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Recovered Municipal Solid Waste Incineration Bottom Ash: Aggregate-Like Products for Civil Engineering Structures

Tampere 2017

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Thesis for the degree of Doctor of Science in Philosophy to be presented with due permission for public examination and criticism in Rakennustalo Building, Auditorium RG202, at Tampere University of Technology, on the 10th of November 2017, at 12 noon.

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Abstract

The European Union is currently aiming towards a circular economy. This economic model focuses on reusing materials and creating added value with recycled products using smart solutions. In this research, such an advanced approach was also chosen. Recovered municipal solid waste incineration bottom ash (MSWI BA) was used to create aggregate-like products for civil engineering structures. The aim was to potentially increase the value and the image of this waste-derived aggregate in civil engineering applications. The use of waste-derived aggregates in civil engineering is especially attractive and beneficial. Natural and crushed rock aggregates are scarce in many locations and vast amounts of materials are required in different types of structures. Conversely, these drivers can also cause drawbacks in the appropriate use of waste-derived aggregates. For example, building highway noise barriers from such aggregates can hardly be considered as utilization; in fact, it is merely dumping the potentially high-value material from one site to another, and thus, avoiding high waste tax costs for landfilling. In this study, the aggregate-like products from recovered MSWI BA were therefore designed as a replacement of natural and crushed rock aggregates in the structural layers of road and field structures. In such structures, the costs of natural and crushed rock aggregates are generally higher than, for example, those used in the noise barriers, and therefore, added value from reusing this waste-derived aggregate could be gained.

Europe produces approximately 20 million tonnes of MSWI BA every year. Untreated MSWI BA contains large amounts of both non-ferrous (NF) and ferrous (F) metals. As a result, the development for metal recovering technologies has been of interest to many parties for the past decade. In this study, an advanced Dutch dry treatment technology called ADR (*Advance Dry Recovery*) was used to treat approximately 60.000 tonnes of MSWI BA from one waste incineration plant in Finland between the years 2013 - 2014. The treatment process efficiently separates NF and F metals from MSWI BA, generating 75 – 85 % of mineral fractions in different grain sizes (0-2, 2-5, 5-12 and 12-50 mm). These mineral fractions were first characterized thoroughly based on their technical and environmental properties. The aim was to properly understand what type of materials were generated from the process. Thereafter, different material mixtures were designed from these mineral fractions using the mathematical proportioning of aggregates. The aim was to create aggregate-like products for different structural layers (filtration, sub-base and base layers) of, for example, road and field structures. Three products were designed, which were considered the most well suited based on their correspondence to

the grain size distribution requirements of respective natural and crushed rock aggregates. These products were further analysed from their technical, mechanical and environmental points of view in the laboratory. The aim of these analyses was to understand the possibly unique material properties (e.g., sensitivity to changes in moisture content) that can affect the usability and constructability of these aggregate-like products in civil engineering. Finally, the laboratory findings were verified with a field performance study in which an interim storage field was built within a waste treatment centre using these aggregate-like products designed from recovered MSWI BA.

Based on the technical and mechanical properties of the material, the aggregate-like products from recovered MSWI BA were considered the most suitable to be used in the lower structural layers of road and field structures. For base layers, the material cannot be recommended unless an additional base layer of natural aggregate or alternatively thicker asphalt pavement is constructed on top. The main reason for this is that MSWI BA particles are prone to crushing and most likely unable to resist the high stresses occurring in the upper parts of road and field structures. This study also demonstrated that the stiffness and strength properties of recovered MSWI BA were strongly dependent on the material's aging and the changes in its moisture content, especially when the material dries out. For example, in this study the resilient modulus (M_r) was even quadrupled when the material's moisture content decreased 5-7 %. With respect to the environmental properties of ADR recovered MSWI BA, the leaching of antimony (Sb) and chloride (Cl^-) were identified as the main possible hindrances to the utilization of this material in civil engineering in Finland. On the other hand, the leaching behaviour of these substances showed consistency between the laboratory experiments and the field studies. These results therefore supported the reliability of laboratory leaching test results on which the utilization decisions in real construction projects are generally based.

In general, the findings of this study indicated that the aggregate-like products designed from recovered MSWI bottom ash can be a valuable replacement of natural aggregates in certain structures as long as their unique properties are taken into account. When properly used, the attractiveness of replacing natural aggregates with the recovered MSWI BA can be increased, and the dumping of this material in landfill sites and noise barriers can be decreased. Finally, this study has also provided important background data for the finnish policymakers in order for them to decide that recovered MSWI BA can be added to the scope of a renewed Government Decree (YM14/400/2016). This Decree will further facilitate the use of waste-derived aggregates such as recovered MSWI BA in civil engineering in Finland.

Tiivistelmä

Euroopan Unionin tavoitteena on tällä hetkellä kiertotalouden edistäminen. Kiertotalouden perusajatus on se, että materiaaleja ja raaka-aineita kierrätetään ja lisäksi kierrätettäville tuotteille pyritään saamaan lisäarvoa erilaisin innovatiivisin ratkaisuin. Kyseinen perusajatus oli myös tämän tutkimuksen lähtökohtana, jossa käsitellystä jätteenpolton pohjakuonasta suunniteltiin kiviaineksen kaltaisia tuotteita maarakennushyötykäyttöön. Jätteiden hyötykäyttö erityisesti maarakentamisessa on houkuttelevaa, koska neitseellisiä kiviaineksia ei enää kaikilla alueilla ole saatavilla ja materiaalia tarvitaan runsaasti erilaisissa rakenteissa. Tällainen kysyntä saattaa toisaalta myös vääristää jätemateriaalien teknis-taloudellisesti tarkoituksenmukaista hyödyntämistä maarakentamisessa. Potentiaalisesti arvokkaita jätemateriaaleja nimittäin sijoitetaan esimerkiksi valtateiden meluvalleihin, vaikka todellisuudessa tämä on vain näiden jätemateriaalien läjittämistä jätekeskusten loppusijoitusalueilta toisaalle, jotta niistä ei tarvitsisi maksaa korkeita jäteveroja. Tämän tutkimuksen tavoitteena oli ottaa uudenlainen näkökulma käsittelyn jätteenpolton pohjakuonan hyödyntämiseen maarakentamisessa. Käsitellystä jätteenpolton pohjakuonasta suunniteltiin kiviaineksen kaltaisia tuotteita teiden ja kenttäalueiden rakennekerroksiin materiaalin arvon ja positiivisen imagon nostamiseksi.

Euroopassa syntyy vuosittain noin 20 miljoonaa tonnia jätteenpolton pohjakuonaa. Käsittelemätön pohjakuona sisältää runsaasti ei-rauta- ja rautametalleja, minkä vuoksi pohjakuonan käsittelytekniikat metallien talteen ottamiseksi ovat kehittyneet nopeasti viimeisen kymmenen vuoden aikana. Tässä tutkimuksessa käsiteltiin noin 60 000 tonnia Mustasaaren arinapolttolaitokselta syntynyttä pohjakuonaa hollantilaiseen ADR (*Advanced Dry Recovery*) kuivaerotustekniikkaan perustuvalla laitteistolla vuosien 2013 – 2014 aikana. Käsittelyn aikana metallit eroteltiin mineraaliaineksesta, jonka osuus koko pohjakuonan määrästä on noin 75 – 85 %. Tutkimuksen ensimmäisessä vaiheessa mineraaliainesten eri raekokojen (0-2, 2-5, 5-12 ja 12–50 mm) tekniset ja ympäristökelpoisuusominaisuudet tutkittiin perusteellisesti. Toisessa vaiheessa mineraaliaineksista suunniteltiin matemaattisen suhteutuksen avulla kiviaineksen kaltaisia tuotteita, jotka rakeisuusjakautumiensa puolesta arvioitiin hyvin soveltuviksi tie- ja kenttäalueiden rakennekerroksiin (suodatin-, jakava ja kantava kerros). Näiden tuotteiden teknisiä, mekaanisia ja ympäristökelpoisuusominaisuuksia tutkittiin erilaisin menetelmin laboratorio-olosuhteissa. Lisäksi selvitettiin materiaalille ominaisia erityispiirteitä, joilla voi olla vaikutusta sen rakennettavuuteen maarakentamisessa. Laboratoriokokeista saatuja tuloksia testattiin lopuksi myös kenttäolosuhteissa Lakeuden Etapin Ilmajoen jätteenkäsittelyalueelle

vuonna 2014 rakennetulla välivarastokentällä, jonka rakennekerroksissa käytettiin pohjakuonasta valmistettuja tuotteita.

Tutkimustulosten perusteella jätteenpolton pohjakuonasta suunnitellut kiviaineksen kaltaiset tuotteet soveltuvat teknisiltä ja mekaanisilta ominaisuuksiltaan erityisen hyvin etenkin alempiin rakennekerroksiin (suodatin- ja jakava kerros). Materiaalia ei kuitenkaan nykytiedon valossa suositella käytettäväksi kantavassa kerroksessa, ellei kyseisen kuonarakenteen päälle rakenneta kantavaa kerrosta sora- tai kalliomurskeesta tai vaihtoehtoisesti paksumpaa asfalttipäällystettä. Suurin syy tähän on se, että kuonapartikkelit hienontuvat herkästi ja näin ollen ne eivät todennäköisesti kestäisi ylempiin rakennekerroksiin kohdistuvaa kovaa kuormitusta. Saadut tutkimustulokset osoittivat myös, että materiaalin jäykkyys- ja lujuusominaisuudet ovat hyvin riippuvaisia materiaalin ikääntymisestä ja vesipitoisuuden muutoksista ja nämä ominaisuudet paranevat etenkin silloin, kun materiaali kuivuu. Tässä tutkimuksessa esimerkiksi havaittiin, että materiaalin jäykkyysmoduuli (M_r) kasvoi nelinkertaiseksi vesipitoisuuden laskiessa 5-7 %. Materiaalin ympäristökelpoisuutta arvioitaessa etenkin antimonin (Sb) ja kloridin (Cl^-) liukoisuudet saattavat heikentää materiaalin hyödyntämismahdollisuuksia maarakentamisessa. Toisaalta näiden yhdisteiden liukoisuuskäyttäytyminen sekä kenttä- että laboratorio-olosuhteissa oli samankaltaista. Näin ollen pohjakuonalle laboratoriossa tehtyjä liukoisuuskokeita voidaan pitää varsin luotettavina kuvaamaan materiaalin liukoisuuskäyttäytymistä myös todellisissa käyttökohteissa, joissa on enemmän olosuhdevaihteluita.

Tämän väitöskirjan tulokset osoittavat, että käsitelty jätteenpolton pohjakuona voi olla arvokas materiaali korvaamaan neitseellisiä raaka-aineita teiden ja kenttäalueiden rakennekerroksissa, kunhan sen erityispiirteet otetaan huomioon. Materiaalin houkuttelevuutta ja arvoa maarakentamisessa voidaan oikein käytettynä lisätä, ja samalla myös vähentää sen loppusijoittamista kaatopaikoille sekä valtateiden meluvalleihin. Lisäksi väitöskirjatutkimuksen tulokset ovat mahdollistaneet sen, että käsitellyt jätteenpolton pohjakuonat ollaan hyväksymässä parhaillaan uudistuksen alla olevaan kansalliseen asetukseen, jonka tavoitteena on entisestään edistää jätemateriaalien hyötykäyttöä maarakentamisessa.

Preface and acknowledgments

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List of Symbols and Abbreviations

AASHTO   American Association of State Highway and Transportation Officials

ADR   Advanced Dry Recovery

APC   air pollution control

ASTM   American Society for Testing and Materials

BL   base layer

c'   effective cohesion

CEWEP   Confederation of European Waste-to-Energy Plants

CVAAS   Cold Vapour Atomic Absorption Spectroscopy

CVAFS   Cold Vapour Atomic Fluorescence Spectroscopy

DOC   dissolved organic carbon

DoC   degree of compaction

E   stiffness modulus

E_i bearing capacity

Ec   electrical conductivity

EC   European Commission

EU   European Union

F   ferrous

FEM   Finite Element Method

FL   filtration layer

FMI   Finnish Meteorological Institute

HS   Hardening soil-model

IBA	incineration bottom ash
IBC	intermediate bulk container
IC	Ion Chromatography
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
IR	Infrared Detector
IS	Ion Selective
ISWA	International Solid Waste Association
k	hydraulic conductivity
λ	thermal conductivity
LDPE	low-density polyethylene
$L\ S^{-1}$	liquid to solid ratio, $L\ kg^{-1}$
M_r	resilient modulus, MPa
M_s	secant modulus, MPa
MSW	municipal solid waste
MSWI	municipal solid waste incineration
MSWI BA	municipal solid waste incineration bottom ash
NDG	nuclear density gauge
NF	non-ferrous
OWC	optimum water content
θ	the sum of principal stresses
PANK ry	Päällystealan neuvottelukunta Ry [Advisory board of pavement sector]
PEH	polyethylene, high density

ρ_d	dry density
ρ_{dmax}	maximum dry density
RDF	refuse derived fuel
RIL	Suomen Rakennusinsinöörien Liitto ry [Finnish Association of Civil Engineers]
RTS	Rakennustietosäätiö [Building Information Foundation]
SBL	sub-base layer
SFS	Suomen Standardisoimisliitto ry [Finnish Standard Association]
SPLT	static plate load test
Tekes	Innovaatiorahoituskeskus [Finnish Funding Agency for Technology and Innovation]
TOC	total organic carbon
UEPG	Union Européenne des Producteurs de Granulats [European Aggregates Association]
WHO	World Health Organization
W-t-E	Waste-to-Energy
WV	water volymeter
w	water content

List of Publications

This thesis is based on the following publications, which are referred to in the text by their respective Roman numerals (*Papers I-V*).

I.   Sormunen, L. A. & Rantsi, R. 2015. To fractionate municipal solid waste incineration bottom ash: Key for utilisation? *Waste Management & Research,* 33: 995 – 1004. Published by SAGE Publications.

II.   Sormunen, L. A, Kalliainen, A., Kolisoja, P. & Rantsi, R. 2016. Combining mineral fractions of recovered MSWI bottom ash: improvement for utilization in civil engineering structures. *Waste and Biomass Valorization*, 8: 1467 – 1478. Published by Springer.

III.   Sormunen, L. A. & Kolisoja, P. 2016. Mechanical properties of recovered municipal solid waste incineration bottom ash: the influence of aging and changes in moisture content. *Road Materials and Pavement Design*, 1 – 19. Published by Taylor & Francis Online.

IV.   Sormunen, L. A. & Kolisoja, P. 2017. Construction of an interim storage field using recovered municipal solid waste incineration bottom ash: Field performance study. *Waste Management*, 64: 107 – 116. Published by Elsevier.

V.   Sormunen, L. A., Kaartinen, T. & Rantsi, R. MSWI BA treated with Advanced Dry Recovery: comparing materials leaching properties in three different study scales. Manuscript submitted to *International journal of sustainable engineering*

Contribution of the author to the publications

Publication I

The author of this dissertation is responsible for initiating this paper and had the main responsibility in data gathering, analysis, and writing. Sample collection and analysis were done by the personnel of Suomen Erityisjäte Oy and two private laboratories (Envitop Oy, VTT). The co-author commented on the manuscript.

Publication II

The author of this dissertation is responsible for initiating this paper and had a responsibility in data gathering. Most of the analysis and writing was done by the author, but Antti Kalliainen was solely responsible for the FEM-modelling and writing the methodologies and results for that process. Sample collection and laboratory analysis was done by the personnel of Suomen Erityisjäte Oy and private laboratories (Envitop Oy, VTT, and Ahma Ympäristö Oy). Other co-authors commented on the manuscript.

Publication III

The author of this dissertation was mainly responsible for writing the paper and the co-author mainly commented on the manuscript. The data collection and analysis was done in co-operation with the co-author. The triaxial tests were performed by the personnel of TUT civil engineering laboratory.

Publication IV

The author of this dissertation had the responsibility for data gathering, analysis and writing. The co-author commented on the manuscript. Sample collection and field measurements were done by private companies (Suunnittelutoimisto Aluetekniikka Oy and Ramboll Finland Oy).

Publication V

The author of this dissertation had the main responsibility for data gathering, analysis and writing of the paper. Tommi Kaartinen participated in data analysis and all co-authors commented on the manuscript. Ute Kalbe from BAM also commented on the manuscript. Leachate sample collection and laboratory analysis were done by the personnel of Lakeuden Etappi Oy and a private laboratory Ahma Ympäristö Oy.

1 Introduction

1.1 Background of the study

In Europe, the demand for aggregates used in civil engineering is approximately 2.6 billion tonnes every year (UEPG, 2016). From all these produced aggregates, the proportion of natural resources from quarries and pits is up to 87%, whereas only 8% are secondary raw materials such as recycled, re-used, and manufactured aggregates (UEPG, 2016). Considering the massive aggregate demand, it is certain that natural resources will become scarcer in the future, especially in countries with densely populated areas. In addition, the negative environmental impacts of large quarries and pits will also continue to raise concern in those countries where substantial mineral reserves still exist.

To preserve natural resources and in turn increase the utilization of waste-derived aggregates in civil engineering, many political and economic drivers have been established in Europe. For example, the Circular Economy Package of European Commission has set considerable targets for maximizing the recycling and re-use of waste materials (EC, 2016). Furthermore, the high waste tax costs for landfilling in many countries (e.g., 70 € t^{-1} in Finland, according to the Finnish Waste Tax Act 1126/2010) are already pushing towards waste recycling and utilization instead of landfilling. Conversely, these demands and drivers can also cause drawbacks in the appropriate use of waste-derived aggregates. For instance, building highway noise barriers from certain waste-derived aggregates can hardly be considered as utilization, when in fact it is only transferring potentially high-value material from one site to another. Of course, with such structures plenty of material can be used at once, but it certainly does not increase the image nor the value of waste materials as replacement for natural and crushed rock aggregates.

In Finland, natural and crushed rock aggregates with tolerable prices are still available in almost every part of the country. In addition, the technical, mechanical, and environmental properties of certain waste-derived aggregates are not in many cases fully understood by material producers, designers, and construction companies. This in turn leads to the fact that the disadvantages and the possible risks associated in using these materials are generally considered too high, and natural or crushed rock aggregates are used instead.

In this thesis, aggregate-like products from recovered municipal solid waste incineration bottom ash (MSWI BA) were designed for the unbound structural layers of, for example, road and field structures. To assure the suitability and functionality of these aggregate-like products in the designated structures, their different material properties (technical, environmental and mechanical) were investigated thoroughly with various types of laboratory analysis and further verified with field experiments. Before discussing the methodologies and the results obtained in this study, the following three chapters (1.2 - 1.4) will first provide an overview of the origin of MSWI BA and its properties, followed by its treatment processes and utilization options based on the previously published literature.

1.2 Municipal solid waste incineration bottom ash (MSWI BA)

In Europe, waste incineration has increased up to 100% from 1995 to 2014, and approximately 88 million tonnes of waste were burnt in the European Waste-to-Energy (W-t-E) plants in the year 2014 (CEWEP, 2016, Eurostat, 2016). The benefits of waste incineration are twofold. First, it allows energy recovery from waste and, second, it reduces the amount of waste drastically (Chandler et al. 1997). Conversely, many different types of solid residues, such as MSWI BA, fly ash and air pollution control (APC) residues remain from the process (Astrup et al. 2016). The MSWI BA is the most abundant solid residue, accounting for 85 – 95% by weight of the solid by-products resulting from waste incineration (Izquierdo et al. 2001). For example, around 18 million tonnes of MSWI BA was generated in W-t-E-plants in Europe in the year 2014 (CEWEP, 2016). Most European W-t-E plants have adopted mass-burn technology for incinerating municipal solid waste (Astrup et al. 2016). Therefore, the following discussion of the MSWI BA properties and its treatment and utilization options considers only the MSWI BA generated from such plants. Other systems (e.g., refuse-derived fuel (RDF) systems) and their MSWI BAs are not discussed in this thesis, since they are beyond the scope of this study.

MSWI BA is the non-combustible part of incinerated waste that is discharged in most waste incineration plants at the end of the grate in to quenching tanks with water (Rogoff and Screve, 2011). Water cools down the material and prevents tertiary air from entering the combustion chamber (Astrup et al. 2016). As illustrated in Figure 1, MSWI BA is a highly heterogeneous material that consists of mainly minerals (glass, ceramics, ash, and melting products), ferrous (F) and non-ferrous (NF) metals, and unburnt organic material. Roughly speaking, 80 – 89 w-% of MSWI BA is minerals,

8 – 12 w-% F metals, and 2 – 5 w-% NF metals (CEWEP, 2016, Holm and Simon, 2017). The proportion of unburnt organic material is small (<1 w-%) in modern waste incineration plants (Holm and Simon, 2017), as it should be less than 3% (measured as TOC, Total organic carbon) according to the European Directive 2010/75/EU on industrial emissions (EU, 2010). The relative proportion of different components in MSWI BA is dependent on several things, such as the burning process conditions and the type of waste fed into the combustion chamber (Hyks and Astrup, 2009).

Figure 1 General composition of municipal solid waste incineration bottom ash

MSWI BA is alkaline material. The pH value for fresh MSWI BA is generally 10 – 12, and it decreases to 8 – 8.5 because of carbonation (Chandler et al. 1997, Meima and Comans, 1997). Initially high pH values are related to the presence of calcium hydroxide, which is one of the major elements present in MSWI BA (Stegemann et al. 1995). Other major elements of MSWI BA are aluminium (Al), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), natrium (Na), phosphorus (P) and silicon (Si), of which most are assumed to be present as oxides, hydroxides, and carbonates (An et al. 2014, Chandler et al. 1997, Hjelmar, 1996). From minor and trace elements, copper (Cu), lead (Pb) and zinc (Zn) are mostly enriched in MSWI BA (Chandler et al. 1997, Izquierdo et al. 2001, Hjelmar, 1996), but MSWI BA also contains small amounts of rare elements, such as gold (Au), silver (Ag), palladium (Pd), and platinum (Pt) (Allegrini et al. 2014, Funari et al. 2015).

The exact speciation of different substances in MSWI BA is not known and often especially metals are assumed to appear as oxides (e.g., ZnO, CuO, PbO) (Wahlström et al. 2016). This, however, is not the case in reality, and only a certain proportion of metals is present as oxides in waste from

thermal processes (Wahlström et al. 2016). The speciation of elements in MSWI BA has raised plenty of discussions between the European Commission and the stakeholders after the European Waste Framework Directive (2008/98/EC, Annex III) (EC, 2008a) was harmonized with the product legislation No 1272:2008 (CLP: Classification, labelling and packaging of substances and mixtures) (EC, 2008b). This is because CLP regulation defines that material hazardousness is related not to its total elemental or leachable content, but to the actual form in which an element is present in the product. As the speciation of elements in heterogeneous waste materials such as MSWI BA is not known and cannot be reliably measured with existing analytical methods (Wahlström et al. 2016), it is not that straightforward to assess the hazardousness of wastes according to the CLP regulation. Many studies have also shown that no correlation exists between the total concentration and the leaching of metals (e.g., Zn, Pb) in particular from MSWI BA (Hyks and Astrup, 2009, Saveyn et al. 2014). Therefore, it has been recognized that the risks posed by the potentially harmful substances from BA to surface water, soil, and groundwater should be determined based on the leaching and not on the total content of substances in the waste material (Dijkstra et al. 2006). All in all, the discussion on waste classification for MSWI BA continues, especially with regard to the definition for hazard property HP14 ("ecotoxicity"). Yet currently MSWI BA is mainly classified as non-hazardous waste in the EU member states (Lewin, 2009).

When considering further the leaching of potentially harmful substances from MSWI BA, soluble salts (chloride, sulphate) and certain metals (antimony, copper and molybdenum) have been considered especially critical substances with regard to the environmental impact of MSWI BA (Saveyn et al. 2014). As for highly soluble salts such as chloride, the leaching is determined by their availability (Hjelmar, 1996), whereas the leaching of major and trace elements from MSWI BA is mostly dominated by the changes in the material's mineralogical composition, interaction with reactive surfaces or complexing components with organic matter (e.g., Arickx et al. 2006, Cornelis et al. 2006, Dijkstra et al. 2006, Hjelmar, 1996, Meima and Comans, 1997). It varies between the elements which controlling mechanisms are affecting. For example, antimony leaching has been observed to be related to the presence of Ca antimonates and incorporation into ettringite (Cornelis et al. 2006, Cornelis et al. 2012), whereas copper leaching can be related to the residual amount of DOC (dissolved organic carbon) in MSWI BA (Arickx et al. 2006, Hyks et al. 2009). In addition, sulphate can remain in MSWI BA over long time periods, and its leaching is most likely related to the dissolution of ettringite because of carbonation (Freyssinet et al. 2002, Baranger et al. 2002).

