	9.384	9.692	0.091	0.168		32.16
	5	6.802	9.759	0.066	0.168		23.47
	6	5.491	9.693	0.053	0.168		18.82

Table 22. The calculated amount of sulfate in each sample from the washing steps.

Sample	**Washing step**	**Average (µM)**	**Dilution**	**Total (mM)**	**Water (dm^3)**	**Ash (kg)**	**Sulfate (mg/kg DS)**
1	1	126.641	100.680	12.75	0.165	0.0165	12222.84
	2	30.950	96.615	2.99	0.165		2868.41
	3	18.243	100.169	1.83	0.165		1751.34
	4	167.067	9.897	1.65	0.165		1584.76
	5	146.663	9.808	1.44	0.165		1378.94
	6	132.252	9.723	1.29	0.165		1232.58
2	1	118.199	99.531	11.76	0.166	0.0166	11291.38
	2	28.129	98.864	2.78	0.166		2670.10
	3	17.911	98.885	1.77	0.166		1699.61
	4	169.394	9.782	1.66	0.166		1590.15
	5	144.702	9.804	1.42	0.166		1361.71
	6	134.405	9.755	1.31	0.166		1258.53
3	1	115.712	98.817	11.43	0.168	0.0169	10954.67
	2	28.887	98.440	2.84	0.168		2723.74
	3	18.255	99.767	1.82	0.168		1744.59
	4	170.647	9.692	1.65	0.168		1584.76
	5	147.918	9.759	1.44	0.168		1382.84
	6	135.037	9.693	1.31	0.168		1254.04

APPENDIX VII

Table 23 shows how much of the chlorides that are removed after each washing step and Table 24 shows the amount of removed sulfur.

Table 23. The amount of removed chlorides during the washing steps.

Wash nr	Concentration chloride in bottom ash (% DS)	Average leached chloride (mg/kg DS)	Average leached chloride (% DS)	Amount of removed chloride (%)	Total amount of removed chloride (%)
1	0.26	1698.245	0.170	65.32	65.32
2		195.070	0.020	7.50	72.82
3		130.540	0.013	5.02	77.84
4		30.658	0.003	1.18	79.02
5		23.130	0.002	0.89	79.91
6		24.365	0.002	0.94	80.85

Table 24. The amount of removed sulfur from the washing steps.

Wash nr	Concentration sulfur in bottom ash (% DS)	Average leached sulfate (mg/kg DS)	Average leached sulfate (mmol/kg DS)	Average leached sulfur (mg/kg DS)	Average leached sulfur (% DS)	Amount of removed sulphur (%)	Total amount of removed chloride (%)
1	1.5	11489.63	119.60	3835.23	0.38	25.57	25.57
2		2754.08	28.67	919.31	0.09	6.13	31.70
3		1731.85	18.03	578.09	0.06	3.85	35.55
4		1586.56	16.52	529.59	0.05	3.53	39.08
5		1374.50	14.31	458.81	0.05	3.06	42.14
6		1248.39	13.00	416.71	0.04	2.78	44.92

APPENDIX VIII

Table 25 shows the water amount in the sieved 0-5 mm bottom ash less than 4 mm. Table 26 shows the water amount in the washed bottom ash used for casting the WashedBA concrete samples.

Table 25. The amount of water in bottom ash with particle sizes less than 4 mm.

Sample	Ash before (g)	Ash after drying (g)	Water amount (%)
1	65.65	53.85	17.97
2	69.15	57.00	17.56
3	67.41	55.32	17.94

Table 26. The amount of water in the washed bottom ash used for the WashedBA concrete cubes.

Sample	Ash before (g)	Ash after drying (g)	Water amount (%)
1	72.32	61.87	23.62
2	72.82	62.71	23.02
3	72.97	62.00	24.11

APPENDIX IX

Table 27 shows the results from the compressive strength tests for REF, BA100, BA50-50 and WashedBA samples after 9-11 days. Table 28 shows the values used for calculating the w/c ratio. Table 29 shows the compressive strength of the REF, BA100 and BA50-50 concrete cubes after 26 and 27 days.

Table 27. The compressive strength after 9-11 days for REF, BA50-50, BA100 and WashedBA

Sample	Compressive strength (MPa)	Tested after X days
REF 1	45.89	10
REF 2	43.72	10
REF 3	39.78	10
BA100_T1	18.74	10
BA100_T2	19.23	10
BA100_T3	19.41	10
BA50-50_T1	27.43	9
BA50-50_T2	26.60	9
BA50-50_T3	25.17	9
WashedBA_T1	15.98	11
WashedBA_T2	15.83	11
WashedBA_T3	15.98	11

Table 28. The amount of water in the concrete cubes and the calculated w/c ratio for the mixtures.

Mixture	Cement (g)	Bottom ash (g)	Water in bottom ash (%)	Total water amount (g)	w/c ratio
REF	450.04	0	0	225.11	0.50
BA100	450.02	1350.10	17.82	533.23	1.18
BA50-50	450.02	675.07	17.82	379.07	0.84
WashedBA	450.11	1350.04	23.58	543.37	1.21

Table 29. The compressive strength after 26-27 days for three cubes of each mixture; REF, BA100 and BA50-50.