1.3 MSWI BA treatment processes

Increasingly, MSWI BA is considered a source of high-value materials, especially due to its high F and NF metal contents (for average amounts, see Chapter 1.2). Much effort has been devoted to improving the treatment technologies of MSWI BA in order to increase the recovery rate of these metals (e.g., De Vries et al. 2012, Heinrichs et al. 2012, Holm and Simon, 2017, Rem et al. 2004). Conversely, the enhanced recovery of metals has also been expected to result in technically and environmentally more suitable minerals to be used as aggregates in different applications such as road construction and concrete product manufacturing (Astrup et al. 2016). For example, the removal of metallic aluminium can prevent problems with swelling and cracking of the final product, which has been considered one of the main hindrances to using MSWI BA in concrete products (e.g., Müller and Rübner, 2006, Pera et al. 1997). Additionally, metal recovery can improve the environmental behaviour of minerals to meet the regulatory limit values set in several countries for the use of waste-derived aggregates in different applications, such as road construction.

MSWI BA treatment processes can be generally divided into three categories as listed in Astrup et al. 2016: extraction and separation, chemical processes, and thermal processes (Table 1). From these techniques, mechanical separation (especially dry separation) is the most commonly applied technique in Europe (Holm and Simon, 2017, Hu et al. 2009). Additionally, natural aging and weathering is routinely used in many countries along with some sort of mechanical separation (e.g., Astrup, 2007). The following paragraphs will shortly explain these techniques in more detail. Other methods, such as chemical binding and thermal processes, are not further discussed in this thesis, since they are beyond the scope of this study.

Natural aging of MSWI BA entails stockpiling the material for a couple of weeks to several months under atmospheric conditions. In contact with atmospheric agents such as water (H_2O), oxygen (O_2), and carbon dioxide (CO_2) weathering reactions occur similar to those found in volcanic ashes (Zevenbergen and Comans, 1994, Zevenbergen et al. 1998). These weathering reactions include, for example, hydrolysis, hydration, dissolution/precipitation, carbonation, and oxidation/reduction that over time will lead to more stable mineral phases or phase assemblages (Meima and Comans 1997, Zevenbergen and Comans, 1994). Slow mineralogical changes (e.g., hydration of oxides such as CaO and MgO) and major ion leaching (e.g., chlorides and Ca) can in turn alter the mobility of metals (Astrup et al. 2016). For example, the leaching of zinc, copper, and lead has been observed to decrease during MSWI BA weathering (e.g., Arickx et al. 2006, Meima and Comans, 1997). Conversely, the leaching of oxyanion-forming metals such as antimony can increase during the weathering when the pH decreases (e.g., Keulen et al. 2016) or when sparingly soluble antimonates are formed with calcium (e.g., Cornelis et al. 2006, Cornelis et al. 2012 and Johnson et al. 1999). Additionally, the various mineralogical and chemical changes during MSWI BA weathering can lead to physical changes, such as pore cementation and changes in grain and pore size distribution (Sabbas et al. 2003).

Table 1 Different types of treatment processes for MSWI BA

Process	Technique	Method
Extraction and separation		
	Integrated scrubbing	Surplus water is added into a quenching tank
	Mechanical separation	Sequence of different types of processing and classification units, dry or wet process
	Extraction with liquids	Washing with water, acids, or chelating agents
Chemical		
	Natural aging and weathering	Stockpiling outdoors (weeks, months), where material reacts with atmospheric agents (H_2O, O_2 and CO_2)
	Forced carbonation	Accelerating natural aging and weathering by feeding atmospheric agents into the material (H_2O, O_2, CO_2)
	Chemical binding	Forming low-soluble mineral phases with stabilizing chemicals
Thermal		
	Vitrification/melting	Processing at 1000-1500°C together with glass-forming materials and melting/stabilizing oxides into single-phase glassy product
	Sintering	Heating ash alone or mixed with additives to temperatures below melting points (typically 900°) of the main constituents

(Source: Astrup et al. 2016)

MSWI BA weathering is affected by several factors, including pH, redox potential, temperature, and humidity conditions, as well as the concentration of, for example, CO_2 onsite (Sabbas et al. 2003). In addition, the time span for completion of all chemical and mineralogical transformations can be hundreds or thousands of years (Astrup et al. 2016). Depending on the metal in question, some studies have shown that even during a shorter period of natural weathering (i.e., less than 3 months), the leaching of Pb and Zn reached below the limit values imposed by the Flemish regulation for granulates used in construction materials (e.g., Arickx et al. 2006). Conversely, in other countries such as Denmark, natural weathering has not been considered sufficient to meet the respective regulatory limit values (Astrup, 2007, Sabbas et al. 2003), and other methods are recommended instead. Natural aging also forms mineral coatings on top of metal particles (Holm and Simon, 2017), which means that the recovery rate of metals can also decrease.

The mechanical separation of metals and minerals can be accomplished by dry and wet processing techniques or with a combination of the two. As already mentioned above, dry processing is still the most commonly applied technique in Europe (Holm and Simon, 2017, Hu et al. 2009), whereas different types of wet processing techniques or combinations of wet and dry processes have also been suggested (Berkhout et al. 2011, Holm and Simon, 2017, Hu and Bakker, 2015, Muchová and Rem, 2006, Muchová, 2010, Hu and Rem, 2009). Additionally, such techniques are already applied in some full-scale treatment plants, especially in the Netherlands (Born, 2016, Keulen et al. 2016). There the aim of these treatment plants is, first, to upgrade the MSWI BA minerals into construction materials that could be used as "freely applicable building materials", and second, to increase the recovery rate of NF metals (Born, 2016).

Conventional mechanical separation of MSWI BA normally consists of different types of sieves, crushers, magnetics, eddy current separators, manual separation and air classification (Holm and Simon, 2017). All these units either aim for grading, crushing or separating different types of materials, such as F and NF metals from MSWI BA. With conventional separation techniques, the recovery rate for ferrous metals can exceed 80% (Allegrini et al. 2014, Meylan and Spoerri, 2014, Muchová and Rem, 2006). Conversely, the recovery rate of NF metals can be limited especially due to the excessive amounts of fines on top of MSWI BA particles (e.g., Allegrini et al. 2014, Hu and Bakker, 2014, Hu et al. 2009, Muchová and Rem, 2006). For this reason, modern MSWI BA treatments usually aim to separate the material into many different size fractions, with special attention to the removal of fine particles (<2mm) (e.g., Allegrini et al. 2014, De Vries et al. 2009, De Vries et al. 2012, Holm and Simon, 2017, Hu and Bakker, 2015, Hu and Rem, 2009, Hu et al. 2009, Rem et al. 2004). The recovery of rare elements such as Au and Ag has been of particular interest due to their high market value (Allegrini et al. 2014). So far, however, the recovery of these elements has not been considered economically feasible with the current technologies applied for MSWI BA (Astrup et al. 2016).

Table 2 summarises some reported values on the recovery efficiencies of valuable NF metals from wet and dry treatment processes. As can be seen from Table 2, the recovery efficiencies of NF metals (~60-80%) and aluminium (Al: ~29 – 83%) can be to some extent higher in the wet treatment processes than those reported for dry treatment processes (NF: ~60%, Al: ~60-70%). As mentioned above, dry treatment processes are still more common in most European countries, even though wet processes can yield higher recovery efficiencies. Possible reasons for this are the lower investment costs and additional water, which is not needed for running the dry treatment processes. In addition, the sludge generated from the wet treatment processes can be difficult material to handle.

Table 2 Recovery efficiencies of MSWI BA treatment processes (wet and dry)

Type of technology	Recovery Efficiencies (%)			Reference
Wet	NF	Aluminium	Others (Cu/Zn)	
	58	67	38	Rem et al. 2004
	82	29	_[a]	Muchová, 2010
	73	83	_[a]	Hu and Bakker 2015, Muchová and Rem 2006, Hu and Rem, 2009
Dry				
	61	_[a]	_[a]	Meylan and Spoerri, 2014
	61	62	61	Allegrini et al. 2014
	_[a]	66	_[a]	De Vries et al. 2012, Hu et al. 2009

[a]Not reported

1.4 MSWI BA utilization

Over the past few decades, several possible utilization applications for MSWI BA have been studied. For example, MSWI BA has been used in different types of civil engineering applications, such as road construction (e.g., Astrup, 2007, Arm, 2003, Bruder-Hubscher et al. 2001, Dabo et al. 2009, de Windt et al. 2011, Hjelmar et al., 2007, Lidelöw and Lagerkvist, 2007) and landfill site structures (e.g., Puma et al. 2013). Several studies have also been conducted using MSWI BA as a replacement for Portland cement (e.g., Pan et al., 2008) or as an aggregate in hot-mix asphalts (e.g., An et al., 2014) and concrete products (e.g., Bertolini et al., 2004, Jurič et al., 2006, Keulen et al. 2016, Kokalj et al., 2005, Müller and Rübner, 2006, Pera et al., 1997, Toraldo et al. 2013). Additionally, some studies have considered other less common utilization possibilities, such as the use of MSWI BA in production of glass and ceramics (Barberio et al. 2010, Shalunenko and Korolyuk, 2010) or lightweight aggregates (Bethanis and Cheeseman, 2004, Cheeseman et al. 2005). MSWI BA has also been studied as a component in growing media of plants (Glordano et al. 1983, Rosen et al. 1994, Milla and Huang, 2013, Milla et al. 2013, Sormunen et al. 2016). In many European countries, MSWI BA is most commonly utilized in civil engineering structures (Astrup, 2007, Bruder-Hubscher et al. 2001, ISWA, 2006). Therefore, a more detailed discussion on this utilization application, especially with respect to road construction, is given in the following paragraphs of this chapter. Other utilization applications mentioned above are not further discussed in this thesis, since they are beyond the scope of this study.

Table 3 summarises previously reported studies on MSWI BA utilization in road construction. Figure 2, on the other hand, illustrates a typical structure on how MSWI BA has been utilized in civil engineering projects in the Netherlands (modified from Born, 2016). Another rather common utilization option for MSWI BA has also been highway noise barriers (e.g., Kivirock, 2011, Lamers and Kokmeijer, 2013). MSWI BA is most commonly used as either filling material in embankments or in the lower structural layers of roads (i.e. sub-base layers) (Table 3). It is also rather common that a liner such as HDPE-foil is used to cover the material in order to prevent excessive leaching of potentially harmful substances (Figure 2). MSWI BA is generally not considered suitable for the upper structural layers of roads, since MSWI BA particles are prone to crushing (Arm, 2003, Bendz et al. 2006), and therefore may not be able to resist the higher stresses that occur in the upper parts of road structures. This, however, has not been thoroughly investigated, since only a few studies in the past have focused on studying the mechanical properties of MSWI BA whether in the laboratory (e.g., Arm, 2004, Becquart et al. 2009, Chimenos et al. 2005, Wiles and Shepherd, 1999) or on a larger field scale (Arm, 2003, Bendz et al. 2006, Hartlén et al. 1999, Reid et al. 2001). In fact, even though MSWI BA is commonly used in many countries such as France, Denmark, the Netherlands, and the United Kingdom (Astrup, 2007, Becquart et al. 2009, Born, 2016 and York, 2014), especially the mechanical behaviour of MSWI BA is poorly known and is mainly based on empirical studies (Becquart et al. 2009).

Table 3 Examples of MSWI BA utilization in road construction

Country	Part of road structure in which MSWI BA was used	Treatment of MSWI BA before use	Reference[a]
Sweden	Filling / Embankment	Not defined	Åberg et al. 2006
France	Sub-base	Screening for metal removal + weathering	Dabo et al. 2009
Sweden	Sub-base	Screening for metal removal + weathering	Lidelöw and Lagerkvist 2007
Sweden /France	Sub-base	Not defined	de Windt et al. 2011
Denmark	Sub-base	Screening and magnetics for metal removal + weathering	Hjelmar et al. 2007
France	Filling / Embankment / Sub-base	Screening and magnetics for metal removal + weathering	Bruder-Hubscher et al. 2001

[a]These studies have only investigated the leaching of potentially hazardous substances from MSWI BA in the field, but not the material's technical or mechanical properties.
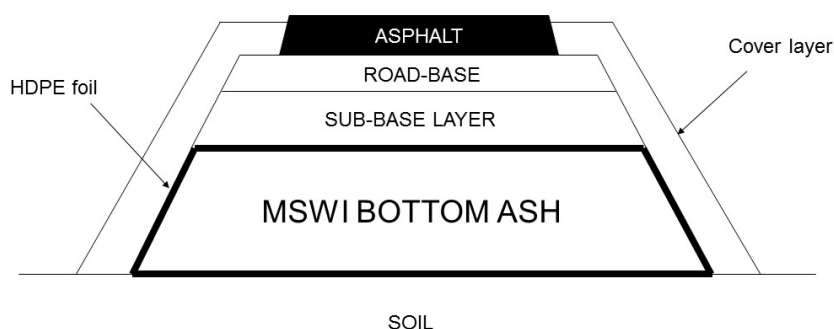
Figure 2 Schematic picture of a typical structure for the MSWI BA utilization in the Netherlands (modified from Born, 2016. Not to scale)

In regard to safe and sustainable use of MSWI BA in civil engineering, the environmental properties of this waste-derived aggregate should also be well understood. Therefore, several past studies have been conducted to understand the leaching behaviour of MSWI BA, either in the laboratory (e.g., Dijkstra et al. 2006, Ecke and Åberg, 2006, Forteza et al. 2004) or in the field conditions (e.g., Bruder-Hubscher et al., 2001, Dabo et al., 2009, De Windt et al., 2011, Hjelmar et al., 2007, Lidelöw and Lagerkvist, 2007, Åberg et al. 2006). The field studies are considered especially important, since in such studies the leaching of potentially harmful substances can be examined under more realistic conditions. As summarised in Table 3, most of the field studies conducted on understanding the leaching behaviour of MSWI BA has used bottom ash that has been treated with conventional treatment technologies (e.g., natural aging or moderate screening of metals). Conversely, comprehensive laboratory or field analysis on the different properties of MSWI BA minerals generated from any of the advanced treatment processes (see Chapter 1.3) has not yet been reported in the literature.

Finally, legislation regarding the assessment of waste materials suitability in civil engineering applications varies from one country to another (Saveyn et al. 2014). This means that different types of leaching tests and procedures are used for basic characterization and compliance testing among different European countries. In Finland, for example, the applicability of certain waste-derived aggregates in civil engineering applications is mainly assessed based on the Government Decree 591/2006 and its modifications 403/2009 and 1825/2009. At the time of writing, this Decree is being revised, and the Finnish Ministry of Environment aims to craft a new Decree (YM14/400/2016) in force in the year 2018. Compared with the old Government Decree, new waste materials have been added in this renewed legislation, and the leaching limit values have been recalculated with a risk-assessment approach for different types of structures (e.g., roads, fields, and embankments). At the

moment, it seems that the limit values for certain substances such as antimony and copper would be higher in most designated structures than under the old Government Decree. Conversely, in certain structures the limit values of, for example, chloride (2 400 mg kg^{-1}) would remain the same as in the old Decree.

It should also be mentioned that in the European Union (EU), the Construction Product Legislation (CPR 305/2011/EU) has been in force for a few years. Among many other things, this legislation aims to create a level playing field between EU member states with regard to using waste and secondary aggregates in construction (Keulen et al. 2016). For example, the CEN/TC 351 working group is currently developing harmonized leaching tests for the assessment of potential release of harmful substances in Europe (Saveyn et al. 2014). In the future, this can potentially influence the assessment criteria for waste utilization in Finland as well.

1.5 Problem statement

As already mentioned in Chapter 1.2, almost 20 million tonnes of MSWI BA are produced in Europe every year. Conversely, vast amounts of materials are needed in civil engineering structures (UEPG, 2016), whereas natural and crushed rock aggregates are or will be scarce, especially in densely populated areas where most of the construction takes place. In many European countries, including France and the Netherlands, MSWI BA has been used for decades in road construction, but mainly in embankments or in highway noise barriers with additional liners that impede the leaching of potentially harmful substances (Becquart et al. 2009, Born, 2016). These structures resemble those of landfill disposal sites, and therefore their construction with recovered MSWI BA can hardly be considered as utilization, but merely transferring potentially high-value material from one site to another in order to avoid high waste tax costs for landfilling.

Conversely, natural and crushed rock aggregates are available at moderately low prices in many European countries such as Finland, which does not make use of waste-derived aggregates that appealing. This is especially common if the properties of waste-derived aggregates are not well understood among designers, material producers, or construction companies. To increase the utilization of waste-derived aggregates in civil engineering, it is important to understand their technical, mechanical, and environmental properties thoroughly. As discussed in Chapter 1.3, the treatment processes for MSWI BA have developed rapidly over the past decade, whereas most of the studies conducted in the past on investigating the properties of MSWI BA have considered only the material that has been treated with conventional treatment technologies (see Chapter 1.4). It is therefore of utmost importance to investigate what the quality of MSWI BAs intended to be used in civil engineering structures currently is. This, however, does not only entail laboratory experiments, but also larger field performance studies, where the alternative waste-derived materials are tested in more realistic conditions. With such an approach, these materials could be steered for those structures that are

most suitable for their properties. When the suitability of using MSWI BA in those designated struc-tures has been comprehensively studied, it can be possible to avoid problems and high repair costs that may occur if the waste-derived aggregates are used in unfavourable locations and structures. In addition, added value and image may also be gained when the waste materials are used as ag-gregate-like products in those structures where the economic and environmental costs for natural and crushed rock aggregates are higher. This means, for example, using these materials in the structural layers of roads instead of embankments and noise barriers. The problem and a possible solution investigated in this study is further illustrated in Figure 3. In a linear economy, MSWI BA is treated with conventional technologies, and thereafter the MSWI BA minerals are dumped into high-way noise barriers or landfill sites. In this study, the aim was to move from this old economic model towards a circular economy. In practice, this means that first advanced treatment technology is used to treat MSWI BA, and then added value is gained from the outcome, i.e. the recycled aggregate-like products, that are used, for example, in road construction.
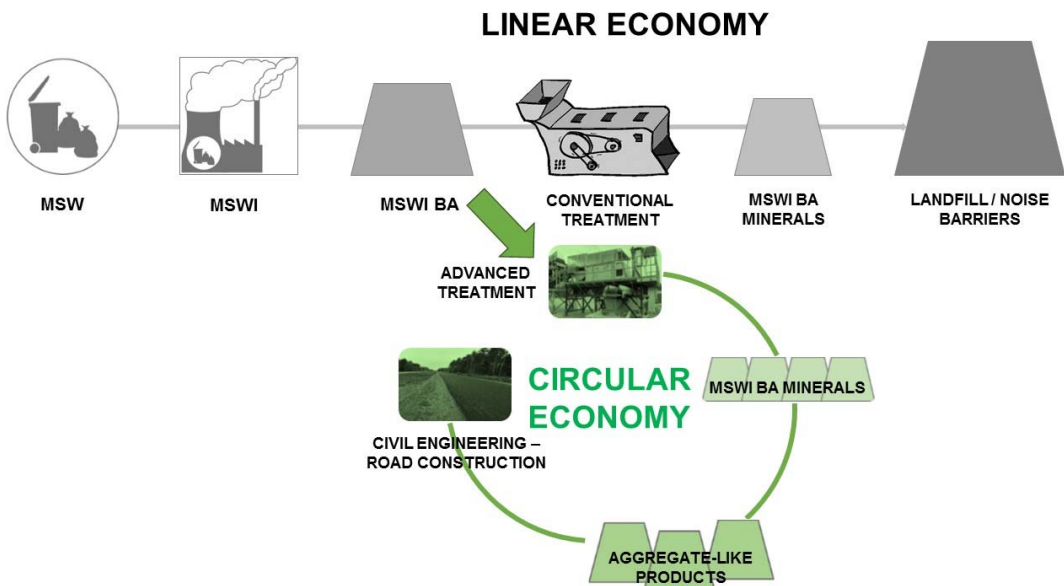
Figure 3 Towards circular economy with the recovered MSWI BA

1.6 Research objectives and questions

The main objective of this study was to design *aggregate-like products from recovered MSWI BA mineral fractions for civil engineering purposes* and to investigate *the technical, mechanical, and environmental properties of these products with different study scales.* The following specific objectives and research questions were formulated and addressed in the study:

Objective 1

To *characterize* the *recovered MSWI bottom ash mineral fractions* with respect to *their technical and environmental properties* in *laboratory experiments*.

1. What are the technical properties (e.g., grain size distributions) of recovered MSWI BA mineral fractions?
2. What is the total concentration (mg kg^{-1}) of potentially harmful substances in recovered MSWI BA mineral fractions?
3. How much do potentially harmful substances (mg kg^{-1}, LS^{-1} 10) leach from recovered MSWI BA mineral fractions?

Objective 2

To *combine* the *recovered MSWI bottom ash mineral fractions* into suitable **aggregate-like products for civil engineering structures** (unbound structural layers) based on their grain size distribution and to *investigate* the *technical, mechanical, and environmental properties* of these products in *laboratory experiments*.

4. Can mathematical proportioning of aggregates be used for the recovered MSWI BA mineral fractions in order to design aggregate-like products suitable to the unbound structural layers (filtration, sub-base, base) of roads and field structures?
5. What are the technical properties (e.g., maximum dry density, optimum water content) of the recovered MSWI BA mineral fraction products designed for the unbound structural layers (filtration, sub-base, base) of roads and field structures?
6. What are the mechanical properties (e.g., resilient modulus and shear strength) of the recovered MSWI BA mineral fraction products designed for the unbound structural layers (filtration, sub-base, base) of roads and field structures?
7. How much do potentially harmful substances (mg kg^{-1}) leach from the recovered MSWI BA mineral fraction products designed for the unbound structural layers (filtration, sub-base, base) of roads and field structures?

Objective 3

To **investigate** the **technical, mechanical, and environmental properties of recovered MSWI BA mineral fraction products** through a **field performance study** and to compare these results with the obtained laboratory results.

8. What are the measured degrees of compaction (DoC) of the recovered MSWI BA aggregate-like products in the different structural layers (filtration, sub-base and base) of a full-scale field structure?
9. What are the measured bearing capacities of the recovered MSWI BA aggregate-like products in the different structural layers (filtration, sub-base and base) of a full-scale field structure?
10. Are there any differences in the technical and mechanical properties of the recovered MSWI BA aggregate-like products between the laboratory and the field studies?
11. What is the concentration of potentially harmful substances (e.g., Cl$^-$ and Sb) in relation to the cumulative liquid-to-solid ratio (L S^{-1}) of the leachate collected from the field?
12. Are there any differences in the leaching behaviour of potentially harmful substances from the recovered MSWI BA mineral fraction products between the laboratory and the field studies?

1.7 Thesis structure

A general introduction to the European aggregate market, MSWI BA, its treatment processes and different utilization applications is presented in Chapter 1 (this chapter). This is followed by the problem statement and the general objectives and research questions set for this study. Figure 4 illustrates the overall research structure, which was used as a means to answer the research questions (Chapter 1.6). The research was outlined for investigating the technical, mechanical and environmental properties of the different mineral fractions generated during the advanced dry treatment process, and the aggregate-like products designed from these minerals for civil engineering purposes (i.e., filtration, sub-base and base layers of road and field structures).

Each MSWI BA mineral fraction was first characterized based on its technical and environmental properties in the laboratory. Detailed description of the analysis and the obtained results are given in the first publication (*Paper I*) of this dissertation, and a summary of methodologies and results is presented in Chapters 2.2 and 3.1, respectively.

The second publication (*Paper II*) presents the technical, mechanical, and environmental properties of the aggregate-like products designed from the separate MSWI BA mineral fractions based on their grain size distributions and their suitability for unbound structural layers of, for example, roads and field structures. In the third publication (*Paper III*), the mechanical properties (i.e., stiffness and shear

strength) of these MSWI BA aggregate-like products were studied in more detail in the laboratory in order to define design parameters for these products in civil engineering structures. The focus of this laboratory study was, in particular, to investigate the influence of aging and changes in moisture content on the mechanical properties of recovered MSWI BA over time. A summary of methodologies and the results from this part of the study are given in Chapters 2.3 and 3.2 of this dissertation, respectively.

In the final part of the study, a larger field performance study was conducted in the waste treatment centre of Lakeuden Etappi in Ilmajoki, Finland, where an interim storage field was constructed with those recovered MSWI BA aggregate-like products. The aim of this field study was twofold: first, to study the technical and mechanical properties of the structural layers built from MSWI BA aggregate-like products in the interim storage field, and second, to investigate the leaching behaviour of different substances in the field leachate and then compare those results with the previous laboratory leaching test results. In addition, a lysimeter study constructed elsewhere with the same materials was also used to obtain more data for comparison. The technical and mechanical properties of this field performance study are discussed in *Paper IV,* and the leaching behaviour of potentially harmful substances from the field, lysimeter and the laboratory experiments is compared in *Paper V*. A summary of the methodologies and the obtained results are given in Chapters 0 and 3.3 of this dissertation, respectively.

The general discussion and conclusions of this dissertation are given in Chapter 4, including the evaluation of the obtained results in respect to their reliability and validity. Finally, this is followed by suggestions for further research.

Research structure

Methods

Publications

MSWI BA Recovery (ADR)

MSWI BA mineral fractions
0-2, 2-5, 5-12, 12-50 mm

Technical / Mechanical properties	Environmental properties

Characterization of MSWI BA mineral fractions

Paper I

Laboratory studies

Combining MSWI BA mineral fractions into aggregate-like products for civil engineering

Paper II

Defining design parameters for aggregate-like products in civil engineering structures

Paper III

Field studies

Test site, field performance study

Paper IV	*Paper V*

Figure 4 Research structure

2 Research methodologies

This chapter provides a summary of the materials and methodologies used in this research. A detailed description of the test arrangements and the analysis are given in the respective publications, which are referred to by their Roman numerals.

2.1 Origin of MSWI BA and its treatment

Figure 5 illustrates the location of all W-t-E plants that are currently in operation in Finland. Most of the Finnish W-t-E plants (~78 %) use grate design technology to recover energy from municipal solid waste (MSW). This MSW is mainly generated by households, but also to some extent local industry. The MSWI BA used in this study originated from the W-t-E plant located in Mustasaari, Vaasa. The plant incinerates annually around 180,000 tonnes of mainly source-separated household waste, from which approximately 30,000 tonnes remains as MSWI BA (*Paper I*).

MSWI BA was first transported to a waste treatment centre located in Ilmajoki and then treated with an advanced dry treatment technology called the ADR (*Advanced Dry Recovery*). Altogether, 60,000 tonnes of MSWI BA was treated between the years 2013 – 2014. This ADR technology has been developed in the Netherlands at the end of the 2000s. Compared with conventional dry treatment technologies that normally include some sort of sieving and metal recovery with magnets and eddy currents (EC), the ADR process uses a ballistic separator for the enhanced removal of sticky and moist fine particles (<2mm) on top of MSWI BA particles (de Vries et al. 2009). This in turn improves the efficiency of ECs in separating NF metals from BA minerals (2-12 mm) (de Vries and Rem, 2013). Currently, up to 5 million tonnes of BA is annually treated with the ADR technology in Europe, North America, and Asia (Personal communication, Rogier van de Weijer, Inashco B.V.).

The ADR technology was chosen for the current study for several reasons. First, the enhanced re-covery of NF metals was expected to improve the environmental properties of the minerals and thus possibly facilitate their more widespread utilization in civil engineering structures. Second, additional water is not needed when using the ADR technology, and therefore no excessive wastewater or sludge is generated during the process. Third, the treatment plant is mobile and can be transported to those locations where the material is produced. This is necessary in the local Finnish conditions, where the distances can be rather long and excessive material transportation should be avoided. In addition, the economic costs for a fixed treatment plant would be too high, if compared with the annual amount of MSWI BA produced in each W-t-E plant in Finland (on average 30,000 – 40,000 MSWI BA/year/plant). Finally, material aging is not required with the ADR technology, which allows for a higher recovery rate of metallic aluminium if compared with the aged MSWI BA (de Vries et al. 2009). However, it should be mentioned that due to practical reasons, the untreated BA was stored over the winter in storage piles, since the treatment would not have been feasible at freezing tem-peratures. Figure 6 illustrates a schematic overview of the whole MSWI BA treatment process that was used with the MSWI BA investigated in this study (*Paper II*).
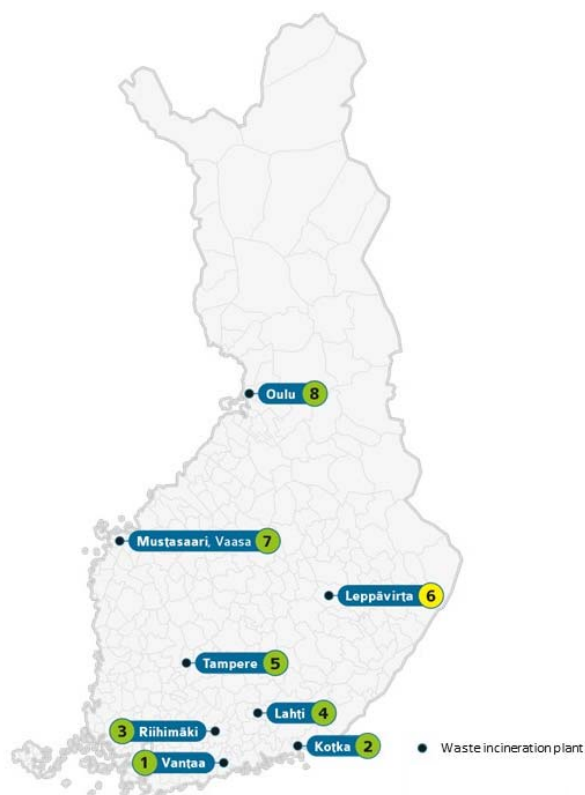
Figure 5 Waste incineration plants in Finland
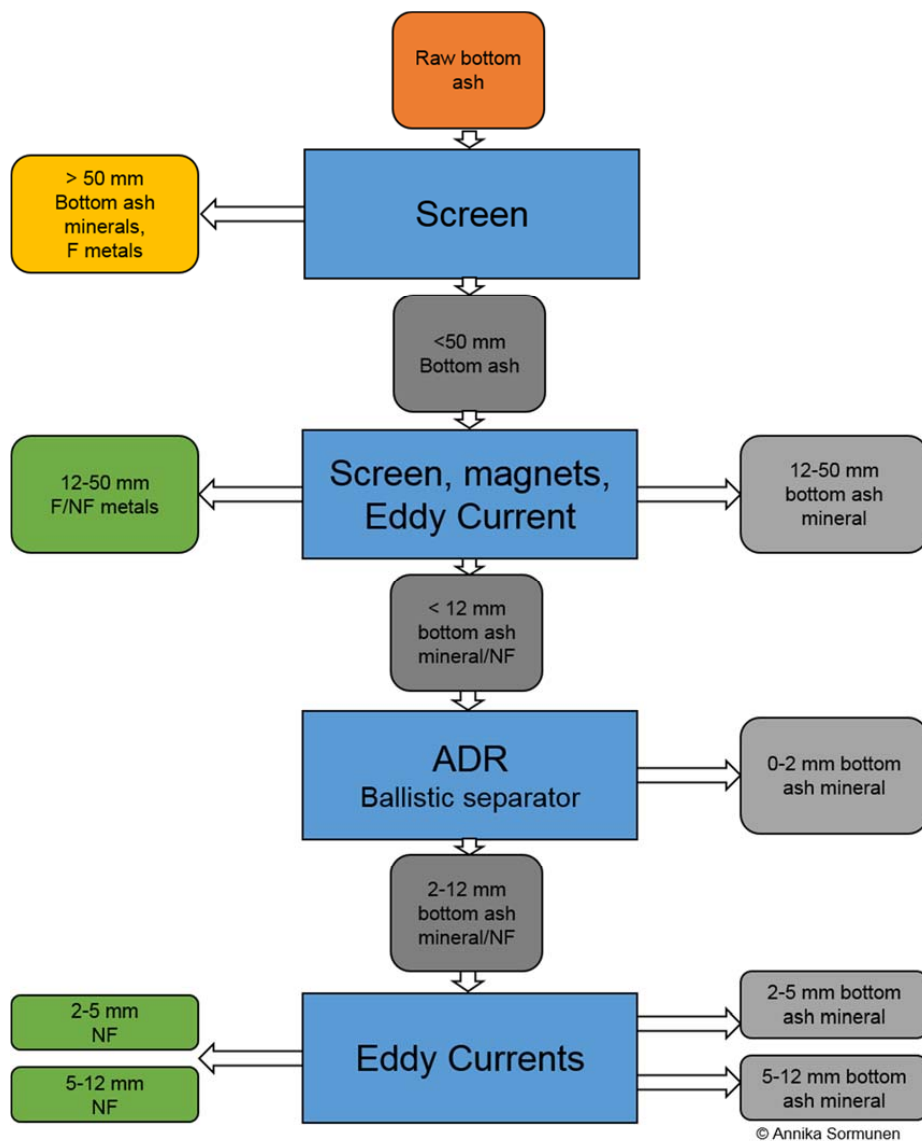
Figure 6 Schematic overview of the MSWI BA treatment process

2.2 Characterisation of recovered MSWI bottom ash mineral fractions

Figure 7 outlines the methodology used for the characterisation of recovered MSWI BA mineral fractions from the ADR treatment process (marked in green). The following chapters (2.2.1-2.2.3) explain the sampling and summarize the different analysis used in the characterisation of recovered MSWI bottom ash mineral fractions. The analyses are presented in more detail in the first publication of this thesis (*Paper I*).
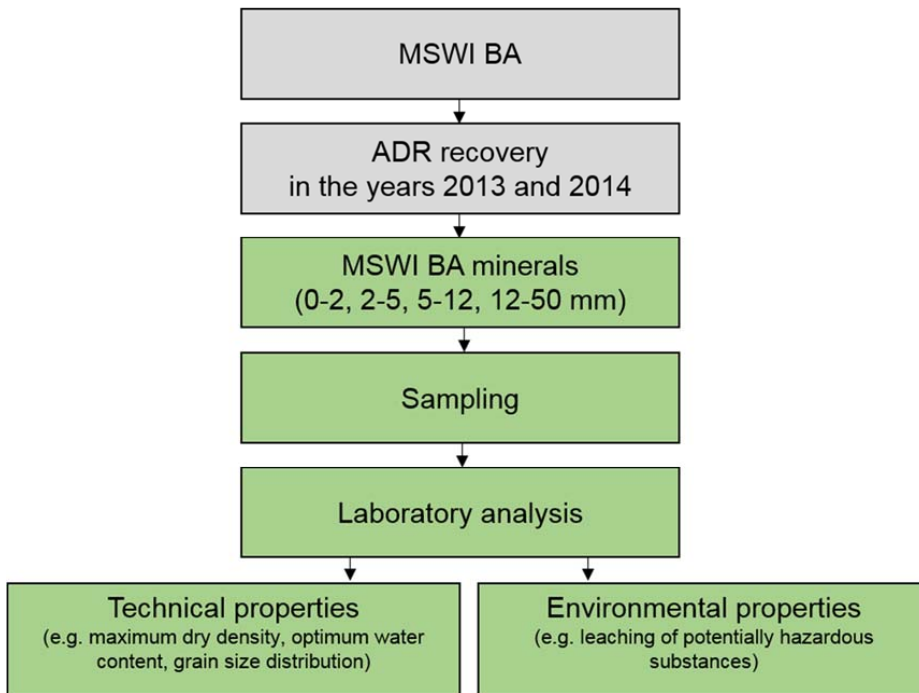
Figure 7 Summary of methodology for the characterisation of mineral fractions

2.2.1 Sampling

The MSWI BA minerals come out from the process in four different size fractions (0-2, 2-5, 5-12, 12-50 mm) (Figure 6). During the treatment of MSWI BA in the years 2013 and 2014, each mineral fraction was first sampled separately in order to obtain a representative number of subsamples for the characterisation of each mineral fraction. Table 4 summarises the number of subsamples taken from each mineral fraction during both treatment years (*Paper I*). The number of subsamples was higher in 2013, since that was the first treatment year and a more comprehensive sampling scheme

was considered appropriate for the basic characterisation. In 2014, the sampling scheme was de-signed for testing material compliance. Either the collected subsamples or combined samples from these subsamples were used for the different analyses, as explained in *Paper I* of this thesis.

Table 4 Number of subsamples taken from the MSWI BA mineral fractions

Year	Number of subsamples			
	0-2 mm	2-5 mm	5-12 mm	12-50 mm
2013	12	12	12	12
2014	4	2	2	2

2.2.2 Technical properties

Table 5 summarises the different technical analyses that were performed for the separate MSWI BA mineral fractions for their basic characterisation. The respective standards for each analysis and the studied material properties are listed as well. The aim of these basic analyses was to obtain infor-mation on, for example, the geometrical, physical, and thermal properties of MSWI BA mineral frac-tions. In addition to these technical analyses, a coarse assessment of frost susceptibility was made based on the analysed grain size distributions of each MSWI BA mineral fraction. This was done according to the Finnish guidelines published by Suomen Rakennusinsinöörien Liitto RIL ry (2013). With this coarse assessment, aggregates can be divided into two categories: frost-susceptible and non-frost-susceptible.

Table 5 Technical analyses performed for MSWI BA mineral fractions

Technical analysis	Unit	Standard	Material property
Maximum dry density (ρ_{dmax})	kN m^3	SFS-EN 13286-2	Compactivity
Optimum water content (OWC)	%	SFS-EN 13286-2	
Grain size distribution	-	SFS-EN 933-1[b]	Geometrical
Water content (w)	%	SFS-EN 1097-5	Physical
Hydraulic conductivity (k)	m s^{-1}	ASTM 5084D-03[a]	Physical
Water suction height	mm	SFS-EN 1097-10[a]	Physical
Thermal conductivity (λ)	W mK^{-1}	ASTM D 5334-13[a]	Thermal

[a]Not performed for 12-50 mm MSWI BA mineral fraction since these methods were not suitable for a material with such large grain size
[b]Performed before and after the Modified Proctor-test (SFS-EN 13286-2) to investigate the MSWI BA particle crushing during compaction

When considering the applied technical testing methods in general, it should be considered that these methods have originally been designed for natural and crushed rock aggregates. Therefore, the suitability of these standardized test methods should be considered for different waste-derived aggregates separately. For example, in the standardized Proctor compaction method (SFS-EN 13286-2), the compaction effort can be too heavy for MSWI BA minerals with weak particle strength (Izquierdo et al. 2011). This in turn can lead to an overestimation of the obtained maximum dry density values that are used as reference points for evaluating the sufficient Degree of Compaction (DoC) in the field. Similarly, the assessment of frost-susceptibility based on the materials' grain size

distribution is originally designed from the experiences obtained with natural and crushed rock aggregates. Therefore, the results obtained with this assessment should only be used as a coarse evaluation of frost-susceptibility for other types of materials, including MSWI BA. In this study, however, the conventional test methods were used because no other standardized test methods are particularly available for the recovered MSWI BA. In addition, while using these conventional standardized test methods, the comparability of the obtained results is easier to gauge with the previous knowledge on natural and crushed rock aggregates.

2.2.3 Environmental properties

Table 6 summarises the test methods used for investigating the environmental properties of the MSWI BA mineral fractions. In the basic characterisation, both the total (mg kg^{-1}) and the leachable concentrations (mg kg^{-1}, LS 10) of MSWI BA mineral fractions were analysed. In the compliance testing, only the two-stage leaching tests were performed, since the focus of the study was more on the leachable part of potentially harmful substances rather than their total concentration. The analysed elements and the substances were chosen based on previous knowledge of potentially harmful substances in MSWI BAs as listed, for example, in Astrup et al. 2016.

Table 6 Test methods used for investigating the environmental properties

Environmental properties	Unit	Standard	Equipment	Elements / Substances
Basic characterisation				
Total concentration	mg kg^{-1}	SFS-EN 13656	ICP-MS or ICP-OES	Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Ni, P, Pb, Sb, Se, Sn, Zn, Hg
Percolation test, leaching	mg kg^{-1}, LS 10	CEN/TS/ 14405	CVAAS, CVAFS, ICP-MS, ICP-OES, IC, IS, IR	As, Ba, Cd, Co, Cr, Cu, Mo, Ni, Pb, Sb, Se, V, Zn, Hg, DOC, Cl$^-$, SO$_4^{2-}$ F$^-$ and pH, EC
Compliance testing				
Two-stage leaching test	mg kg^{-1}, LS 10	SFS-EN 12457-3	CVAAS, CVAFS, ICP-MS, ICP-OES, IC, IS, IR	As, Ba, Cd, Co, Cr, Cu, Mo, Ni, Pb, Sb, Se, V, Zn, Hg, DOC, Cl$^-$, SO$_4^{2-}$ F$^-$ and pH, EC

The obtained leaching values of different substances were further compared with the leaching limit values defined and imposed by certain countries (Finland, the Netherlands, and France) to assess the utilization possibility of different waste-derived aggregates in civil engineering structures. It should be mentioned that none of these limit values are fully comparable with the material or the test methods used in this study, since the limit values defined in different European countries are derived based on different scenarios and only comply with the specific leaching test used in each country (Saveyn et al. 2014). In addition, the Finnish limit values are based on Government Decree (591/2006 and its modifications 403/2009 and 1825/2009), which has been defined for the utilisation of ashes from coal, wood- and peat-burn facilities. In this study, the use of these limit values was, however, seen as appropriate since no national limit values exist, particularly for the recovered MSWI BA. Therefore, the leaching limit values used in this study were mainly used for illustrating the accepted level of leaching in different countries and scenarios.

2.3 MSWI BA aggregate-like products for civil engineering structures

Figure 8 outlines the methodology used for combining recovered MSWI BA mineral fractions into aggregate-like products (marked in blue).

These aggregate-like products were designed for the three unbound structural layers of roads and field structures: filtration, sub-base and base layers. The product design was based on the grain size distribution requirements given for natural or crushed rock aggregates in each structural layer given by the Finnish quality criteria for infrastructure construction (RTS, 2010). These requirements were chosen in order to obtain more comparable results with the corresponding natural and crushed rock aggregates. Mathematical proportioning of aggregates was used as a tool for the aggregate-like product design. This rather simple calculation method is used, for example, in preparing suitable aggregates for asphalt mixtures (PANK ry, 2011). In principle, the grain size distributions of aggregates of interest are mathematically combined and tested until a wanted outcome i.e., suitable grain size distribution is obtained (PANK ry, 2011). In this study, several mixtures were tested until the most suitable mixtures for the three structural layers were obtained. These mixtures were then used in all the following laboratory analyses and the field performance study that is explained in more detail in Chapter 2.4. The following Chapters (2.3.1–2.3.3) summarize the different analyses used for investigating the technical, mechanical, and environmental properties of the aggregate-like products designed in this study. These analyses are described in more detail in the second and the third publication (*Papers II and III)* of this thesis.
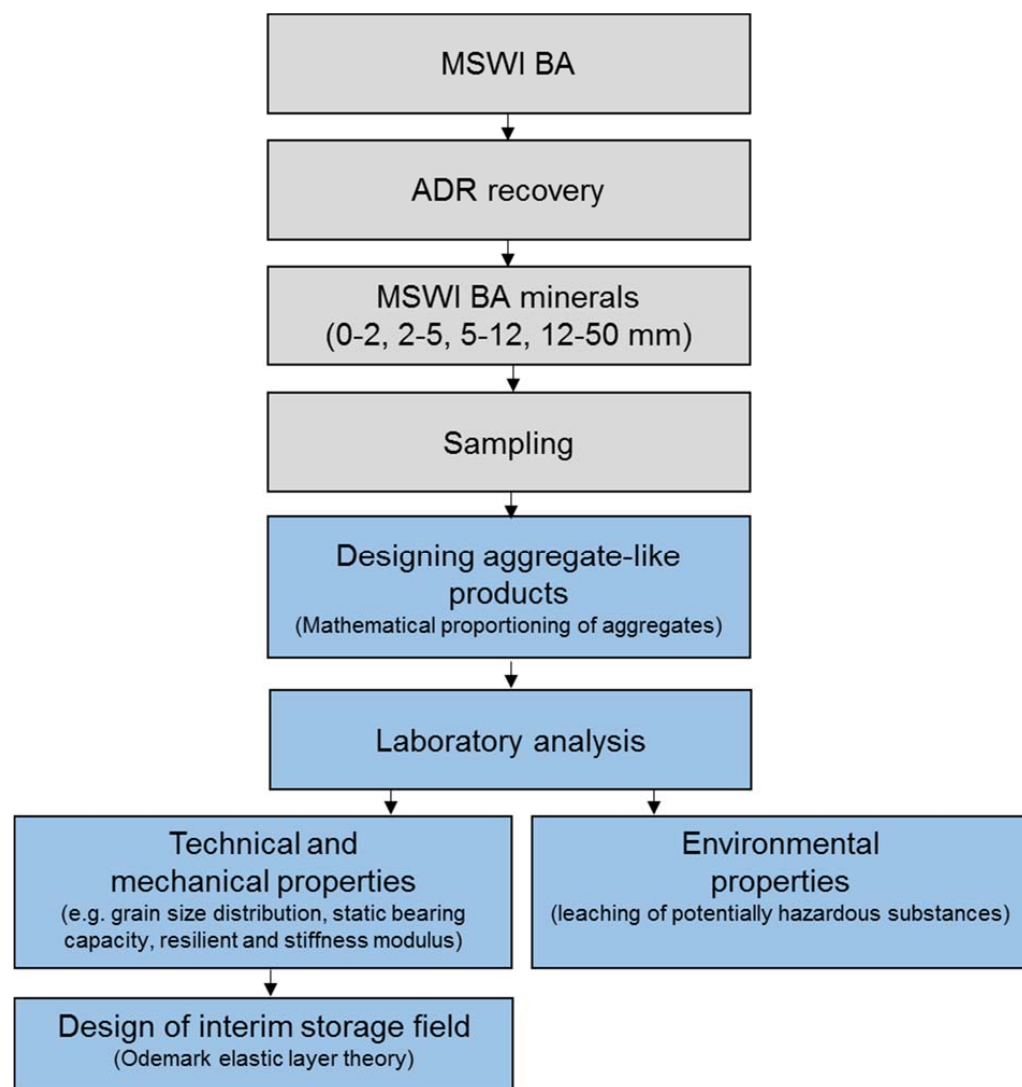
Figure 8 Summary of methodology for designing aggregate-like products

2.3.1 Technical and mechanical properties

Table 7 summarises the test methods used for investigating the technical and mechanical properties of aggregate-like products designed from recovered MSWI BA. The corresponding standards (if available) are listed as well, and a reference is given to the two publications of this thesis (*Papers II and III*), in which these test methods are described in more detail.

Technical properties were mostly tested with the same methods used in the characterisation of recovered MSWI BA mineral fractions. In addition to these, the abrasion resistance (Los Angeles test), the freeze-thaw resistance, and the total organic carbon (TOC) were also tested from the designed aggregate-like products in order to understand better the durability of MSWI BA particles in different conditions. For example, according to Arm (2003), organic matter can decrease the resilient modulus of MSWI BA.

Table 7 Technical and mechanical laboratory tests for aggregate-like products

Technical property	Unit	Standard / Reference	Paper
Maximum dry density (ρ_{max})	kN m^3	SFS-EN 13286-2	II
Optimum water content (OWC)	%	SFS-EN 13286-2	II
Grain size distribution	-	SFS-EN 933-1	II & III
Water content (w)	%	SFS-EN 1097-5	II & III
Thermal conductivity (λ)	W mK^{-1}	ASTM D 5334	II
Abrasion resistance	%	SFS-EN 1097-2	II
Freeze-thaw resistance	%	SFS-EN 1367-1	II
Total organic carbon (TOC)	%	SFS-EN 13137	III
Mechanical property			
Static bearing capacity (E1, E2)	MPa	-	II
Resilient modulus (M_r)	MPa	SFS-EN 13286-7	III
Secant modulus (M_s), friction angle (φ'), cohesion (c')	MPa, °, kPa	(Kolisoja, 2013)	III

The testing of different mechanical properties of aggregate-like products was conducted in two phases. First, the bearing capacities (E1 and E2, MPa) were determined with a static plate loading test (SPLT) in the laboratory (*Paper II*). This test is commonly used in the field to measure the bearing capacity of, for example, structural layers of roads. The main difference between the field and the laboratory tests was that the tested materials were compacted into intermediate bulk containers (IBC). This creates a confined system where the distribution of stresses and strains cannot take place as freely as in an ideal elastic half-space. Therefore, the confining effect was further modelled with FEM (Finite Element Method) in order to understand how much on average the test arrangement overestimated the obtained bearing capacities for each material. A more detailed description of the whole test arrangement and the FEM modelling is given in the second publication (*Paper II*) of this thesis.