Sample	Compressive strength (MPa)	Tested after X days
REF 4	48.60	27
REF 5	50.63	27
REF 6	44.01	27
BA100_T5	20.21	27
BA100_T6	22.70	27
BA100_T7	22.23	27
BA50-50_T4	28.15	26
BA50-50_T5	28.26	26
BA50-50_T6	28.89	26

APPENDIX X

Table 30 and Table 31 represents the concentrations of the investigated elements from the leaching of the bottom ash, the washed bottom ash and the concrete samples; REF, BA50-50, BA100 and WashedBA. Table 30 shows the concentrations from ICP-MS in ppb and Table 31 shows the concentrations of copper and zinc in from ICP-OES in ppm. All the samples were diluted around 10 times with 0.1 M HNO_3, and the dilution factor, ash/concrete amount and the amount of deionized water for each sample used for the leaching can be seen in Table 32.

Table 30. The concentrations in ppb from ICP-MS.

Sample	Cr (ppb)	Ni (ppb)	As (ppb)	Cd (ppb)	Sb (ppb)	Hg (ppb)	Pb (ppb)
1. Bottom ash_1	5.420	0.794	0.427	0.032	0.965	0.490	0.336
2. Bottom ash_2	2.935	0.776	0.395	0.033	1.195	0.746	0.385
3. Bottom ash_3	1.515	0.789	0.373	0.031	0.878	0.536	0.468
4. Washed bottom ash_1	5.435	2.814	0.293	0.025	1.926	0.422	0.355
5. Washed bottom ash_2	5.686	0.752	0.243	0.021	2.003	0.331	0.293
6. Washed bottom ash_3	3.582	0.746	0.246	0.024	2.403	0.346	0.348
7. Ref 1	0.943	1.027	0.204	0.015	0.282	0.090	6.757
8. Ref 2	0.873	1.303	0.230	0.064	0.350	0.082	4.228
9. Ref 3	1.169	1.065	0.218	0.015	0.330	0.079	2.601
10. BA100_T1	1.904	0.966	0.197	0.019	0.489	0.093	10.210
11. BA100_T2	1.628	0.999	0.232	0.020	0.544	0.083	67.804
12. BA100_T3	1.876	1.016	0.234	0.019	0.488	0.075	29.867
13. BA50-50 T1	1.153	1.016	0.247	0.016	0.631	0.074	11.832
14. BA50-50 T2	1.228	1.066	0.218	0.017	0.465	0.057	12.324
15. BA50-50 T3	1.310	1.222	0.214	0.017	0.449	0.057	10.477
16. Washed BA_T1	1.910	1.404	0.230	0.016	0.906	0.052	9.362
17. Washed BA_T2	1.064	1.008	0.191	0.027	0.618	0.054	18.036
18. Washed BA_T3	3.049	2.139	0.173	0.021	0.535	0.049	21.270

Table 31. The concentrations of copper and zinc in ppm from the ICP-OES.

Sample	Cu (ppm)	Zn (ppm)
1. Bottom ash_1	0.014	0.004
2. Bottom ash_2	0.013	0.010
3. Bottom ash_3	0.012	0.005
4. Washed bottom ash_1	0.012	0.002
5. Washed bottom ash_2	0.008	0.003
6. Washed bottom ash_3	0.009	0.004
7. Ref 1	0.008	0.008
8. Ref 2	0.013	0.040
9. Ref 3	0.011	0.007
10. BA100_T1	0.008	0.005
11. BA100_T2	0.007	0.007
12. BA100_T3	0.010	0.008
13. BA50-50 T1	0.011	0.005
14. BA50-50 T2	0.010	0.005
15. BA50-50 T3	0.007	0.006
16. Washed BA_T1	0.006	0.005
17. Washed BA_T2	0.010	0.004
18. Washed BA_T3	0.016	0.005

Table 32. The dilution factor for the ICPOES and ICP-MS measurements and the amount of ash/concrete and water used for the leaching.

Sample	Dilution factor	Ash/concrete DS (g)	Amount of leached water (g)
1. Bottom ash_1	9.933	8.003	80.030
2. Bottom ash_2	9.969	8.003	80.002
3. Bottom ash_3	9.883	8.007	80.028
4. Washed bottom ash_1	9.878	8.005	80.019
5. Washed bottom ash_2	9.858	8.009	80.010
6. Washed bottom ash_3	9.809	8.001	80.027
7. Ref 1	9.893	8.008	80.015
8. Ref 2	9.811	8.001	80.027
9. Ref 3	9.886	8.006	80.028
10. BA100_T1	9.904	8.034	80.358
11. BA100_T2	9.853	8.027	80.288
12. BA100_T3	9.788	8.059	80.586
13. BA50-50 T1	9.782	8.006	80.036
14. BA50-50 T2	9.768	8.007	80.014
15. BA50-50 T3	9.834	8.002	80.033
16. Washed BA_T1	9.857	8.008	80.014
17. Washed BA_T2	9.867	8.006	80.029
18. Washed BA_T3	9.859	8.008	80.014

APPENDIX XI

Table 33 shows the concentrations of chloride from the leached bottom ash, washed bottom ash and the concrete samples; REF, BA50-50, BA100 and WashedBA and Table 34 shows the concentration of sulfate. For the first six samples (sample 1-6) the limit of detection was calculated to 0.56 µM for chloride and 1.28 µM for sulfate with LINEST in Excel. For sample 7-9 and 13-18 was the limit of detection calculated to 0.79 µM for chloride and 0.48 µM for sulfate. For sample 10-12 the limit of detection calculated to 0.70 µM for chloride and 1.64 µM for sulfate.