The second part of testing the mechanical properties of recovered MSWI BA aggregate-like products was comprised of a series of cyclic load and static triaxial tests. These tests were chosen since they are commonly used methods in investigating the stiffness and strength properties of natural and crushed rock aggregates (e.g., AASHTO T249-92 I, SFS-EN 13286-7, Kolisoja, 2013). In addition, even though recovered MSWI BA is commonly used in road construction in many European countries such as the Netherlands and Denmark (Astrup, 2007, ISWA, 2006), only a few performance-related test results on MSWI BA have been published in the previous literature (Arm, 2003, Arm, 2004, Bendz et al. 2006). As pointed out by Becquart et al. (2009), the knowledge of the mechanical properties of MSWI BA is still mainly based on empirical studies, and therefore the current study aimed to fill this gap in existing knowledge.

The arrangement of cyclic and static triaxial tests also aimed to investigate the influence of aging and changes in moisture content in relation to the development of stiffness and strength properties of recovered MSWI BA over time. The mechanical properties of granular materials can be considerably affected by, for example, moisture content, as has been demonstrated in the past in many laboratory studies (Rada & Witczak, 1981; Thom 1988, Sweere, 1990 and Kolisoja et al. 2002), in accelerated pavement tests (Saevarsdóttir and Erlingsson, 2014), and in-situ (Salour and Erlingsson, 2014). MSWI BA is different from natural and crushed rock aggregates due to, for example, its origin, its chemical properties and its porosity (Chandler et al. 1997). Thus, the mechanical behaviour of recovered MSWI BA can be different in changing moisture conditions than it is with normal unbound aggregates. This is important to understand in order to ensure that recovered MSWI BA is used in a proper way in those structures, in which the material is suitable based on its mechanical properties. A more detailed description of the methodologies used in the second part for testing the mechanical properties of recovered MSWI BA aggregate-like products is given in the third publication (*Paper III*) of this thesis.

2.3.2 Design of the interim storage field

The flexible pavement structure for the interim storage field built during this study was designed with the simplified (Odemark) elastic layer theory (e.g., Ullidtz, 1998). This is a commonly used theory for structural design of field, road, and street structures in Finland (e.g., Tiehallinto, 2004). The theoretical background, the Odemark equation, the boundary conditions, and the parameters used for the interim storage field design are given in the second publication (*Paper II*) of this thesis. It should be noted that the bearing capacities (E2, MPa) obtained in the laboratory with the SPLTs were used as the stiffness moduli (E) values for the filtration, sub-base, and base layers in the field design. As was mentioned in Chapter 2.3.1, these values were obtained in a confined system, which can overestimate the actual material's stiffness. However, the bearing capacity values (E2, MPa) were used because at the time of interim storage field design, no other stiffness values were available (i.e., due to practical reasons, the cyclic load tests performed in this study were done after the interim storage field was already built).

2.3.3 Environmental properties

As mentioned by Dijkstra et al. (2006), the risks of potentially harmful substances from MSWI BA to groundwater, surface water, and soil should be determined based on their leaching and not the total concentration of substances in the waste material. Therefore, the environmental properties of three recovered MSWI BA aggregate-like products (filtration, sub-base, and base layer) were investigated only with the standardized percolation test (CEN/TS/14405). The obtained results from these three aggregate-like products were compared with the leaching limit values of different countries in a similar way, as was done for the separate mineral fractions (see Chapter 2.2.3). A more detailed description of the sample preparation, the leaching tests, and the analysis is given in the second publication of this thesis (*Paper II*).

2.4 Field performance studies

Figure 9 outlines the methodology in the field performance study, in which an interim storage field was built within the waste treatment centre of Lakeuden Etappi (marked in yellow).
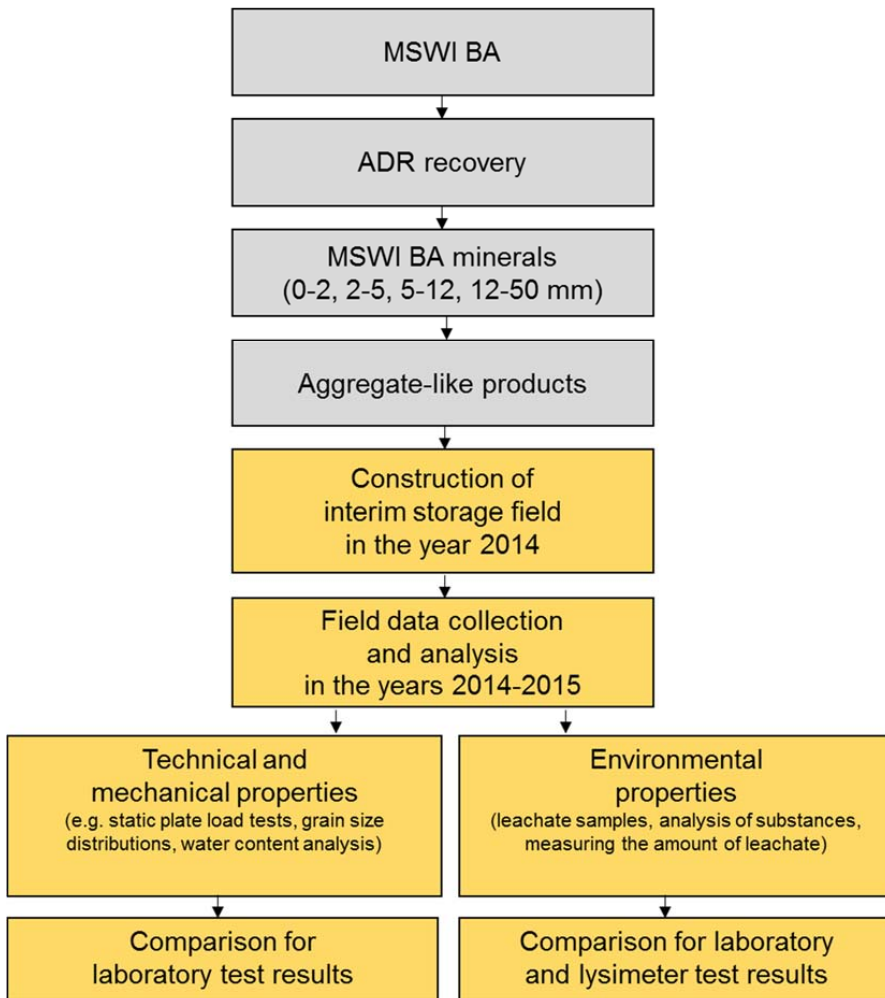
Figure 9 Summary of methodology for the field performance studies

The construction site was in Ilmajoki in the western part of Finland. The field was constructed in the summer of 2014 from the MSWI BA recovered with the ADR technology in 2013. The aggregate-like products designed from the recovered MSWI BA were used in the three structural layers of the field (i.e., filtration, sub-base, and base layer). Field data on the technical, mechanical, and environmental properties of the recovered MSWI BA aggregate-like products were collected between the years 2014 – 2015.

The following chapters (2.4.1 – 0) summarize the construction of the interim storage field and the methodologies used in this final part of the research. More detailed description of these methodologies is given in the last two publications of this thesis (*Papers IV and V)*.

2.4.1   Construction of the interim storage field

The construction of the interim storage field is described in more detail in the fourth and fifth publication of this thesis (Paper IV and V), and this chapter only presents a short summary of the construction. Figure 10 illustrates the interim storage field under construction in the summer of 2014. The size of the field is approximately 9,900 m2, and around 15,400 tonnes of recovered MSWI BA was used in the unbound structural layers of the field (filtration, sub-base and base layers, Table 8).

Figure 10 Interim storage field under construction © Suomen Erityisjäte Oy

Table 8 Amount of recovered MSWI BA aggregate-like products used in the field

Aggregate-like product / Structural layer	Amount (t, dry weight)
Base	4622
Sub-base	4749
Filtration	6055
Total	**15 426**

The filling material underneath the structural layers was crushed concrete, glass and brick aggregates. An LDPE (Low-density polyethylene) film (0.5 mm) was placed underneath the MSWI BA layers and on the field edges to steer the leachate water into the sub-surface drains and to minimize the water flow from the edges in to the structure. This allowed for taking samples from the leachate and analysing the concentration of potentially harmful substances, as explained in more detail in Chapter 2.4.3. For preventing the formation of holes in the LDPE film, fine crushed aggregate (#0…2mm) was used as backfill material between the embankment and the film. An additional base layer of crushed rock aggregate (#0…32mm) was designed and constructed on top of the MSWI BA layers. One of the reasons for this was that MSWI BA particles can be prone to crushing (e.g., Bendz et al. 2006), and thus may not be able to resist the higher stresses occurring in the upper structural layers of roads and field structures due to heavy wheel loads.

Conventional construction machinery (e.g., excavators and trucks) was used in the construction. The construction materials (i.e., the recovered MSWI BA aggregate-like products) were prepared with a drum sieve from separate mineral fractions according to the proportions (w-%) given in Chapter 3.2.1(Table 16). A wheel vibrator roller (Amman AC 110, 12 000 kg) was used for compaction. The number of required roller overruns to obtain a sufficient degree of compaction (DoC) was first investigated with a smaller test field (20x20 m), as explained in more detail in the fourth publication of this thesis (Paper IV). The cross-section of the interim storage field is illustrated in Figure 11.
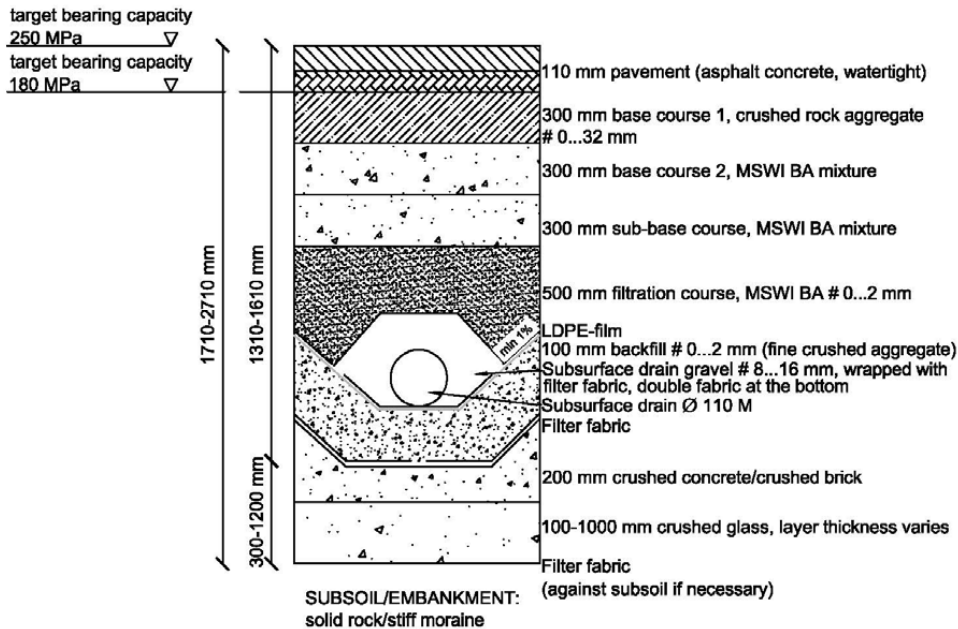
Figure 11 Cross-section of the interim storage field

2.4.2 Technical and mechanical properties in the field

Table 9 summarises the different quality control measurements taken during and half a year after the construction of the interim storage field. The aim of these measurements was to investigate the technical and mechanical properties of MSWI BA aggregate-like products on a larger scale and then to compare these results with those obtained previously in the laboratory and during the structural design of the field (Odemark). The general Finnish target value (160 MPa) set for crushed rock aggregates in the unbound base layers of main roads in Finland (Tiehallinto, 2005) was used for comparison as well.

Some of the field measurements were repeated half a year after the construction (Table 9). This was done to find out whether, for example, the bearing capacities (E2, MPa) on top of the base layers or the materials moisture content (w-%) had changed over time. The number of samples and measurement points and a detailed explanation of the applied test procedures are given in the fourth publication (*Paper IV*) of this thesis.

Table 9 Summary of quality control measurements in the field

Technical property	Unit	Standard	D / Aª
Grain size distribution	-	SFS-EN 933-1	D / A
Water content (w)	%	SFS-EN 1097-5	D / A
Maximum dry density (ρ_{dmax})	kN m^3	SFS-EN 13286-2	D
Optimum water content (OWC)	%	SFS-EN 13286-2	D
Degree of compaction (DoC)	%	Nuclear Density Gauge (NDG)	D / A
Mechanical property		**Equipment**	
Bearing capacity (E1 and E2)	MPa	Static plate load test	D / A

ªDuring construction/after construction

The collected field data was also used to estimate the stiffness modulus (i.e., E-modulus) values of MSWI BA aggregate-like products. The first assessment was based on the analysed grain size distributions of each material and the second on a back-calculation with the simplified (Odemark) elastic layer theory, as explained in the following paragraphs. This Odemark equation was also used for the structural design of the interim storage field, as explained in Chapter 2.3.2.

The E-modulus values of natural and crushed rock aggregates intended to be used in the Odemark's equation during the design of road and field structures are commonly estimated based on materials' grain size distribution in Finland (Tiehallinto, 2005). Therefore, the same approach was used in this study for the recovered MSWI BA aggregate-like products. In practice, this meant that the grain size distributions of aggregate-like products were compared with the E-Modulus classes defined by Tiehallinto (2005) for respective natural gravels (filtration and sub-base layer) or crushed rock aggregates (base layer) based on their grain size distribution.

As mentioned above, the E-modulus values for MSWI BA aggregate-like products were also back-calculated with the Odemark elastic layer theory (Ullidtz, 1998). This was done based on the bearing capacity (E2, MPa) measurements that were made on top of each structural layer in the interim storage field during construction. The whole back-calculation process is explained in more detail in the fourth publication (*Paper IV*) of this thesis. It should, however, be mentioned that the E-modulus values obtained with the grain size distributions and with the back-calculation of the Odemark elastic layer theory can only be used as coarse evaluation of E-modulus values for these MSWI BA aggregate-like products. This is because both methods make many assumptions and are originally developed for natural and crushed rock aggregates. Finally, the obtained E-modulus values were compared with the stiffness values obtained from the previously conducted laboratory experiments (i.e., SPLT) that were explained in Chapter 2.3.1.

2.4.3 Leaching of potentially harmful substances in the field

As explained in Chapter 2.4.1, the LDPE film (0.5 mm) was placed in the interim storage field underneath the structural layers that were constructed from the recovered MSWI BA aggregate-like products. This allowed for collecting the leachate water in to the subsurface drains and to sample and analyse the collected leachate. The amount of leachate was also measured because it was needed for the liquid to solid ratio (L S^{-1}, L kg^{-1}) calculations that were used for the comparison of data from previously conducted laboratory experiments and the field leaching data (see further explanation below).

The leaching of potentially harmful substances was also studied with a smaller scale lysimeter study that was constructed with the same recovered MSWI BA aggregate-like products. This was done to obtain more data for comparison, since the LS^{-1} (L kg^{-1}) obtained at the end of sampling period was rather small in the interim storage field (Table 10). The lysimeters were located in Oulu, which is located near the Gulf of Bothnia approximately 340 kilometres' northeast from the interim storage field site. A more detailed description of the lysimeter structure is given in the fifth publication (*Paper V*) of this thesis.

It is evident that the scales of these three studies (i.e., laboratory, lysimeter, and interim storage field) were very different (see examples from Table 10). Therefore, L S^{-1} (L kg^{-1}) was used to compare the leaching behaviour of potentially harmful substances between these three studies. Such an approach has been used for conventionally treated MSWI BA by other researchers as well (e.g., Hjelmar et al. 2007). In addition, the limited number of data collected during the field tests did not allow for the reliable use of other methods, such as geochemical modelling. Such modelling has been more often used in previous studies for understanding the leaching behaviour of waste-derived aggregates in realistic scenarios (e.g., Dabo et al. 2009, de Windt et al. 2011, Dijkstra et al. 2006, Schreurs et al., 2000, van der Sloot et al. 1996).

Table 10 Differences between the three study scales in leaching testing

Parameter	Laboratory	Lysimeter	Interim storage field
Surface area (m²)[a]	0.002	0.5	9900
Amount of material (t, dry weight)[a]	0.002	0.294	15400
Test duration (months)	<1	25	7.5
Number of test units (n)	3	3	1
LS^{-1} (L kg^{-1}) at the end[a]	1.5	1.6	0.13

[a]Per test unit

The fifth publication (*Paper V*) of this thesis provides a more detailed description of the laboratory, lysimeter, and interim storage field studies that were used for investigating the leaching behaviour of potentially harmful substances from the recovered MSWI BA aggregate-like products. However, certain issues related to the differences between these three tests and the potential uncertainties caused by these differences are mentioned here. First, measuring the collected amount of leachate was relatively easy and accurate in the laboratory and lysimeter studies. However, this was not the case for the interim storage field, since it was not possible to install water meters that would contin-uously measure the amount of leachate. This was because the drainage level in the pipes was too low and the water meter equipment was too large to fit inside the drainage pipes. Thus, the amount of leachate was measured once every weekday with a bucket (5L), which was then used to estimate the daily amount and further the cumulative amount of leachate during the whole test period. This in turn may have caused some uncertainty in the LS (L kg^{-1}) calculations that were used as a basis for data comparison in this study. The second issue is related to the differences in the setup of these three study scales. Laboratory leaching tests were conducted for each MSWI BA aggregate-like products in separate columns, whereas in the both field studies the products were placed on top of each other in a stratified structure. Therefore, it was necessary to calculate a weighted average for the laboratory leaching data based on the amount of material used in the interim storage field, which was given in Table 8. This was not an ideal situation, but was done due to practical reasons, since the laboratory experiments were conducted before the interim storage field was designed.

3 Results and discussion

This chapter provides a summary of the main results obtained in this study and it discusses the meaning of these results. All results are given in the respective publications of this thesis, which are referred to by their Roman numerals.

3.1 Characterisation of recovered MSWI bottom ash mineral fractions

As mentioned in the introduction, it is of utmost importance to understand the quality and the different properties of waste-derived aggregates if they are to be used in civil engineering structures (see Chapter 1.5). Many studies in the past have investigated the different properties of conventionally treated MSWI BAs (see Chapter 1.4). Conversely, comprehensive data on the properties of MSWI BA mineral fractions from novel and advanced treatment technologies such as ADR have not been reported. In this study, such data was collected and analysed between the years 2013 – 2014, when the ADR treatment process was used to recover MSWI BA from one waste incineration plant in Finland (for further details, see Chapter 2.2). In this chapter, the main results from these analyses are described and discussed. The aim of this chapter is to answer the research questions 1-3 under objective 1 (see Chapter 1.6). All the obtained results of the characterisation of the MSWI BA mineral fractions are given in detail in *Paper I* of this thesis.

3.1.1 Technical properties

As an answer to the first (1) research question of this thesis (see section 1.6), Table 11 summarises the average results of the different technical properties analysed from the MSWI BA mineral fractions during the MSWI BA treatments in the years 2013 – 2014. The obtained results suggested that the technical properties of the ADR-recovered MSWI BA mineral fractions had certain similarities with

those of respective natural aggregates. These findings were consistent with those obtained for conventionally treated MSWI BA by other researchers (Chandler et al. 1997, Hu et al. 2010 and Izquierdo et al. 2001). For example, maximum dry densities of MSWI BA mineral fractions (13.7 – 16.4 kN m^{-3}) were lower than they typically are for Finnish sand (20 kN m^{-3}) and gravel (21 kN m^{-3}) (RTS, 2010). Conversely, the optimum water contents of MSWI BA mineral fractions were higher (10.5 – 26.5 %) than those typically for sand (10 %) and gravel (7%) (RTS, 2010). The hydraulic conductivities (m s^{-1}) of the MSWI BA mineral fractions (10^{-7} to 10^{-5}) (Table 11) were on a similar range with those of natural aggregates, such as coarse (10^{-6} to 10^{-2}) and medium (10^{-6} to 10^{-3}) sand, which are classified as good drainage materials (Lade, 2001). In addition, the thermal conductivities (W mK^{-1}) of the MSWI BA mineral fractions (0.6 – 1.1) (Table 11) are comparable or lower than those of unfrozen sands with varying densities and moisture contents (0.5 – 3.0 W mK^{-1}) (Andersland and Anderson, 1978). The capillary heights obtained in this study for the MSWI BA mineral fractions were on average 20 – 40 mm (Paper *I*). Subsequent laboratory tests for the same materials have, however, shown that the capillary heights for these MSWI BA minerals can reach up to 150 – 250 mm. Due to the inconsistency of these results, it is not possible to give exact capillary height values for the MSWI BA minerals in this thesis. However, the obtained results indicated that the capillary heights of these materials can vary from one year's material batch to another. In addition, it seems that a certain amount of water continues to rise in the material for at least several weeks or perhaps even for months. This kind of behaviour is not typical for natural and crushed rock aggregates. It was beyond the scope of this study to investigate this further, and therefore further studies are recommended on this matter.

Table 11 Average technical properties of MSWI BA mineral fractions

		BA mineral fractions			
		0-2 mm	2-5 mm	5-12 mm	12-50 mm
		2013 - 2014			
Maximum dry density (kN m^{-3})		13.7	15.3	16.2	16.4
Optimum water content (%)		26.5	17.8	12.5	10.5
Hydraulic conductivity (m s^{-1})[a]		3.6x10^{-7} - 2.8x10^{-6}	7.8x10^{-7} - 3.6x10^{-6}	9.7x10^{-6} - 1.4x10^{-5}	NA
Thermal conductivity[b] (W mK^{-1})	T=+10°C	0.7	0.8	0.6	NA
	T=-10°C	1.1	1.1	0.6	NA

(*n*=2)
[a]The dry densities of each mineral fraction samples were on average: 0-2 mm: 12.4 kN/m^3, 2-5 mm: 14.0 kN/m^3, 5-12 mm: 10.5 kN/m^3)
[a]The dry densities and water contents of each mineral fraction samples were on average: 0-2 mm: 12.6 kN/m^3 and 26.3 %, 2-5 mm: 13.9 kN/m^3 and 18.2 %, 5-12 mm: 15.3 kN/m^3 and 10.6 %)

Figure 12Figure 12 illustrates the grain size distributions of the MSWI BA mineral fractions 0-2 mm and 2-5 mm before and after the Modified Proctor-test. The limits used for assessing the frost-susceptibility (Area 1) and non-frost-susceptibility (Areas 2, 3, and 4) of natural sand and gravel (RIL, 2013) are given as well. As can be seen in Figure 12Figure 12, the MSWI BA mineral fractions fell within the non-frost-susceptible categories before and after the Modified Proctor tests, even though

a certain level of particle crushing was observed to have taken place during the compaction tests, especially in the larger mineral fractions (Table 12). These findings, coupled with the good drainage properties (i.e., hydraulic conductivity) and the obtained thermal conductivities for the MSWI BA mineral fractions (Table 11Table 11, were considered favourable material properties against the frost action.
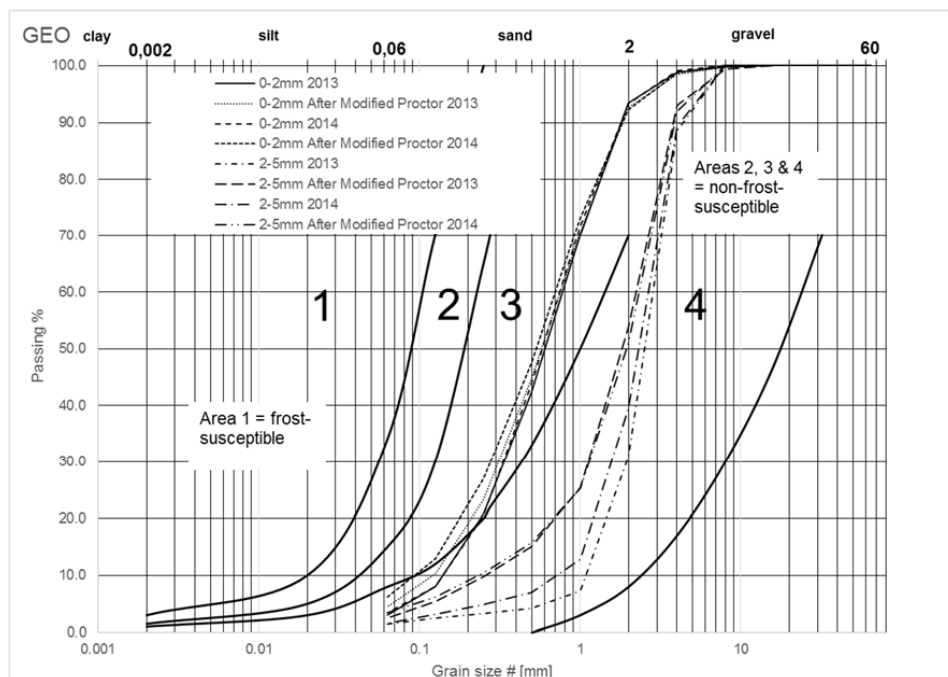
Figure 12 Grain size distributions of 0-2 and 2-5 mm MSWI BA mineral fractions

Table 12 MSWI BA particle crushing before and after Modified Proctor tests

BA mineral fractions	2013		2014	
	Passing (%) before[a]	Passing (%) after[b]	Passing (%) before[a]	Passing (%) after[b]
	Grain size # [0,125 mm / 1 mm]			
0-2 mm	8 / 70	10 / 71	8 / 72	13 / 73
2-5 mm	3 / 7	5 / 25	3 / 13	6 / 25
5-12 mm	1 / 2	4 / 19	3 / 5	5 / 17
12-50 mm	1 / 3	3 / 15	1 / 3	4 / 18

[a]Before Modified Proctor test
[b]After Modified Proctor test

In general, the obtained results on the technical properties of MSWI BA mineral fractions were some-what appealing for using this material in local Finnish conditions. For example, the road pavements from natural and crushed rock aggregates are normally constructed very thickly to prevent the damages caused by seasonal frost. The lower maximum dry densities of MSWI BA mineral fractions and to some extent favourable material properties against the frost action might allow for designing thinner and lighter road pavements. This in turn can decrease problems caused by the settlement of road embankments and the material costs during construction. Conversely, it should be considered that the material's frost behaviour is also affected by many other factors, including water availability. It was therefore concluded in *Paper I* that for understanding the frost-behaviour of these MSWI BA mineral fractions properly, the frost-behaviour should be further investigated in more realistic conditions. At the time of writing, one such test is ongoing in one test road site in Ilmajoki, but these results were not included in this thesis and will be published later elsewhere.

3.1.2 Environmental properties

Table 13 summarises the average total concentrations (mg kg^{-1}) of certain elements analysed from the MSWI BA mineral fractions in the treatment years 2013 – 2014 to answer the second (2) research question of this thesis (see Chapter 1.6). Most major elements recognized in the previous studies and the elements of potential environmental concern (see Chapter 1.2) were analysed and listed in Table 13.

As an answer to the third (3) research question of this thesis, Table 14 summarises the results of the standardized percolation tests for the MSWI BA mineral fractions during the MSWI BA treatment in the years 2013 and 2014. These leaching test results are compared with the current Finnish leaching limit values defined for ashes from coal-, wood-, and peat-burning facilities. A comparison with the leaching limit values of other countries (the Netherlands and France) are given in the first publication of this thesis (*Paper I*), but are not further discussed here, since those limit values are not entirely comparable with the results obtained in this study (for further explanation, please see Chapter 2.2.3 and *Paper I* of this thesis).

Table 13 Average total concentration of elements in MSWI BA mineral fractions

Element	Average total concentration of certain elements (mg kg^{-1}, dry weight) in MSWI BA mineral fractions recovered in the years 2013-2014			
	0-2 mm	2-5 mm	5-12 mm	12-50 mm
Major elements[a]				
Al	4840	5860	6400	16000
Ca	40300	33800	37300	26100
Fe	61100	75200	74100	71400
K	17300	14900	14500	18000
Mg	5720	5250	5100	4320
Mn	1960	1990	2000	946
P	8680	6290	4510	2900
Elements of potential environmental concern[b]				
As	<50	<50	<50	<50
Ba	1460	1470	1380	1090
Cd	11.0	4.00	3.00	3.00
Cu	3530	2780	2330	1620
Cr	552	437	454	298
Mo	16.0	17.0	14.0	13.0
Ni	336	136	134	137
Pb	662	567	667	725
Sb	72.0	50.0	52.0	36.0
Se	<5.00[c]	<5.00[c]	<5.00[c]	<5.00[c]
Sn	266[c]	227[c]	194[c]	139[c]
Zn	4380	3780	2740	2940

[a]*n=1*, Na and Si were not analysed even though they are considered as major elements of MSWI BA (see Chapter 1.2)

[b]*n=5* for 0-2 mm fraction and *n=3* for other fractions, V and Tl were not analysed even though they are recognized as elements of potential environmental concern in MSWI BA (see Chapter 1.2)

[c]Analysed only in the year 2013, therefore *n=1*

Table 14 Standardized percolation test results for MSWI BA mineral fractions

Substance	MSWI BA mineral fractions: Standardized percolation test (mg kg⁻¹ dry weight, L S⁻¹ 10)								Leaching limit values
	0 - 2 mm		2 - 5 mm		5 - 12 mm		12 - 50 mm		Finland[b]
	2013	2014	2013	2014	2013	2014	2013	2014	
pH[a]	11.2–12.0	7.8–10.6	10.9–11.7	7.7–10.7	10.9–11.3	7.9–10.7	11.2–11.7	7.7–10.0	-
As	0.02	<0.15	0.02	<0.15	0.02	<0.15	0.01	<0.15	1.5
Ba	1.1	0.18	0.9	0.21	1.4	0.27	1.1	0.32	60
Cd	<0.01	<0.015	<0.01	<0.015	<0.01	<0.015	<0.01	<0.015	0.04
Co	<0.01	<0.05	<0.01	<0.05	<0.01	<0.05	<0.01	<0.05	-
Cr	6.5	1.3	1	1	0.27	0.23	0.05	<0.1	3
Cu	2.9	1.5	1.5	0.82	0.69	0.45	0.43	0.4	6
Mo	1.7	1.5	1.1	1.1	0.93	0.7	0.58	0.79	6
Ni	0.04	<0.05	0.04	<0.05	0.02	<0.05	0.03	<0.05	1.2
Pb	<0.01	<0.15	<0.01	<0.15	<0.01	<0.15	<0.01	<0.15	1.5
Sb	0.14	0.19	0.11	0.17	0.09	0.18	0.04	0.15	0.18
Se	0.03	<0.05	0.02	<0.05	0.02	<0.05	0.02	<0.05	0.5
V	0.25	0.21	0.14	0.15	0.1	0.12	0.11	0.075	3
Zn	0.19	<0.1	0.15	<0.1	0.22	<0.1	0.24	<0.1	12
F-	8.4	<5	7.8	<5	<10	<5	<10	<5	50
Cl-	4800	4750	2900	3880	1900	1850	1900	1810	2400
SO4²-	3300	5600	3000	3880	2100	3080	1100	2900	10000
Hg	<0.0002	<0.005	<0.0002	<0.005	<0.0002	<0.005	<0.0002	<0.005	0.01
DOC	220	160	110	140	65	120	75	150	500

[a]The range of pH from seven solutions analysed within the standardized percolation test.
[b]The Finnish leaching limit values (CEN/TS 14405) for ashes from coal-, wood- and peat-burning facilities utilized in civil engineering and covered by bitumen course (Government Decree 591/2006, modification 403/2009 and 1825/2009.

The total concentrations of many elements do not normally correlate with the actual leaching of corresponding substances from inorganic waste materials such as MSWI BA (Hyks and Astrup, 2009, Saveyn et al. 2014). This applies especially to metals but not to soluble salts such as chloride, for which leaching is determined by its availability (Hjelmar, 1996). Similar results were observed in this study for the MSWI BA mineral fractions as well. For example, the leachable amount of copper, lead, and zinc (Table 14) was less than 0.1% of the corresponding total concentrations of these elements (Table 13) for all the MSWI BA mineral fractions. Since this study focused more on the leaching of potentially harmful substances, further discussion in this chapter is focused on the leaching properties of MSWI BA mineral fractions.

All the other substances except chrome (Cr), antimony (Sb) and chloride (Cl$^-$) were below the Finnish leaching limit values, according to the standardized percolation test (Table 14). The leaching of these substances and dissolved organic carbon (DOC) also exceeded the Finnish leaching limit values in the two-stage leaching test with certain MSWI BA mineral fractions as illustrated in Table 15. The leaching of chrome and DOC was not considered to be typical for the MSWI BA mineral fractions. Instead, their leaching was most likely related to those special cases when either the waste had not been combusted properly or a specific industrial waste batch was incinerated in the plant (for further explanation, see *Paper I*). Conversely, the leaching of chloride and antimony can possibly be problematic, especially for the smaller MSWI BA mineral fractions, when considering the utilization of these materials in civil engineering structures. These findings were in accordance with the results of other studies on conventionally treated MSWI BA (e.g., Astrup, 2007, Cornelis et al. 2006).

In general, the leaching test results obtained in this part of the study illustrated that the MSWI mineral fractions generated from the ADR process mostly comply with the current national leaching criteria. The only exceptions were chloride and antimony, which cannot be treated with the ADR technology. The removal of chloride would require a wet treatment process and the treatment of antimony can be even more difficult. This is because its leaching is very much pH-dependent, which will be further discussed in Chapter 3.3.2 of this thesis. Conversely, the Finnish leaching limit values used for comparison in this study do not apply to the recovered MSWI BA as such. They are also partly based on old background data that has been updated after the Government Decree was set in to force (for further explanation, see *Paper I*). As the characterization of MSWI BA mineral fractions in this part of the study was based only on laboratory experiments, further studies were recommended and later conducted in more realistic field conditions (see the results in Chapter 3.3)

Table 15 Two-stage leaching test results for chrome, antimony, chloride and DOC

		pH	Ec	Average	Median	Std.	Range
			(ms m^{-1})	(mg kg^{-1} dw L S^{-1} 10)			
Cr							
	0-2mm[a]	11.2 – 11.6	138 – 342	3	0.8	5.3	0.71 – 15.0
	2-5mm[b]	10.8 – 11.6	82 – 150	1.6	0.8	1.8	0.35 – 4.80
	5-12mm[b]	11.1 – 11.4	73 – 100	0.7	0.2	1	0.13 – 2.50
	12-50mm[b]	11.0 – 11.4	60 – 96	0.4	0.2	0.5	0.10 – 0.20
Sb							
	0-2mm[a]	11.2 – 11.6	138 – 342	0.24	0.26	0.05	0.18 – 0.30
	2-5mm[b]	10.8 – 11.6	82 – 150	0.37	0.35	0.14	0.24 – 0.61
	5-12mm[b]	11.1 – 11.4	73 – 100	0.21	0.20	0.08	0.12 – 0.30
	12-50mm[b]	11.0 – 11.4	60 – 96	0.23	0.26	0.12	0.11 – 0.38
Cl$^-$							
	0-2mm[a]	11.2 – 11.6	138 – 342	4843	4820	270	4500 – 5310
	2-5mm[b]	10.8 – 11.6	82 – 150	3094	3200	319	2600 – 3450
	5-12mm[b]	11.1 – 11.4	73 – 100	1960	2000	282	1500 – 2250
	12-50mm[b]	11.0 – 11.4	60 – 96	1816	1860	129	1600 – 1920
DOC[c]							
	0-2mm[a]	11.2 – 11.6	138 – 342	240	160	142	140 – 520
	2-5mm[b]	10.8 – 11.6	82 – 150	133	130	41	93 – 200
	5-12mm[b]	11.1 – 11.4	73 – 100	92	82	30	65 – 140
	12-50mm[b]	11.0 – 11.4	60 – 96	80	69	33	44 – 130

[a](*n=7*)
[b](*n=5*)
[c]Dissolved organic carbon
Exceeding Finnish leaching limit values (Government Decree 591/2006, modification 403/2009, 1825/2009) are bolded; for actual limit values see Table 14.

3.2 MSWI BA aggregate-like products for civil engineering structures

As outlined in the introduction, conventionally treated MSWI BA has been commonly used in embankments, highway noise barriers, and the lower structural layers of roads in many European countries (see Chapter 1.4). It is true that especially in noise barriers and embankments large amounts of materials can be used as once, but the use of this waste-derived aggregate in those structures certainly does not increase the image nor the value of the material. This is especially true if natural and crushed rock aggregates with moderately low prices are also available, which is the case in Finland, for example. In fact, such utilization can be merely seen as transferring the high-value material from one site to another. In this study, a more advanced approach was chosen. The recovered MSWI bottom ash mineral fractions were combined into suitable aggregate-like products for the unbound structural layers of road and field structures (filtration, sub-base, and base layers). The main aim was to steer the use of these products into those structures where an added value for this waste-derived aggregate could also be gained. In this way, the attractiveness of using this waste-derived aggregate instead of primary raw materials could possibly be increased. Without forgetting the importance of understanding the different properties of these aggregate-like products, the technical, mechanical, and environmental properties were again investigated thoroughly. In this chapter, the main results of these analyses are described and discussed. The aim of this chapter is to answer the research questions 4-7 under objective 2 (see Chapter 1.6). All the obtained results of the properties of these recovered MSWI BA aggregate-like products are given in detail in *Papers II and III* of this thesis.

3.2.1 Technical and mechanical properties

As an example, Figure 13 illustrates the grain size distribution of the MSWI BA aggregate-like product designed for a sub-base layer (SBL). The grain size distributions of the MSWI BA aggregate-like products for the filtration (FL) and the base layer (BL) are given in *Paper II*. Table 16 summarises the proportion (%) of each MSWI BA mineral fraction used in these three aggregate-like products. These grain size distributions corresponded well to the grain size distributions of respective natural and crushed rock aggregates that are used in those unbound structural layers of road and field structures. The requirements for these materials were obtained from RTS (2010), as explained in Chapter 2.3. The calculated grain size distributions of designed aggregate-like products were verified several times in the following laboratory and field studies. At all times, the grain size distributions fell within the given limits, even though mainly large MSWI BA particles were crushed to some extent during the different compaction tests used in this study (see *Papers III and IV*). Therefore, as an answer to the fourth (4) research question of this thesis (see Chapter 1.6), it can be concluded that the mathematical proportioning of aggregates was a simple, but useful tool for designing aggregate-like products from recovered MSWI BA mineral fractions.
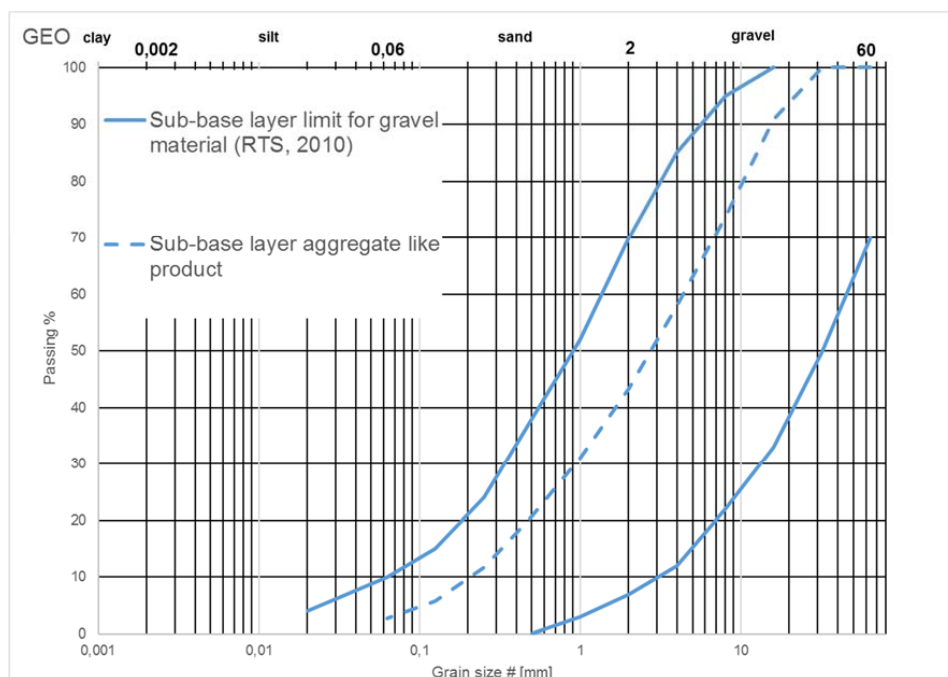
Figure 13 Grain size distribution of MSWI BA aggregate-like product for sub-base layer

Table 16 Proportion of MSWI BA mineral fractions in designed aggregate-like products

Aggregate-like product / Structural layer	Amount of MSWI BA mineral fractions (%)			
	0–2	2–5	5–12	12–50
Base	100	-	-	-
Sub-base	35	25	25	15
Filtration	15	15	15	55

Some technical properties of MSWI BA aggregate-like products are given in Table 17 to answer the fifth (5) research question of this thesis (see Chapter 1.6). The rest of the obtained technical properties are presented in more detail in *Paper II* of this thesis. As can be seen in Table 17, the maximum dry densities and the thermal conductivities of aggregate-like products were of the same order of magnitude as those obtained for separate MSWI BA mineral fractions (see Chapter 3.1.1). On the other hand, the OWC values of SBL and BL products in particular (9.8 – 10%, Table 17) were clearly lower than the typical water contents observed during the triaxial tests in the laboratory (12.2-17.9%) (see Paper III) or the OWCs observed during the field performance study for these two products (15.0 – 18.5%) (see *Paper IV*). The cause of this difference was not clear, but it was suspected that

the OWC values reported in *Paper II* for SBL and BL products do not represent the actual OWCs of these materials and should therefore be disregarded.

Based on the freeze-thaw resistance test, all the MSWI BA aggregate-like products tolerated freeze-thaw cycle well, since the loss of weight observed in the test specimens was only 1% (*Paper II*). Additionally, the amount of TOC was less than 1% in all the MSWI BA aggregate-like products (see *Paper III*). It was thus unlikely that the materials organic matter would affect the stiffness and strength properties of recovered MSWI BA, as was observed by Arm (2003) for conventionally treated MSWI BA. Although, it should be considered that the amount of TOC is mainly related to the efficiency of the burning process in the W-t-E plant and not the actual treatment process of MSWI BA.

Table 17 Technical properties of aggregate-like products

Property			Aggregate-like product / Structural layer		
			Filtration	**Sub-base**	**Base**
Maximum dry density	**(kN m^{-3})**		12.5	16.0	16.8
Optimum water content	**(%)**		27	9.8[a]	10[a]
Thermal conductivity	**(W mK^{-1})**	**(T= +10ºC)**	0.6	0.6	0.4
		(T= -10ºC)	1.0	0.8	0.6

[a]These values are not considered reliable, as explained in the text.

As mentioned in section 2.2.2, all the technical test methods used for the recovered MSWI BA in this study were originally designed for natural and crushed rock aggregates. For example, the Los Angeles test was noted to be too rough as a test method for the recovered MSWI BA, since the particles were crushed during the test and no reasonable LA values were obtained for the material (*Paper II*). The moduli values (E1 and E2, MPa) obtained in the laboratory with a confined static bearing capacity test arrangement (see Chapter 2.3.1) also overestimated the actual moduli values for these MSWI BA aggregate-like products. This can be seen in Table 18, which summarises the moduli values (MPa) from the static laboratory tests (i.e., SPLT) and the FEM simulations in both confined and unconfined model conditions. In the confined model simulation, the moduli values were the same order of magnitude as those obtained in the laboratory SPLT, but still up to 25 – 35% higher than in the unconfined model conditions (Table 18). Therefore, it was clear that the moduli values determined in the IBC containers overestimated the actual material's stiffness to a certain extent. As mentioned in Chapter 2.3.2, these moduli values were, however, used in the interim storage field design (Table 19). This was because, at the time of field design, other moduli (i.e., stiffness) values had not yet been determined for these materials.

Table 18 Moduli values (MPa) from laboratory scale SPLT tests and FEM model

Aggregate-like product	Laboratory scale SPLT		Confined model		Unconfined model		Ratio confined / unconfined model	
	E1	E2	E1	E2	E1	E2	E1	E2
Base	140	320	124	340	93	272	1,33	1,25
Sub-Base	130	270	81	208	61	167	1,33	1,25
Filtration	50	90	23	88	17	81	1,35	1,09

Table 19 Bearing capacity design of the interim storage field

Layer	Filtration	Filtration	Sub-base	Base	Base	Pavement
Material	Bottom ash 0-2 mm	Bottom ash 0-2 mm	Bottom ash mixture	Bottom ash mixture	Aggregate #0-32	Asphalt pavement (water tight)
E_A (MPa)	20	42	63	142	230	260
h (mm)	250	250	300	300	300	110
E (MPa)	90	90	270	320	280	2500
E_Y (MPa)	42	63	142	230	260	435

To investigate further the stiffness and the strength properties of MSWI BA aggregate-like products, cyclic load and static triaxial tests were performed in the laboratory, as explained in Chapter 2.3.1. These results are presented in detail in Paper III, and some of the main findings are given here to answer the sixth (6) research question of this thesis (see Chapter 1.6).

The resilient modulus values (Mr) obtained from the cyclic load triaxial test were the lowest for the FL product (50 – 150 MPa) and the highest for the BL product (100 – 400 MPa) (Table 20). The difference between the resilient modulus values of the BL and the SBL products was rather small (Table 20), which is the case for crushed rock aggregates with similar grain size distributions as well (Kolisoja, 1997). The resilient modulus values of the aggregate-like products designed from the ADR recovered MSWI BA corresponded also to the modulus values previously obtained for conventionally treated MSWI BA (Arm, 2004, Arm, 2004, Bendz et al. 1996, Sweere, 1990). The friction angles (φ') of MSWI BA aggregate-like products (Table 21) were also the same order of magnitude as those obtained for MSWI BA in previous studies (Becquart et al. 2009, Wiles and Shepherd, 1999). However, the cohesion values (c') of MSWI BA aggregate-like products were clearly higher (50.2 - 65.5 kPa, (Table 21) than those obtained, for example, by Wiles and Shepherd (1999) for conventionally treated MSWI BA (13.8 – 27.6 kPa). This difference might be related to the degree of material aging, which is suspected to be more accelerated in the novel MSWI BA treatment process, as the material bypasses several treatment steps. As mentioned in Chapter 1.3, the aging changes the mineralogical composition of MSWI BA, which can also create more cohesion between MSWI BA particles.

Table 20 Summary of cyclic load triaxial test results

Aggregate-like product	Resilient modulus (M_r) MPa				Sum of principal stresses kPa
	fresh[a]	closed[b]	open[c]	water-exposed[d]	
Base	100 - 400	_[e]	_[e]	_[e]	90 - 430
Sub-base	100 - 350	270 - 490	350 - 590	240 – 580[f]	90 - 430
Filtration	50 - 150	330 - 340	660 - 500	170 - 290	90 - 430

[a]Tested directly after compacting the test specimen.
[b]The moisture content was aimed to keep constant by enclosing the test specimen tightly in a plastic film.
[c]The test specimen was allowed to dry out freely by keeping the top of the test specimen open.
[d]Unrestrained water supply was provided on the bottom level of the test specimen.
[e]Could not be tested due to practical reasons; for more details, see *Paper III.*
[f]Sum of principal stresses 485 kPa.

Table 21 Static triaxial test results for freshly compacted samples

Aggregate-like product	φ' °	c' kPa	E_{50} MPa (at 20 kPa)	E_{50} MPa (at 40 kPa)	E_{50} MPa (at 70 kPa)	E_{50} MPa (at 130 kPa)
Base (n=3)	39.7	50.2	184	203	216	287
Sub-base (n=1)	49.6	65.5	194	215	236	290
Filtration (n=1)	34.1	64.5	83	98	112	139

φ': friction angle, c': cohesion, E_{50}: secant modulus values determined at 50 % of the peak of deviator stress at different confining pressures (20, 40, 70, 130 kPa)

In comparison with the behaviour of natural and crushed rock aggregates under cyclic load, certain issues were observed to be different with the MSWI BA aggregate-like products. For instance, the resilient modulus values for the freshly compacted MSWI BA test specimens increased nearly linearly as a function of the sum of principal stresses (e.g., FL product in Figure 14), which is not typical behaviour for natural hard rock aggregates (Kolisoja, 1999). In addition, the resilient modulus increased within two months of storage time for tested products regardless of storage conditions (closed, open, water-exposed) (Table 20 and Figure 14). The most prominent increase in the resilient modulus values was observed when the materials moisture content decreased (e.g., FL product in Figure 14). Similar behaviour was observed also in the static triaxial test, as illustrated in Figure 15 for the SBL product.