Table 33. The concentration of chloride in the leached samples of bottom ash, washed bottom ash and concrete cubes.

Sample	**First/second sampling (µM)**	**Average (µM)**	**Dilution**	**Total (mM)**	**Water (dm^3)**	**Ash/ Concrete DS (g)**	**Chloride (mg/kg DS)**
1. Bottom ash_1	38.534 / 36.856	37.695	94.938	3.579	80.030	8.003	1268.686
2. Bottom ash_2	- / 33.475	33.475	95.311	3.191	80.002	8.003	1130.807
3. Bottom ash_3	32.222 / 32.427	32.325	93.185	3.012	80.028	8.007	1067.321
4. Washed bottom ash_1	4.054 / 4.213	4.134	94.301	0.390	80.019	8.005	138.133
5. Washed bottom ash_2	2.605 / 2.607	2.606	98.626	0.257	80.010	8.009	91.029
6. Washed bottom ash_3	3.155 / 4.118	3.637	97.064	0.353	80.027	8.001	125.162
7. Ref 1	7.378 / 7.311	7.345	19.004	0.140	80.015	8.008	49.443
8. Ref 2	7.248 / 7.823	7.536	18.857	0.142	80.027	8.001	50.388
9. Ref 3	6.909 / 6.639	6.774	19.933	0.135	80.028	8.006	47.851
10. BA100_T1	5.979 / 6.058	6.019	95.886	0.577	80.358	8.034	204.645
11. BA100_T2	5.611 / 5.517	5.564	96.200	0.535	80.288	8.027	189.798
12. BA100_T3	5.397 / 6.610	6.004	95.358	0.572	80.586	8.059	202.956
13. BA50-50 T1	30.356 / 31.308	30.832	18.665	0.575	80.036	8.006	203.974
14. BA50-50 T2	30.789 / 30.092	30.441	18.552	0.565	80.014	8.007	200.079
15. BA50-50 T3	30.841 / 30.161	30.501	18.943	0.578	80.033	8.002	204.861
16. Washed BA_T1	24.059 / 25.68	24.870	18.424	0.458	80.014	8.008	162.321
17. Washed BA_T2	24.039 / 22.422	23.231	18.847	0.438	80.029	8.006	155.151
18. Washed BA_T3	24.863 / 25.001	24.932	18.571	0.463	80.014	8.008	164.024

Table 34. The concentration of sulfat in the leached samples.

Sample	First/second sampling (µM)	Average (µM)	Dilution	Total (mM)	Water (dm^3)	Ash (kg)	Sulfate (mg/kg DS)
1. Bottom ash_1	n.d. / n.d.	n.d.	94.938	-	80.030	8.003	-
2. Bottom ash_2	n.d. / n.d.	n.d.	95.311	-	80.002	8.003	-
3. Bottom ash_3	n.d. / n.d.	n.d.	93.185	-	80.028	8.007	-
4. Washed bottom ash_1	n.d. / n.d.	n.d.	94.301	-	80.019	8.005	-
5. Washed bottom ash_2	n.d. / n.d.	n.d.	98.626	-	80.010	8.009	-
6. Washed bottom ash_3	n.d. / n.d.	n.d.	97.064	-	80.027	8.001	-
7. Ref 1	3.437 / 3.154	3.300	19.004	0.063	80.015	8.008	60.114
8. Ref 2	1.891 / 1.252	1.891	18.857	0.036	80.027	8.001	34.262
9. Ref 3	1.304 / 1.342	<DL	19.933	-	80.028	8.006	-
10. BA100_T1	n.d. / 0.542	0.542	95.886	0.052	80.358	8.034	49.937
11. BA100_T2	0 629 / 0.473	0.629	96.200	0.061	80.288	8.027	58.139
12. BA100_T3	0.556 / 0.185	0.556	95.358	0.053	80.586	8.059	50.931
13. BA50-50 T1	1.454 / 1.440	<DL	18.665	-	80.036	8.006	-
14. BA50-50 T2	1.125 / 0.780	<DL	18.552	-	80.014	8.007	-
15. BA50-50 T3	1.179 / 1.267	<DL	18.943	-	80.033	8.002	-
16. Washed BA_T1	1.035 / 0.774	<DL	18.424	-	80.014	8.008	-
17. Washed BA_T2	0.389 / 0.689	<DL	18.847	-	80.029	8.006	-
18. Washed BA_T3	0.698 / 0.343	<DL	18.571	-	80.014	8.008	-