In general, the results obtained from these cyclic load and static triaxial tests clearly illustrated that the stiffness and strength properties of recovered MSWI BA aggregate-like products improve over time. This was observed to be due to changes in moisture content, but also due to MSWI BA aging, which, according to Reichelt (1996), can affect the materials mechanical properties. However, in this study it was not possible to quantify how much this increase in materials' mechanical properties is

affected by the changes in moisture content, as well as, what the role of different types of chemical reaction is. Further research on this matter is therefore needed, as suggested in Chapter 4.3.

Finally, another important issue related to the MSWI BA moisture content should be kept in mind. During the test specimen compaction inside the compaction mould, it was noticed that the material started to soften when the specimen contained an excessive amount of water (*Paper III*), which in turn decreased the obtained stiffness values. This result demonstrated the importance of avoiding excessive water during compaction, or the durability of those structures built with recovered MSWI BA can decrease.
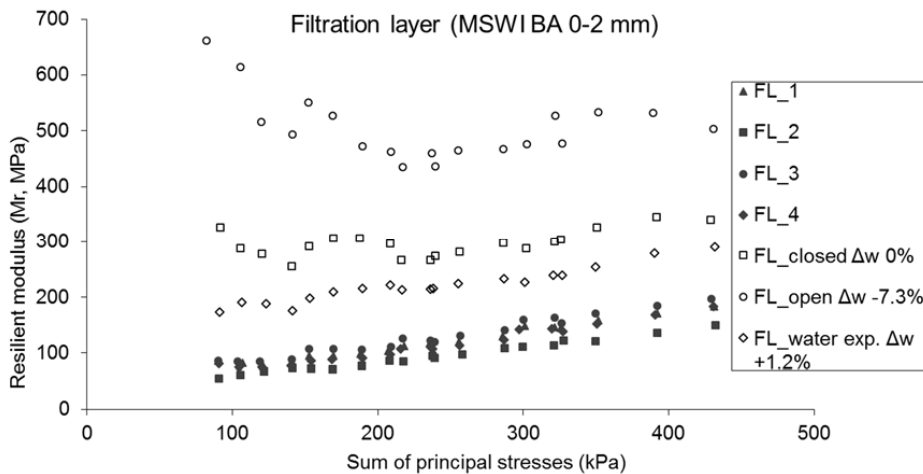
Figure 14 Cyclic load triaxial test results for filtration layer aggregate-like product

Overall, the technical and mechanical properties of the recovered MSWI BA aggregate-like products obtained in the laboratory suggested that this material is especially suitable for lower structural layers of roads (i.e., filtration and sub-base layer). Particle crushing under heavy traffic loading may limit the suitability of recovered MSWI BA in the base layer. This was in accordance with the findings of previous studies, where conventionally treated MSWI BA was considered to be the most suitable material for the lower parts of road structures (e.g., Arm, 2003, Bendz et al. 2006). This in turn implied that the use of advanced MSWI BA treatment technologies such as ADR do not improve the materials' mechanical properties as such, whereas the advantages of using such technologies are more related to the increased recovery rate of metals, as was discussed in Chapter 1.3. However, it should be considered that the use of recovered MSWI BA in the base layer might be feasible if, for example, an additional base layer of natural aggregate or a thicker asphalt pavement is constructed on top. Such approach was taken in this study, when an additional base layer was designed for the interim

storage field (Table 19) in order to meet the durability requirements set for this field (see *Paper II*). However, the feasibility of using this material also in the base layer was further investigated in the field, as will be discussed in Chapter 3.3.1. This was done in order to further verify the laboratory findings presented in this chapter.
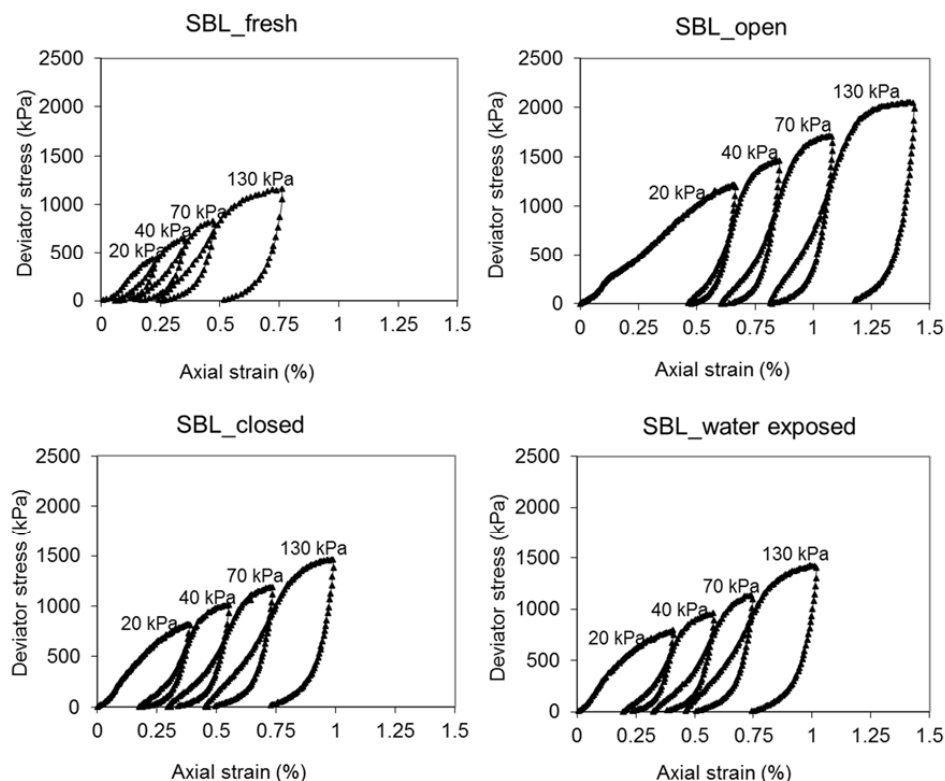
Figure 15 Static triaxial test results for sub-base layer product in different storing conditions

3.2.2 Environmental properties

As an answer to the seventh (7) research question of this thesis (see Chapter 1.6), Table 22 summarises the leaching test results for the MSWI BA aggregate-like products that are compared with the Finnish leaching limit values (Government Decree 591/2006, modification 403/2009 and 1825/2009). All the other substances except chrome (Cr) and chloride (Cl⁻) were below the respective leaching limit values (Table 22). The leaching of antimony did not exceed the leaching limit values in the percolation tests conducted for the MSWI BA aggregate- like products (Table 22), even though that was the case for the separate MSWI BA mineral fractions in some samples (Table 14 and Table 15). This is most likely due to the pH values of eluates that were generally higher (9.6 –

12.0) for the MSWI BA aggregate-like products (Table 22) than they were for those separate MSWI BA mineral fractions where leaching limit values were exceeded (7.8 – 10.7) (Table 14). These observations support the fact that antimony leaching is dependent on the leachate pH as has been demonstrated for MSWI BA in other studies as well (e.g., Keulen et al. 2016). However, it should also be noted that other factors can affect the antimony leaching and therefore further discussion on this matter is given in Chapter 3.3.2, where the field scale leaching test results are reported.

Table 22 Leaching test results for MSWI BA aggregate-like products

| Substance | Bottom ash mixtures: Standardised percolation test (mg kg^{-1}, dry weight, L S^{-1} 10) | | | Leaching limit values |
	Filtration layer[c]	Sub-base layer	Base layer	Finland[a]
pH[b]	11.2 – 12.0	9.9 – 11.3	9.6 – 11.2	-
Ec (mS m^{-1})[b]	51 – 1740	31 – 1651	27 – 1543	-
Redox (mV)[b]	261 – 338	297 – 362	287 – 366	-
As	0.02	0.01	0.01	1.5
Ba	1.1	0.33	0.3	60
Cd	<0.01	<0.01	<0.01	0.04
Co	<0.01	<0.01	<0.01	-
Cr	6.5	0.87	1.4	3
Cu	2.9	0.79	1.2	6
Mo	1.7	0.77	0.94	6
Ni	0.04	0.02	0.02	1.2
Pb	<0.01	<0.01	<0.01	1.5
Sb	0.14	<0.1	0.14	0.18
Se	0.03	0.01	0.02	0.5
V	0.25	0.13	0.16	3
Zn	0.19	0.06	0.08	12
F$^-$	8.4	<1.0	<1.0	50
Cl$^-$	4800	2300	2900	2400
SO$_4^{2-}$	3300	2600	3000	10000
Hg	<0,0002	0.002	0.004	0.01
DOC	220	84	110	500

[a]Government Decree 591/2006, modifications 403/2009 and 1825/2009.
[b]Given as a range of seven eluates.
[c]First published in the *Paper I* of this thesis.
Ec: Electrical conductivity; DOC: dissolved organic carbon; dw: dry weight

3.3 Field performance studies

As explained in the introduction, the laboratory experiments performed for waste-derived aggregates can be very different from the realistic field conditions (see Chapter 1.4). The technical, mechanical, and environmental properties of conventionally treated MSWI BA have been investigated in numerous studies in the past, whereas field data on the properties of MSWI BA recovered with novel treatment technologies such as ADR has not been reported. Therefore, this study investigated the field performance of MSWI BA recovered with a novel dry treatment technology with respect to the materials technical, mechanical, and environmental properties. In this chapter, the main results of these field performance studies and a comparison to the previously presented laboratory data are described and discussed. The aim of this chapter was to answer the research questions 8-12 under objective 3 (see Chapter 1.6). All the results obtained from the field performance studies are given in detail in *Papers IV and V* of this thesis.

3.3.1 Technical and mechanical properties in the field

As an answer to the eighth (8) research question of this thesis (see Chapter 1.6), Figure 16 provides an example of the degrees of compaction (DoC) measured with the NDG in the field. The rest of the NDG measurement results are presented in *Paper IV* of this thesis.
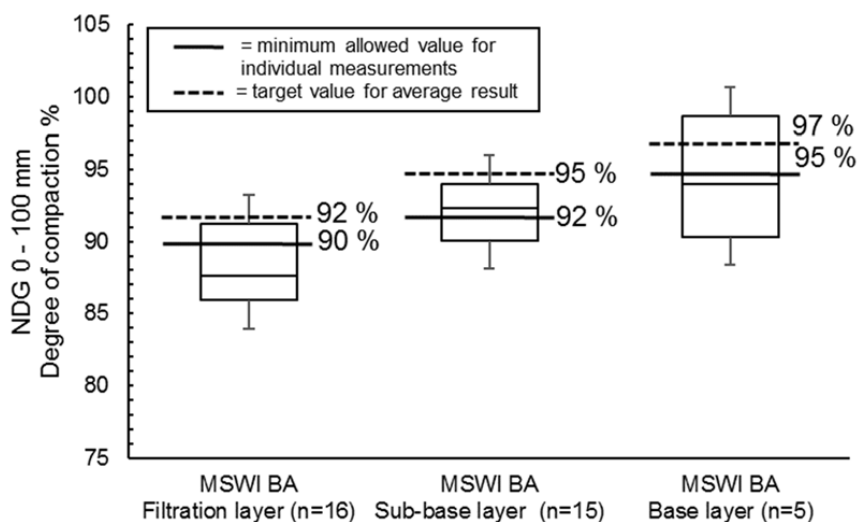
Figure 16 Degrees of compactions measured in the interim storage field

The DoCs measured in the field (see example in Figure 16) did not in all cases fulfil those requirements that are given for natural and crushed rock aggregates in the corresponding structural layers (RTS, 2010). However, such lower DoCs were also obtained for the MSWI BA aggregate-like products with the cyclic load triaxial test specimen compacted in the laboratory (*Paper III*). This implied that the structural layers in the field were altogether sufficiently compacted, even though the target values for DoC were not reached. As illustrated in Table 12, bottom ash particles are crushed to some extent during the modified Proctor compaction test, on which the target values of DoCs are based. Therefore, the target values of DoCs used for natural and crushed rock aggregates may not be suitable for this waste-derived aggregate, since it behaves differently in the Proctor compaction test than natural and crushed rock aggregates, as already discussed in Chapter 2.2.2. These target values were nonetheless used in this study, since no other values exist for DoC in Finland. Further studies are therefore needed to determine more suitable target values of DoC for the recovered MSWI BA in case in-situ density measurement techniques are used for quality control. The use of such techniques may not, however, be that an appealing option for real construction projects, because the NDG equipment does not provide correct water content results with this material as was demonstrated in this study (see *Paper IV*). The water content results can be corrected by taking material samples from each measurement point and then analysing them in the laboratory, but that option is surely more time-consuming and costly in nature.

Figure 17 summarizes the measured bearing capacities (E2, MPa) during and half a year after the construction on top of the structural layers of the interim storage field in order to answer the ninth (9) research question of this thesis (see Chapter 1.6).
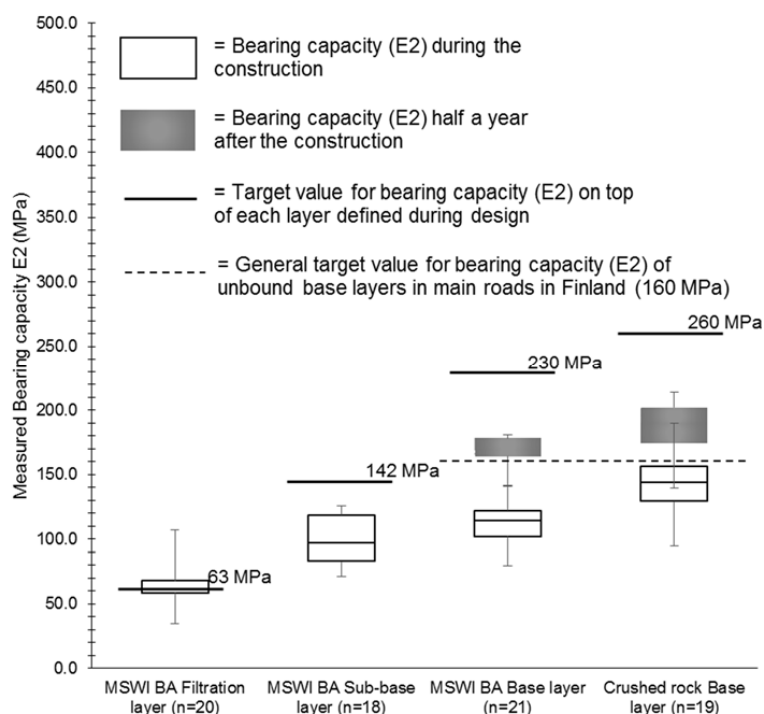
Figure 17 Measured bearing capacities (E2, MPa) in the interim storage field

The measured bearing capacities on top of each layer during the construction (Figure 17) were mainly below the target values set for the bearing capacities on top of each layer (E_Y, MPa) during the structural design of the field (Table 19). The only exception was the filtration layer in which the measured bearing capacities (E2, MPa) on average fulfilled the given requirements (Figure 17). As mentioned in Chapters 2.3.2 and 3.2.1, the moduli values used for the structural design of the field were overestimated up to 35% due to the too small test scale in the laboratory. This in turn reflected on the bearing capacity target values on top of each structural layer (E_Y) that were set with the Odemark elastic layer theory (Table 19). In other words, the bearing capacity requirements calculated for the MSWI BA structural layers were also overestimated and practically impossible to reach in the field. If, for example, the moduli values (E2, MPa) obtained from the unconfined FEM model had been used in the Odemark design (Table 18), the target values of bearing capacity (E_Y) would have been lower for each structural layer: FL: 59 MPa, SBL: 107 MPa, and BL: 185 MPa. These requirements would have been reached at almost half of the measurement points, especially in the filtration and the sub-base layers, but still not in any of the measurement points on top of the base layer.

Conversely, the bearing capacities (E2, MPa) measured half a year after the construction on top of both base layers (i.e., MSWI BA and crushed rock aggregate) had increased almost up to 30%, as illustrated in Figure 17. The laboratory results presented previously in this study demonstrated that the stiffness and strength properties of recovered MSWI BA increase over time due to aging and changes in moisture content (see Chapter 3.2.1). The most prominent increase in these mechanical properties was observed when the material's moisture content decreases (see Chapter 3.2.1 and *Paper III)*. In the field performance study, the moisture content of the MSWI BA aggregate-like product used in the BL of the interim storage field decreased nearly 5% within six months (Figure 18). This supports the conclusion that when the recovered MSWI BA dries out, the stiffness of structures made of this material increase. Albeit it should be taken into account that this increase in material stiffness is not only related to the changes in moisture content, but also material aging, as discussed in Chapter 3.2.1.

During the construction	Δ**w%**	Half a year after the construction
x=14,7 % (*n=5*)	**MSWI BA Base layer** -4,6 %	x=10,1 % (*n=5*)
x=17,5 % (*n=15*)	**MSWI BA Sub-base layer** -0,8 %	x=16,7 % (*n=5*)
x=28,5 % (*n=16*)	**MSWI BA Filtration layer** +3,7 %	x=32,2 % (*n=5*)

Figure 18 Changes in moisture content in the interim storage field

In this study, the stiffness properties of MSWI BA aggregate-like products were evaluated in three different ways: first, preliminarily based on materials' grain size distributions and their correspondence to respective natural and crushed rock aggregates (*Paper IV*); second, in the laboratory with cyclic load triaxial tests (*Paper* III); and third, on a larger scale during the construction of the interim storage field (*Paper IV*). Table 23 summarizes all these results as moduli values of the MSWI BA aggregate-like products investigated in this study.

Table 23 Moduli values (MPa) determined for the MSWI BA aggregate-like products

		Aggregate-like product		
		Filtration	Sub-base	Base
		Moduli values (MPa)		
Preliminary[a]		70	100 (150)	200
Laboratory[b]	fresh, *n=4*	80 - 90[c]	120 - 180[d]	170 - 290[e]
	closed, *n=1*	330 - 290[c]	260 - 330[d]	-
	open, *n=1*	660 - 550[c]	360 - 390[d]	-
	water-exposed, *n=1*	170 - 200[c]	250 - 300[d]	-
Field[f]		75 - 105	115 - 156	103 - 155

[a]Based on materials grain size distribution, correspondence to natural and crushed rock aggregates (*Paper IV*).
[b]Determined with cyclic load tests (*Paper III*).
[c]At sum of principal stresses 90...150 kPa.
[d]At sum of principal stresses 100…200 kPa.
[e]At sum of principal stresses 150…300 kPa, *n=3*.
[f]Back-calculated from the field measurements conducted during the construction of the interim storage field (*Paper IV*).

The results presented in Table 23 illustrate that the stiffness of recovered MSWI BA is not only dependent on the level of applied stresses, but also on material aging and prevailing conditions such as material moisture content. In practice, this influences the quality requirements given for these materials during construction, when their stiffness is evaluated based on the SPLT. These requirements should also consider the increase in material stiffness over time, which is not characteristic for natural and crushed rock aggregates, and therefore not considered in their requirements that were used in this study. It was beyond the scope of this study to define such requirements, but further analysis is planned in order to set proper requirements that can be used for these MSWI BA aggregate-like products during construction in the future.

Table 23 also answers the tenth (10) research question of this thesis (see Chapter 1.6): certain differences do exist in the technical and mechanical properties of the recovered MSWI BA aggregate-like products between the laboratory and the field studies. For example, the aggregate-like product designed from MSWI BA could be suitable for the base layer based on its grain size distribution. However, a more detailed investigation demonstrated that its actual stiffness values (MPa) were lower when tested with proper equipment in the laboratory (i.e., cyclic load triaxial test) or when verified with the field measurements (Table 23). This result illustrates the importance of investigating the different properties of waste-derived aggregates in different scales in order to properly understand how these materials behave in realistic conditions and in which structures they are actually suitable.

Finally, as explained in Chapter 3.2.1 and the earlier paragraph of this chapter, the stiffness of recovered MSWI BA can increase over time due to aging and changes in moisture content. This applies to the recovered MSWI BA used in the base layer as well, as was demonstrated in the current field performance study. However, with current knowledge, recovered MSWI BA cannot be recommended for use in the base layers, even though its stiffness can increase over time. The main reason for this is that MSWI BA particles are prone to crushing and are most likely not able to resist the higher stresses that occur under heavy wheel loads in the upper parts of road and field structures.

This problem could be solved by constructing an additional base layer of natural aggregate or alternatively thicker asphalt pavement on top which, however, may not be the most cost-effective solution in real construction projects. Therefore, it can be concluded that, based on materials' mechanical behaviour, the recovered MSWI BA is especially suitable to be used in the lower structural layers of roads and field structures (i.e., filtration and sub-base layers).

3.3.2 Leaching of potentially harmful substances in the field

As mentioned in Chapter 2.4.1, the leaching of potentially harmful substances was studied with two separate field tests: the lysimeter and the interim storage field study. The results obtained from these field studies were then compared with the previously conducted laboratory leaching test results reported in Chapters 3.1.2 and 3.2.2 and in *Papers I and II* of this thesis. The concentrations of several potentially harmful substances were analysed from the leachates both in the laboratory and in the field studies. However, this chapter summarises only the results of those substances (i.e., chloride and antimony) that were considered the most problematic with regard to MSWI BA utilization possibilities in Finland (see Chapters 3.1.2 and 3.2.2). The results of other substances are presented in more detail in *Paper V* of this thesis.

Figure 19 illustrates the measured concentrations of chloride (Cl^-) plotted against the calculated L S^{-1} (L kg^{-1}) for each sampling point in all three study scales (laboratory, lysimeter and interim storage field). A similar illustration is given for antimony (Sb) in Figure 20. Figures 19 and 20 answer to the eleventh (11) research question of this thesis (Chapter 1.6). The measured concentrations of many substances in the leachate were rather high in the interim storage field, especially at the beginning of the test (Figure 19 and Figure 20). Similarly, the concentrations of some other substances (e.g., Cu, Mo and V) were also higher at the end of the field test if compared with the laboratory and the lysimeter test results (see *Paper V*). One possible reason for this was the difference in sampling schemes between these study scales. In the interim storage field, the concentrations were measured from individual point measurements, whereas in the laboratory and lysimeter studies, the analysis was done from composed samples collected within a certain sampling period (*Paper V*). In practice, this meant that the leachate collected in the interim storage field was most likely not as diluted as it was in the other two studies.

In addition, when interpreting the obtained results, it should be considered that the L S^{-1} (L kg^{-1}) reached at the end of the sampling period in the interim storage field was only 0.13 L kg^{-1}. Thus, the collected field data was only comparable for the first two measurement points of the laboratory leaching test results. This, coupled with the uncertainty related to the measuring of leachate amount in the interim storage field (see Chapter 2.4.3), means that the leaching test results obtained in the interim storage field should only be considered as suggestive results. On the other hand, as pointed out in *Paper V* of this thesis, in many large-scale studies, different technical issues can cause uncertainties in result interpretation. This should not, however, prevent conducting and reporting such

studies, since at the end of the day, those studies provide valuable information on the leaching prop-
erties of waste-derived aggregates in more realistic conditions.
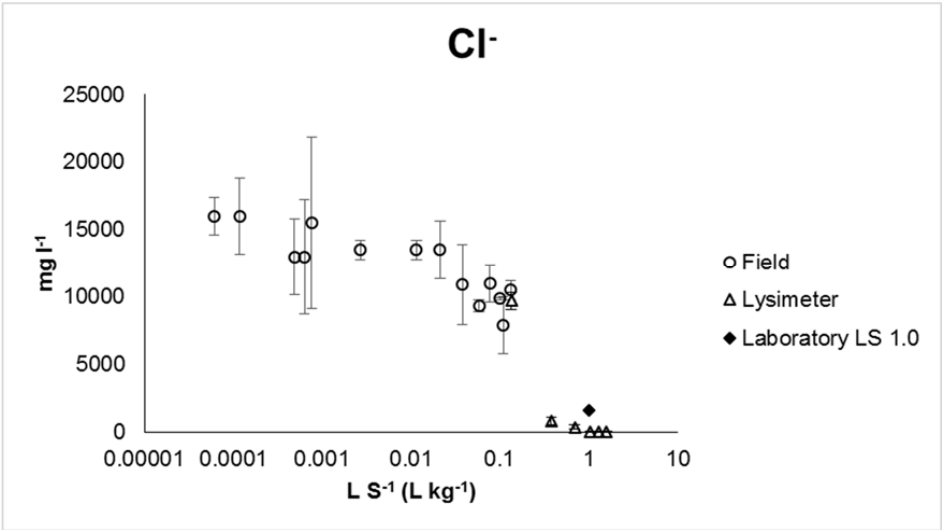

Figure 19 Leaching of chloride in laboratory and field studies
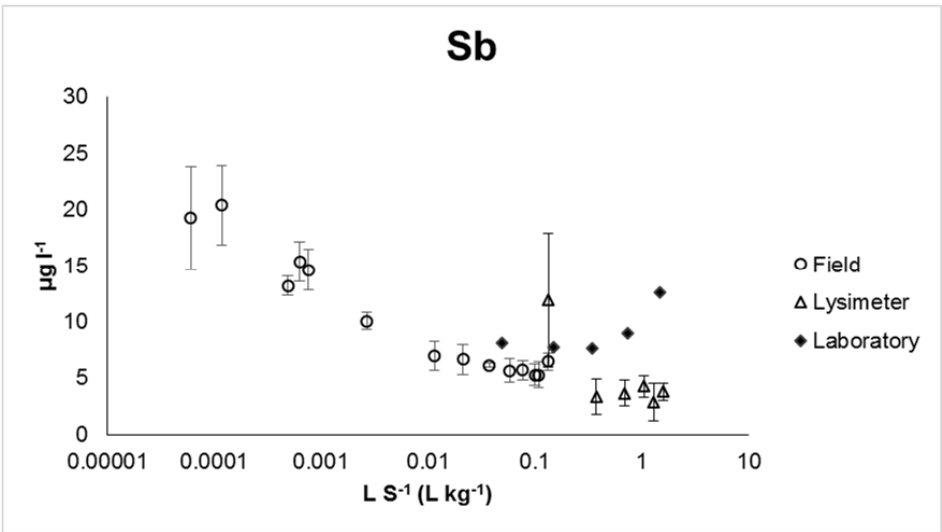
Figure 20 Leaching of antimony in laboratory and field studies

Despite the differences in the concentration levels of potentially hazardous substances, a reasonable agreement was observed for the leaching behaviour of chloride and antimony in all three study scales (Figures 19 and 20). Similarly, reasonable agreement was observed for the leaching behaviour of most other substances as well, as illustrated in *Paper V.* Only exception was vanadium (V), for which leaching increased to some extent at the beginning of the interim storage field study. However, this was not prominent increase, since after the test continued (i.e., L S^{-1} (L kg^{-1}) increased), the leaching behaviour of vanadium in the interim storage field started to follow those obtained in the lysimeter and laboratory studies (i.e., decreasing behaviour) (for further discussion see *Paper V*). This result, however, yields an answer to the twelfth (12) research question of this thesis (see Chapter 1.6): certain differences do exist between the leaching behaviour of potentially harmful substances from the recovered MSWI BA mineral fraction products between the laboratory and the field scale studies.

As discussed in Chapter 1.4, the leaching behaviour of different substances in realistic conditions is not only related to L S^{-1} (L kg^{-1}), but also to other factors, such as leachate pH. This applies especially to metals but not to highly soluble salts such as chloride, for which leaching is more availability based (Hjelmar, 1996). In the current field performance study, the leaching of antimony was observed to be very much dependent on the leachate pH, which was clearly lower in the field scale studies than in the laboratory leaching tests (Figure 21). These lower pH values were considered to be related to the aging of MSWI BA. This material aging takes place in atmospheric conditions and causes decrease in MSWI BA pH values, as was explained in Chapter 1.3. In the interim storage field study, when the pH values decreased from nearly 12 to 8, the leaching of antimony increased. Similar observations have been made by many other researchers as well (e.g., Cornelis et al. 2006, Cornelis et al. 2012, Johnson et al. 1999, Keulen et al. 2016). This phenomenon is further illustrated in Figure 22, where the analysed antimony concentrations (mg kg^{-1}) from the interim storage field are plotted against the measured pH values. However, it should be considered that the leaching of antimony is also controlled by the formation of sparingly soluble antimonates such as $Ca(Sb(OH)_6)_2$ (Cornelis et al. 2006, Cornelis et al. 2012, Johnson et al. 1999). In this study, calcium concentrations were not measured in the field, and thus no comparison could be made between the antimony and calcium concentrations in the leachate. It is thus recommended that in future studies, the concentrations of major elements should be analysed as well in order to properly interpret the relationship of these elements with the leaching of potentially hazardous substances.
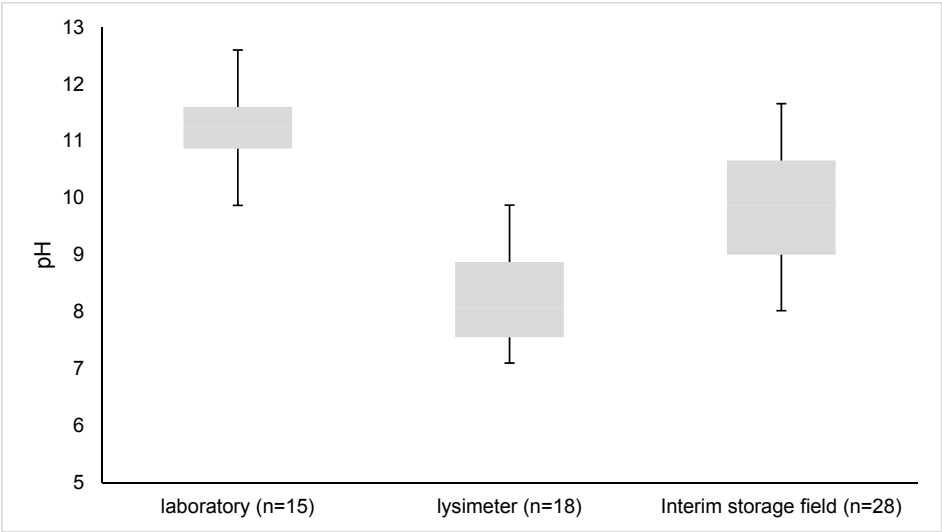
Figure 21 Measured pH values of the three study scales

Figure 22 Antimony concentrations against pH values in the interim storage field
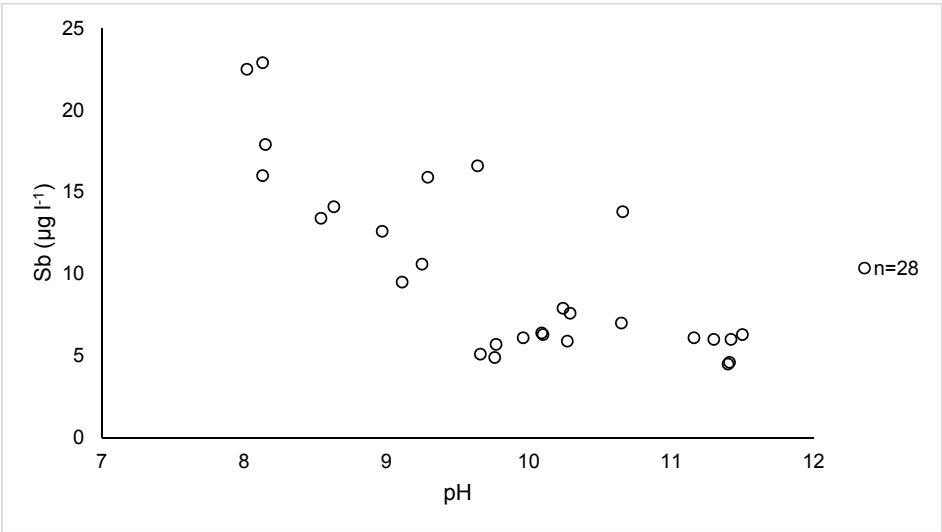
In general, the observations made in this study indicated that the leaching of different substances in realistic field conditions can be a sum of many factors that cannot be easily controlled. A reasonable agreement was, however, observed in the leaching behaviour of different substances between the

laboratory and the field scale experiments. This in turn increases the reliability of laboratory experiments on which the utilization decisions of waste-derived aggregate are normally based.

As discussed in Chapter 1.3, the novel MSWI BA treatment technologies increase the recovery rate of metals. Therefore, these technologies are supposed to improve the environmental compatibility of MSWI BA minerals as well. Even though the leaching of most substances from MSWI BA minerals recovered with ADR technology were observed to be below the current limit values imposed by Finnish legislation, certain substances such as antimony and chloride still exceeded their limit values in the laboratory experiments (see Chapters 3.1.2 and 3.2.2). Elevated concentrations of antimony and chloride were also observed in the field, even though their leaching decreased when the $L\ S^{-1}$ ($L\ kg^{-1}$) increased. It can thus be concluded that ADR technology can improve the environmental properties of MSWI BA minerals to some extent, but not entirely.

This matter is also related to the risk level that is accepted for the utilization of MSWI BA or other waste materials in different countries (i.e. the leaching limit values). As mentioned in Chapter 1.4, the new leaching limit values for the utilization of waste-derived aggregates have been currently proposed in Finland. For some substances (e.g., antimony), higher leaching limit values have been suggested, whereas for others (e.g., chloride), the limit values would remain the same in certain structures (YM14/400/2016). This means that if we want to comply with all these limit values, improvements should be made to the MSWI BA treatment technology that was used in this study.

Such an approach has already been practiced in the Netherlands, where the government and industry have agreed on a "Green Deal" (Born, 2016). One of the aims of this deal is that the MSWI BA should be treated in such way that these materials comply with the stringent criteria for "freely applicable building materials" (Born, 2016). In practice, this has required large investments in new treatment plants where, for example, dry and wet treatment processes are used simultaneously. In Finland, such an approach may not be economically feasible, since the amount of produced MSWI BA is much less here than in the Netherlands. The waste incineration plants are also located far from each other, which would require too much material transportation that is not economically or environmentally reasonable. Therefore, other less expensive but still efficient options for improving the treatment of MSWI BA should be considered, in case the leaching of potentially harmful substances needs to be decreased in the future.

In general, it should be mentioned that the results obtained in this study have enabled the authorities to decide that recovered MSWI BA can be added within the scope of the renewed Government Decree (YM14/400/2016). This Decree further aims to facilitate the use of waste-derived aggregates, such as recovered MSWI BA, in civil engineering in Finland.

4 Conclusions

The main aim of this study was to follow the core principle of the circular economy launched by the European Union: to promote the reuse of materials and to create added value with such reused products. Recovered MSWI BA was used as a material to design aggregate-like products for the structural layers (filtration, sub-base and base layers) of roads and field structures. This approach was novel, since MSWI BAs are in many cases only dumped in embankments, noise barriers, or landfill sites, where the added value of this material is non-existent.

This chapter provides the final conclusions of this dissertation. The main research outcomes are given, together with an evaluation of the reliability and validity of the obtained results. Some suggestions for further research are given as well.

4.1 Research outcomes

The following outcomes can be drawn from this research project as regards of *the technical and mechanical properties* of recovered MSWI BA.

- The aggregate-like products designed from recovered MSWI BA can be safely used in the lower structural layers of road and field structures (i.e., filtration and sub-base layers) based on the materials stiffness and strength properties. In base layers, the material is not able to resist the high stresses occurring in the upper structural layers of roads and field structures. One of the main reasons for this phenomenon is that MSWI BA particles are prone to crushing. This was tested with the Los Angeles test that did not give any reasonable result for this material. Therefore, at this point, it is not possible to recommend the use of recovered MSWI BA in the base layers unless an additional base layer of natural aggregate or alternatively thicker asphalt pavement is constructed on top. However, the cost effects of such structural designs should be evaluated in more detail.

- The stiffness and strength properties of recovered MSWI BA increase over time due to material aging and changes in its moisture content, which was demonstrated both in the laboratory and the field experiments. The most prominent increase in material stiffness was observed when the material dries out. Conversely, excessive water was observed to soften the material, which in turn decreased the material's stiffness. Therefore, these materials should only be used in locations where excessive water cannot seep into the structure and thus weaken its durability. It should be noted that it was beyond the scope of this study to investigate further how much the increase in materials stiffness and strength properties is affected by the changes in moisture content, and what the role of chemical reactions is. Further studies are therefore needed in order to fully understand this multifaceted matter.

- The recovered MSWI BA can be considered non-frost susceptible when the frost susceptibility is assessed only based on its grain size distribution. Its other analysed technical properties, such as proper freeze-thaw resistance and moderate hydraulic and thermal conductivities, were also considered favourable material properties against the frost action. These properties, coupled with the observed maximum dry densities, which were lower than those of natural and crushed rock aggregates, might allow for designing thinner and lighter road and field structures than those normally designed with natural and crushed rock aggregates in Finland. However, it should be taken into account that the material's frost behaviour is also affected by other factors, such as water availability. As the frost-susceptibility of the recovered MSWI BA was only coarsely assessed in this study, further large-scale studies are needed on the frost behaviour of recovered MSWI BA before such thinner and lighter structures can be recommended.

The following outcomes can also be drawn from this project with regard to the environmental properties of recovered MSWI BA.

- The leaching of most potentially harmful substances were below the current Finnish limit values used in this study to assess the utilization potential of recovered MSWI BA from its environmental perspective. A reasonable agreement was observed in the leaching behaviour of different substances between the laboratory and field experiments, even though some uncertainties were related to the largest field test. These observations therefore increased the reliability of laboratory leaching tests on which the utilisation decisions of waste-derived aggregates are normally based.

- Conversely, even though the MSWI BA used in this study was treated with an advanced MSWI BA treatment technology (ADR), the leaching of certain substances such as chloride and antimony still exceeded the current limit values. It can thus be concluded that ADR technology can improve the environmental properties of MSWI BA minerals to some extent, but not entirely. The national legislation regarding the utilization of waste-derived aggregates is

currently under renewal. During this process, the leaching limit values have also been recalculated and, it seems that for certain substances and applications, stringent limit values will be imposed. In practice, this means that improvements are likely needed for the MSWI BA treatment technology used in this study in order to comply with all the given limit values, and the cost effects of such improvements should be calculated as well.

The following outcomes hold for *national impact*.

- Nationally, this research has provided important background data on the different properties of recovered MSWI BA in Finland. The leaching data obtained in this study has enabled policy makers to decide that recovered MSWI BA can be added within the scope of the renewed Government Decree (YM14/400/2016), which further aims to facilitate the use of waste-derived aggregates in civil engineering in Finland.

- In addition, the results of this study have been used as a basis for a Finnish guidebook. This book describes the different properties of recovered MSWI BA, and how the material should be used in civil engineering structures. The book is intended for material producers, designers, and constructors to help them steer recovered MSWI BA to those structures that are especially suitable for its properties, and where added value can also be gained. In such way, the dumping of this material into embankments and highway noise barriers can also be decreased and, thus, the circular economy of recovered MSWI BA can be promoted.

4.2 Validity, reliability and limitations

The present study investigated the technical, mechanical and environmental properties of recovered MSWI BA aggregate-like products both in the laboratory and in the field. The laboratory tests that investigated the technical properties of recovered MSWI BA were generally conducted according to the different standardized test methods, which have been originally designed for natural and crushed rock aggregates. These laboratory tests may not in all cases be completely suitable for the waste-derived aggregate used in this study. It was, however, beyond the scope of this study to fully evaluate the suitability of different analyses for this particular material. In addition, it was considered that when using the same test methods for investigating the properties of recovered MSWI BA, more comparable data would be obtained with the existing knowledge on natural and crushed rock aggregates and their properties.

Another limitation of this study was that it investigated the bottom ash of only one waste incineration plant in Finland. The quality of bottom ashes can vary from one plant to another due to, for example, the differences in the fuel quality. These quality differences can in turn influence the different properties of bottom ashes, although the material is treated with the same technology. It was, however,

beyond the scope of this study to include data of recovered bottom ashes from other plants. Such studies are therefore recommended in chapter 4.3.

The main uncertainty of the results obtained in this study concern those obtained from the interim storage field study, when the leaching properties of potentially harmful substances were investigated. The amount of leachate was not measured in an ideal way (see Chapter 2.4.3), which in turn caused uncertainty for the final $L\ S^{-1}$ ($L\ kg^{-1}$) calculations that were used as the basis for comparing the leaching data of different study scales. On the other hand, the water balance calculations from the field illustrated that the total collected amount of leachate was reasonable when the precipitation data of the whole sampling period was considered. Nevertheless, the leaching test results from the interim storage field should only be considered as approximate. It should also be acknowledged that the larger the study scale, the higher the level of uncertainty, since the study conditions cannot be as easily controlled as they can be in the laboratory.

In the field performance study, also the dispersion in density and bearing capacity measurements was quite substantial. This is rather normal phenomenon in the field conditions, albeit it adds uncertainty for the results obtained in this study.

4.3 Suggestions for further research

Based on the work carried out for this thesis, the following suggestions are given for further research:

The suitability of recovered MSWI BA in the base layers of low-volume roads

This study demonstrated that MSWI BA can be used, especially in the lower structural layers of roads and field structures (i.e., filtration and sub-base), based on their technical and mechanical properties. The study also showed that the materials' stiffness and strength properties increase over time. When considering this, the suitability of recovered MSWI BA could be investigated further in the base layers of, for example, low-volume roads where high stresses occur less frequently. In such studies, one could investigate the required thickness of structural layers built on top of MSWI BA base layer (e.g., asphalt concrete surfacing or an additional base layer), which would still minimize the possible risks caused by MSWI BA particle crushing.

The frost behaviour of recovered MSWI BA

In this study, the frost-behaviour of recovered MSWI BA aggregate-like products was only preliminary studied in a laboratory. Therefore, field studies should be conducted to investigate the frost-behaviour of these materials in more realistic conditions.

General quality requirements and standardized test methods for recovered MSWI BA

Most of the quality requirements used in this study have originally been defined for natural and crushed aggregates. Considering the certain unique properties of recovered MSWI BA, such as the improvement in the stiffness and strength properties over time, more descriptive quality requirements should be defined for this waste-derived aggregate. Further field studies and long-term monitoring is therefore recommended in order to establish reliable quality control requirements for the recovered MSWI BA used in civil engineering structures.

In addition, the standardized test methods used for investigating the technical properties of MSWI BA in this study have originally been defined for natural and crushed rock aggregates. Therefore, the suitability of these methods should be thoroughly investigated for the recovered MSWI BA, and new test methods developed in case the current ones are considered unsuitable for this particular material. For example, the suitability of standardized test method for analysing the water suction height (SFS-EN 1097-10) of construction materials could be further tested. This is because laboratory findings have later shown that a certain amount of water continues to rise in the material for at least several weeks or perhaps even for months, which is not typical for natural and crushed rock aggregates.

Quality of MSWI BA treated with recently emerging technologies

Even though the ADR technology increases the recovery rate of metals, some substances can still hinder its utilization in civil engineering applications. Especially in the Netherlands, new technologies have emerged for MSWI BA treatment in which wet and dry treatment processes are combined. In future studies, different properties (i.e., technical, environmental, and mechanical) of MSWI BA minerals generated from those processes should also be comprehensively investigated and compared with the results obtained in this study for the ADR-treated MSWI BA. It is likely that the leaching properties would be different, but perhaps differences in the technical and mechanically properties of recovered MSWI BA could be observed as well.

Quality of recovered MSWI BA generated in other plants

Comparison studies using recovered MSWI BA from different waste incineration plants in Finland should be conducted. It is suggested that the future field performance studies should use material from other plants and those results could be compared with the results obtained in this study. Especially the increase in materials stiffness and strength properties over time due to changes in moisture content and aging should be investigated more thoroughly.

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ORIGINAL PAPERS

I

TO FRACTIONATE MUNICIPAL SOLID WASTE INCINERATION BOTTOM ASH: KEY FOR UTILISATION?

by

Sormunen, L. A. & Rantsi, R., 2015

To fractionate municipal solid waste incineration bottom ash: Key for utilisation?

Laura Annika Sormunen[1] and Riina Rantsi[2]

Abstract

For the past decade, the Finnish waste sector has increasingly moved from the landfilling of municipal solid waste towards waste incineration. New challenges are faced with the growing amounts of municipal solid waste incineration bottom ash, which are mainly landfilled at the moment. Since this is not a sustainable or a profitable solution, finding different utilisation applications for the municipal solid waste incineration bottom ash is crucial. This study reports a comprehensive analysis of bottom ash properties from one waste incineration plant in Finland, which was first treated with a Dutch bottom ash recovery technique called advanced dry recovery. This novel process separates non-ferrous and ferrous metals from bottom ash, generating mineral fractions of different grain sizes (0–2 mm, 2–5 mm, 5–12 mm and 12–50 mm). The main aim of the study was to assess, whether the advanced bottom ash treatment technique, producing mineral fractions of different grain sizes and therefore properties, facilitates the utilisation of municipal solid waste incineration bottom ash in Finland. The results were encouraging; the bottom ash mineral fractions have favourable behaviour against the frost action, which is especially useful in the Finnish conditions. In addition, the leaching of most hazardous substances did not restrict the utilisation of bottom ash, especially for the larger fractions (>5 mm). Overall, this study has shown that the advanced bottom ash recovering technique can be one solution to increase the utilisation of bottom ash and furthermore decrease its landfilling in Finland.

Keywords

Municipal solid waste incineration bottom ash, advanced dry recovery, mineral fraction, technical and environmental properties, utilisation

Introduction

Incineration has recently become a more widespread solution for treating municipal solid waste in Finland. Waste incineration results in several different types of residues, of which bottom ash (BA) is the most abundant material (Chandler et al., 1997). The utilisation possibilities of municipal solid waste incineration (MSWI) BA has been commonly studied in several countries in different applications, such as road construction (Bruder-Hubscher et al., 2001; Hjelmar et al., 2007; Izquierdo et al., 2001) and in the cement and concrete industry (Bertolini et al., 2004; Kokalj et al., 2005; Pera et al., 1997). In Finland, on the other hand, the MSWI BA is mainly dumped in landfill sites. Dumping is neither a sustainable nor an economically feasible solution. For example, the recently renewed Finnish Waste Tax Act (Jäteverolaki, 1126/2010) sets high taxes per tonne (55 € t⁻¹ in 2015) for the landfilling of BA.

While the Finnish national waste plan has previously set targets for replacing 5% of natural aggregates with recycled materials, such as MSWI BA (Suomen Ympäristö, 2008), the national legislation does not promote the utilisation of MSWI BA. For example, the MSWI BA is not included within the scope of the application of the Government Decree concerning the recovery of certain wastes in earth construction (591/2006, modifications

403/2009 and 1825/2009). This Decree facilitates the utilisation of concrete waste and ash from wood- and peat-based incinerators by allowing the use of an easier and a less time-consuming notification procedure when certain boundary conditions are fulfilled. In contrast, the utilisation of MSWI BA always requires an environmental permit. In most of the cases, these permits are not issued within the strict timetables of construction contracts and natural aggregates are used instead.

In order for Finland to preserve the rather large, but decreasing storage of natural aggregates, different practices need to be developed for encouraging the recycling and utilisation of alternative materials, such as the MSWI BA. This can only be done by acquiring deeper knowledge on the materials technical and environmental properties, which enables to assess whether a material is suitable for a particular utilisation purpose.

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This study reports the comprehensive results of the technical and the environmental properties of a BA from one MSWI plant in Finland treated with a novel technique called advanced dry recovery (ADR) (de Vries and Rem, 2013). This Dutch technique has been mainly used in Western Europe, and this was the first time it was operated in Finland. The ADR process separates effectively non-ferrous and ferrous metals from MSWI BA and produces different size fractions of minerals, the smallest fraction having grain size of 0 to 2 mm, and the largest fraction of grain size 12 to 50 mm. In many other countries, the properties of MSWI BAs have been studied extensively (e.g. Chandler et al., 1997; Chimenos et al., 1999; Hjelmar, 1996; Izquierdo et al., 2001). However, to authors' best knowledge, no extensive studies have been published on the quality of the mineral fractions generated from this particular treatment process. The article aims to evaluate whether the advanced BA treatment technique, producing mineral fractions of different grain sizes and therefore properties, facilitates the utilisation of MSWI BA in Finland and furthermore minimises its landfilling.

Material and methods

The origin of the MSWI BA

The BA used in this study originated from a waste incineration plant in Mustasaari, Finland. The plant uses a grate design for waste combustion with a burning temperature of over 1000 °C. It incinerates approximately 180 000 t of waste consisting mainly (90%) of source-separated refuse from 50 municipalities and over 400 000 inhabitants. Other sources of waste fuels are, for example, agricultural waste and industrial waste (e.g. leather and fur industry). The amount of annually generated BA accounts for approximately 30 000 t in the plant, which is cooled down with water after its removal from the grate.

The treatment of MSWI BA

The MSWI BA was transported to a waste treatment centre located in Ilmajoki, Finland, where it was first screened with a drum screen to remove >50 mm fragments. Thereafter, the remaining fraction (<50 mm) was treated with a Dutch dry treatment technology called ADR. In brief, using dry screens, magnets, wind sifters, eddy current separators and the ADR, the process separates ferrous (F) and non-ferrous (NF) metals from the BA generating mineral fractions of different grain sizes (0–2 mm, 2–5 mm, 5–12 mm and 12–50 mm). These mineral fractions are the most abundant materials from the process, accounting for 75–80% of the total mass treated. This particular treatment technology was chosen, since it is able to treat BAs with moisture contents up to 20% (Hu et al., 2009) and no waste water or sludge is generated in the process. In addition, the removal of fines (<2 mm) with the ADR separator enhances the recovery of non-ferrous metals (aluminium, copper) from the size fractions <12 mm. A more detailed description of the ADR technology can be found in de Vries & Rem (2013). The ADR treatment was performed in the years

Table 1. The number of subsamples taken from the MSWI BA mineral fractions during the treatments in the years 2013 and 2014.

Year	The number of subsamples			
	0–2 mm	2–5 mm	5–12 mm	12–50 mm
2013	12	12	12	12
2014	4	2	2	2

2013 and 2014 for the annual amount produced in the waste incineration plant (ca. 30 000 t y^{-1}). In both of the years, the treatment lasted approximately 2 months.

Sampling

The different mineral fractions (0–2 mm, 2–5 mm, 5–12 mm and 12–50 mm) were sampled during the BA treatments in the years 2013 and 2014. The subsamples (10 L) were taken from the falling streams at the end of the conveyor belt for each separate fraction. Table 1 shows the number of subsamples taken from each fraction during the treatments in both years, 2013 and 2014. In the year 2013, the subsamples were taken two times a week, as it was the first year when the treatment was performed and a more comprehensive sampling scheme was needed for the basic characterisation. In the second year 2014, the sampling scheme was based on the quality control, and the number of subsamples was calculated based on the approximate mass distribution of the minerals generated from the process (0–2 mm: 35%; 2–5 mm: 13%; 5–12 mm: 15%; and 12–50 mm: 14%). Each mineral fraction was then sampled at the start of every 2500 t of produced material.

The collected subsamples were divided with the coning and quartering method (Gy, 1979) to a smaller representative subsamples (3 L). These subsamples were then used to generate separate combined samples for each size fraction in the both treatment years. The different analyses described in sections 'Environmental analyses' and 'Technical analyses' were performed either for the subsamples or for the combined samples of each size fraction.

Analyses

Environmental analyses. For basic characterisation, the combined samples from the year 2013 for each mineral fraction (0–2 mm, 2–5 mm, 5–12 mm and 12–50 mm) were prepared according to SFS-EN 13656 (SFS, 2003) and the acquired solutes were analysed with ICP-MS (Inductively coupled plasma mass spectrometry) or ICP-OES (Inductively coupled plasma optical emission spectrometry) in order to obtain the total concentration (mg kg^{-1}, dry weight) of different elements (aluminium, arsenic, barium, calcium, cadmium, cobalt, chromium, copper, iron, potassium, magnesium, manganese, molybdenum, nickel, phosphorus, Pb=lead, antimony, selenium, tin, zinc and mercury). Using the same methods, a few of these elements were also analysed for all the subsamples for each fraction taken from the year 2014.

The combined samples from the year 2013 and one subsample from the year 2014 for each mineral fraction (0–2 mm, 2–5 mm, 5–12 mm and 12–50 mm) were analysed using a standardised percolation test CEN/TS/14405 (SFS, 2004). This is a test used for the basic characterisation of waste materials. It provides information on the short and long term leaching behaviour and the characteristics of waste materials.

Three subsamples of each mineral fraction from the year 2013 and all subsamples from the year 2014 were then analysed with a standardised two-stage leaching test EN-12457-3 (SFS, 2012a). This is a compliance test providing information on the leaching of granular wastes and sludge. It is normally used for measuring the leaching behaviour of key variables previously identified by the basic characterisation test.

The leaching and the percolation test filtrates were analysed for the different hazardous substances as follows.

- Mercury (Hg): Cold vapour atomic fluorescence spectroscopy or cold vapour atomic absorption spectrometry.
- Other elements (arsenic, barium, cadmium, cobalt, chromium, copper, molybdenum, nickel, lead antimony, selenium, vanadium, zinc): ICP-MS or ICP-OES.
- Chloride, fluoride and sulphate (Cl⁻, F⁻, SO₄²⁻): Ion chromatography or ion selective.
- Dissolved organic carbon (DOC): Standardised test method SFS-EN1484 (SFS, 1997) using infrared detector (IR).

In addition, the pH and the electrical conductivity (EC) of each sample were analysed.

The leaching of different elements were then compared with the Finnish, the Dutch and the French emission boundary values set for assessing the utilisation possibility of waste-derived materials in civil engineering structures. The emission boundary values for the Netherlands (Lamers and Kokmeijer, 2013), and France (Michel, 2011) are used in these countries to evaluate the utilisation possibility of, for example, MSWI BA in civil engineering structures. In contrast, the Finnish limit values (Government Decree 591/2006 and modification 403/2009) are set for the utilisation of ashes from wood- and peat-burn facilities. All of these three limit values were used as references since, at the moment, the national legislation in Finland has not set any emission boundary values directly for the utilisation of MSWI BA in civil engineering or other applications, and the utilisation of MSWI BA in the Netherlands and France has been common practice for many years.

Technical analyses. The following technical analyses were performed on the combined samples of both treatment years, 2013 and 2014.

The maximum dry density and the optimum water content (%) of each combined sample were analysed with a modified Proctor-test that was performed corresponding to the SFS-EN 13286-2/AC standard (SFS, 2013). Before and after the modified Proctor-test, the grain size distribution of each combined sample was determined with a standardised SFS-EN 933-1 dry sieving method (SFS, 2012b).

The water content (w%, dry weight) of each combined sample was measured according to the SFS-EN 1097-5 standard (SFS, 2008). The water permeability of each combined sample was acquired with flexible-walled cells using back pressure (ASTM D5084-03). The samples of 12–50 mm mineral fraction could not be analysed, since this method is not suitable for materials with such large grain size.

The capillary rise of water was measured by adapting the standardised test method SFS-EN 1097-10 (SFS, 2014). Each combined sample was first dried in an oven (105 °C). They were then placed in transparent tubes in which a 1 mm mesh prevented the material from flowing out from the tubes. The materials were compacted to approximately a 90% degree of compaction. Then the tubes were placed securely in separate containers in which water was added. This allowed free water capillary rise within the material, which was observed daily. The balance of water capillary rise in each sample was acquired in two weeks. Thereafter, the samples were divided into 50 mm fractions from which water content (w%, dry weight) was measured according to the SFS-EN 1097-5 standard (SFS, 2008). The samples of 12–50 mm mineral fraction could not be analysed, since this method is not suitable for materials with such large grain size.

The frost susceptibility was estimated based on the grain size distribution of the mineral fractions using the Finnish guidelines published by Suomen Rakennusinsinöörien Liitto RIL ry (2013). This coarse evaluation allows materials to be divided into two categories: frost-susceptible and non-frost-susceptible.

The thermal conductivity of combined samples, excluding the 12–50 mm samples owing to their large grain size, was measured with a thermal conductivity probe according to the ASTM (D5334-14) standard.

Results and discussion

Environmental analyses

Table 2 presents the results of the basic characterisation test for the combined samples from the year 2013 and for the subsamples from the year 2014 of each mineral fraction (0–2 mm, 2–5 mm, 5–12 mm, 12–50 mm). The results are shown for different elements as mg kg⁻¹, dry weight.

Table 3 summarises the results of the percolation test for the combined samples from the year 2013 and for the subsamples from the year 2014 of each mineral fraction (0–2 mm, 2–5 mm, 5–12 mm, 12–50 mm). The results are shown as a cumulative liquid to solid ratio 10 (LS⁻¹ 10) and compared with the Finnish, Dutch and French emission boundary values used for assessing the utilisation possibility of either wood- and peat-burn ashes or MSWI BA in civil engineering applications.

In the percolation test (Table 3), the leaching of chrome (Cr) exceeded the emission boundary values of Finland (3.0 mg kg⁻¹ LS⁻¹ 10) and France (2.0 mg kg⁻¹ LS⁻¹ 10) in the combined sample of 0–2 mm fraction analysed from the year 2013 (6.5 mg kg⁻¹ LS⁻¹ 10). The leaching of antimony (Sb) was close to the Finnish limit value (0.18 mg kg⁻¹ LS⁻¹ 10) for the 0–2 mm and 5–12 mm

Table 2. The results of the basic characterisation test for the BA samples from years 2013 and 2014.

Element	Total concentration of elements (mg kg^{-1}, dry weight) in BA mineral fractions							
	0–2 mm		2–5 mm		5–12 mm		12–50 mm	
	2013	2014	2013	2014	2013	2014	2013	2014
Combined sample	x		x		x		x	
Subsamples (n = 4)		x						
Subsamples (n = 2)				x		x		x
Hg	<0.09	NA	<0.09	NA	<0.09	NA	<0.09	NA
Al	4839	NA	5861	NA	6399	NA	15,959	NA
Aσ	<50	<50	<50	<50	<50	<50	<50	<50
Ba	1520	1393	1190	1745	1410	1350	886	1295
Ca	40,300	NA	33,800	NA	37,300	NA	26,100	NA
Cd	15	6	4.07	3	2.85	3	2.77	2.9
Co	59	28	33.3	26	32.1	148	36.3	18
Cr	786	318	589	284	577	330	313	283
Cu	4540	2523	3810	1740	1240	3420	1620	1610
Fe	61,100	NA	75,200	NA	74,100	NA	71,400	NA
K	17,300	NA	14,900	NA	14,500	NA	18,000	NA
Mg	5720	NA	5250	NA	5100	NA	4320	NA
Mn	1960	NA	1990	NA	2000	NA	946	NA
Mo	18.3	14	20.9	14	13.4	15	11.5	15
Ni	521	150	164	108	128	140	139	134
P	8680	NA	6290	NA	4510	NA	2900	NA
Pb	723	600	484	650	813	520	1040	410
Sb	96	48	62.7	37	63.6	40	36.8	36
Se	<5	NA	<5	NA	<5	NA	<5	NA
Sn	266	NA	227	NA	194	NA	139	NA
Zn	3880	4883	4040	3510	2130	3345	1330	4540

BA: bottom ash; NA: not analyzed.

samples analysed from the year 2014 (0.19 mg kg^{-1} LS^{-1} 10 and 0.18 mg kg^{-1} LS^{-1} 10, respectively). The leaching of chloride (Cl^{-}) was above the Finnish limit value (2400 mg kg^{-1} LS^{-1} 10) for the 0–2 mm and 2–5 mm samples analysed from both years (4750–4800 mg kg^{-1} LS^{-1} 10 and 2900–3880 mg kg^{-1} LS^{-1} 10). The acquired leaching values for the rest of the samples and elements were below the emission boundary values of the three different countries also when the measurement uncertainty of the laboratory tests for different elements (ca. ±30%) was taken into account.

Table 4 summarises the results of the standardised two-stage leaching test for the subsamples of each mineral fraction (0–2 mm, 2–5 mm, 5–12 mm, 12–50 mm) from the years 2013 and 2014. The results are shown as cumulative LS^{-1} 10 only for chrome (Cr), antimony (Sb), chloride (Cl^{-}) and Dissolved organic carbon (DOC), since these compounds exceeded in some of the fractions the Finnish emission boundary values (see Table 3) for assessing the utilisation possibility of other types of ashes in civil engineering applications. These exceeding's are highlighted in grey in Table 4. All the other elements analysed were below the emission boundary values shown in the Table 3, even when the measurement uncertainty of the laboratory tests for different elements (ca. ±30%) were taken into account.

It is worth mentioning that the emission boundary values of the Netherlands and France are at least three times higher than the limit values of Finland for some of the elements, such as antimony (Sb) and chloride (Cl^{-}) that were found critical in this study (see Tables 3 and 4). On the other hand, Finland has mainly used the European Union leaching waste acceptance criteria for landfilling of inert waste as a basis for the leaching values given in Table 3, whereas the Netherlands and France have fully or partly used specific scenario-based risk/impact assessments to derive their emission boundary values (Saveyn et al., 2014). Thus, these emission boundary values are not directly comparable with each other, but can be used as reference to illustrate the acceptance of BA leaching in different cases.

The increased leaching of Cl^{-}, Sb and Cr from MSWI BA has been problematic in other countries as well (Astrup, 2007; Cornelis et al., 2006; Van Gerven et al., 2005), which can hinder the utilisation possibilities of the material. Nevertheless, in this study, the leaching of Cr had strong variation within the samples (see Table 4). Therefore, the leaching of Cr cannot be concluded to be common for the MSWI BA used in this research. The highest leaching values of Cr for the two smallest fractions (0–2 mm: 15.0 mg kg^{-1} LS^{-1} and 2–5 mm: 4.80 mg kg^{-1} LS^{-1}) were acquired with the standardised two-stage leaching test in the beginning of the treatment process in the year 2013 (see Table 4). This may be owing to a separate batch of waste burnt in the waste incineration plant during that time. For example, several leather industry

Table 3. The results of the percolation test (mg kg $^{-1}$, dw L S^{-1} 10) for the combined samples from the year 2013 and for the subsamples from the year 2014 for each mineral fraction (0-2 mm, 2-5 mm, 5-12 mm, 12-50 mm) generated from the bottom ash (BA) treatment process.

| Element | BA mineral fractions: Standardized percolation test (mg kg^{-1} dw L S^{-1} 10) | | | | | | | | Emission boundary values (mg kg^{-1} dw L S^{-1} 10) | | |
| | 0 - 2 mm | | 2 - 5 mm | | 5 - 12 mm | | 12 - 50 mm | | Finland[a] | The Netherlands[b] | France[c] |
	2013	2014	2013	2014	2013	2014	2013	2014			
pH*	11,2-12,0	7,8-10,6	10,9-11,7	7,7-10,7	10,9-11,3	7,9-10,7	11,2-11,7	7,7-10	-	-	-
As	0,02	<0,15	0,02	<0,15	0,02	<0,15	0,01	<0,15	1,5	2	0,6
Ba	1,1	0,18	0,9	0,21	1,4	0,27	1,1	0,32	60	100	56
Cd	<0,01	<0,015	<0,01	<0,015	<0,01	<0,015	<0,01	<0,015	0,04	0,06	0,05
Co	<0,01	<0,05	<0,01	<0,05	<0,01	<0,05	<0,01	<0,05	-	2,4	-
Cr	6,5	1,3	1	1	0,27	0,23	0,05	<0,1	3	7	2 (Tot Cr)**
Cu	2,9	1,5	1,5	0,82	0,69	0,45	0,43	0,4	6	10	50
Mo	1,7	1,5	1,1	1,1	0,93	0,7	0,58	0,79	6	15	5,6
Ni	0,04	<0,05	0,04	<0,05	0,02	<0,05	0,03	<0,05	1,2	2,1	0,5
Pb	<0,01	<0,15	<0,01	<0,15	<0,01	<0,15	<0,01	<0,15	1,5	8,3	1,6
Sb	0,14	0,19	0,11	0,17	0,09	0,18	0,04	0,15	0,18	0,7	0,7
Se	0,03	<0,05	0,02	<0,05	0,02	<0,05	0,02	<0,05	0,5	3	-
V	0,25	0,21	0,14	0,15	0,1	0,12	0,11	0,075	3	20	-
Zn	0,19	<0,1	0,15	<0,1	0,22	<0,1	0,24	<0,1	12	14	50
F$^-$	8,4	<5	7,8	<5	<10	<5	<10	<5	50	1500	60
Cl$^-$	4800	4750	2900	3880	1900	1850	1900	1810	2400	8800	10000
SO$_4$$^{2-}$	3300	5600	3000	3880	2100	3080	1100	2900	10000	20000	10000
Hg	<0,0002	<0,005	<0,0002	<0,005	<0,0002	<0,005	<0,0002	<0,005	0,01	0,08	0,01
DOC	220	160	110	140	65	120	75	150	500	-	-

*the range of pH values from seven solution analysed within the percolation test.

**both chromium-6 and chromium-3 should be analyzed (see further explanation EPA, 2013).

[a]The Finnish emission boundary values (CEN/TS/14405) for ashes from wood- and peat-burn facilities utilized in civil engineering structures covered by bitumen coatings (SFS,2004). Exceeding's of these Finnish emission boundary values with the obtained results are highlighted in grey.

[b]The Dutch emission boundary values (NEN 7373) for utilization of MSWI BA in isolated conditions (Lamers & Kokmeijer, 2013).

[c]The French emission boundary values (NF INTO EN 12457-2) for MSWI BA utilization in non-shaped structures covered by bitumen coatings (Michel, 2011).

BA: bottom ash; DOC: dissolved organic carbon; dw: dry weight.

factories are located within the area of the plant and burning their waste, which can contain large amounts of Cr, may cause the amount of Cr to accumulate into the plants residues.

The leaching of DOC can vary considerably in the MSWI BA and it is related to the unburnt organic material (Hjelmar, 1996). Therefore, the exceeded value of DOC in the one sample of 0–2 mm fraction (520 mg kg^{-1} L S^{-1} 10) from the treatment year 2014 (see Table 4) can be related to a batch of poorly burnt material brought to the waste treatment centre for BA treatment. In order to avoid problems with the exceeded DOC leaching in the utilisation of BA, the quality of the BA should be visually controlled at all times, and poorly burnt material should be sent back to the plant for re-incineration.

In this study, the leaching of antimony and Cl$^-$ were considered to be the most problematic elements, as these elements exceeded, in most cases, the Finnish emission boundary values, especially in the case of the two smaller fractions, 0–2 mm and 2–5 mm (Tables 3 and 4). In addition, the variation within the leaching values of these critical elements was greater for the smaller fractions than it was for the two larger ones (i.e. 5–12 mm and 12–50 mm) (see Table 4.). This suggests that compared with the smaller fractions, the larger fractions are more homogeneous regarding the solubility of antimony and Cl$^-$. This, coupled with the lower leaching of hazardous substances in the larger fractions suggests that the fractions >5 mm can be more easily accepted for utilisation in civil engineering based on the current Finnish regulations.

Furthermore, one important issue worth mentioning is the leaching of critical element antimony and the difference in the pH values between the years 2013 (pH 10.9–12) and 2014 (pH 7.7–11.7). It is known that a carbonation process decreases the pH value of initially alkaline material, such as BA, when its alkaline components (e.g. Calcium hydroxide Ca(OH)$_2$) react with atmospheric carbon dioxide CO$_2$ (Meima et al., 2002). The decrease of pH value increases the leaching of some trace elements, such as antimony (Cornelis et al., 2006, 2012). In the year 2013, the whole mass of BA (approximately 30,000 t) was sieved with a drum screen just shortly before the actual treatment, whereas in the year 2014 this treatment was done throughout the whole year in smaller batches after the material was brought to the waste treatment centre. Therefore, one possible explanation for the lower pH values and the higher antimony leaching in the year 2014, compared with the year 2013, can be the accelerated

Table 4. The leaching of chrome (Cr), antimony (Sb), chloride (Cl$^-$) and DOC (average $\bar{x}$, median M, standard deviation σ and range) obtained with the standardised two-stage leaching test (mg kg^{-1}, dry weight L S^{-1} 10) for each BA mineral fraction (0–2 mm, 2–5 mm, 5–12 mm, 12–50 mm).

	pH	EC	$\bar{x}$	M	σ	Range
		(ms m^{-1})	(mg kg^{-1}, dry weight L S^{-1} 10)	(mg kg^{-1}, dry weight L S^{-1} 10)	(mg kg^{-1}, dry weight L S^{-1} 10)	(mg kg^{-1}, dry weight L S^{-1} 10)
Cr						
0–2 mm[a]	11.2–11.6	138–342	3	0.8	5.3	0.71–15.0
2–5 mm[b]	10.8–11.6	82–150	1.6	0.8	1.8	0.35–4.80
5–12 mm[b]	11.1–11.4	73–100	0.7	0.2	1	0.13–2.50
12–50 mm[b]	11.0–11.4	60–96	0.4	0.2	0.5	0.10–0.20
Sb						
0–2 mm[a]	11.2–11.6	138–342	0.24	0.26	0.05	0.18–0.30
2–5 mm[b]	10.8–11.6	82–150	0.37	0.35	0.14	0.24–0.61
5–12 mm[b]	11.1–11.4	73–100	0.21	0.2	0.08	0.12–0.30
12–50 mm[b]	11.0–11.4	60–96	0.23	0.26	0.12	0.11–0.38
Cl$^-$						
0–2 mm[a]	11.2–11.6	138–342	4843	4820	270	4500–5310
2–5 mm[b]	10.8–11.6	82–150	3094	3200	319	2600–3450
5–12 mm[b]	11.1–11.4	73–100	1960	2000	282	1500–2250
12–50 mm[b]	11.0–11.4	60–96	1816	1860	129	1600–1920
DOC						
0–2 mm[a]	11.2–11.6	138–342	240	160	142	140–520
2–5 mm[b]	10.8–11.6	82–150	133	130	41	93–200
5–12 mm[b]	11.1–11.4	73–100	92	82	30	65–140
12–50 mm[b]	11.0–11.4	60–96	80	69	33	44–130

[a]*(n = 7).
[b]**(n = 5).

carbonation owing to earlier pre-screening of the material throughout the whole year. This, however, cannot be ascertained with the available data and thus, it is recommended that pH-static tests, such as CEN/TS 14997, should be included in the list of analysis in further studies.

Finally, for example, Bruder-Hubscher et al. (2001) found that BA in road construction releases the same amount of Cl$^-$ as winter salting. Thus, if utilising even the smallest mineral fractions in the lower structural layers of Finnish roads, the leaching of Cl$^-$ may not cause additional problems, as salting is routinely used for de-icing roads in winter time. Furthermore, when regarding the leaching of antimony, the Finnish emission boundary values are partly derived from the old World Health Organization (1993) drinking-water standard. The newest drinking-water standard (World Health Organization, 2011) has quadrupled the allowed maximum concentration of antimony in drinking water after new information on the antimony toxicity has been obtained. Therefore, the current Finnish emission boundary values should be revised in order to set proper limit values for the assessment of utilisation possibility of waste-derived materials in civil engineering applications. As the results in this study are strictly based on laboratory testing, it is however recommended that large-scale studies should be conducted in order to have more information on the actual leaching of antimony and Cl$^-$ from the MSWI BA. These studies would allow, more specifically, assessment of the potential of these elements to cause risks to humans and the environment in Finnish conditions, and thus provide more information for the policy

makers when setting national legislations that promote the utilisation of waste derived materials in civil engineering.

Technical analyses

Figures 1 and 2 illustrate the grain size distributions of all BA mineral fractions before and after the Modified Proctor-tests compared with the limits of frost-susceptible (Area 1) and non-frost-susceptible (Areas 2, 3 and 4) materials published by Suomen Rakennusinsinöörien Liitto RIL ry (2013). During the Proctor-tests, the particles were crushed to some extent. This was observed in d50, which is the grain size corresponding to the passing value of 50%. The particle crushing in terms of change in d50 was greater for the larger fractions; 5–12 mm = 20–36% and 12–50 mm = 50–63%, than it was for the smaller ones; 0–2 mm = 9–10% and 2–5 mm = 23–28%. Based on the grain size distributions given in Figures 1 and 2, all the BA mineral fractions fall within the class of non-frost-susceptible materials before and after the Proctor test was performed. This suggests that even though the compaction increases the amount of fine-grained particles, especially in the largest BA mineral fractions, this does not have an effect on the frost-susceptibility of these fractions.

Table 5 summarises the maximum dry density (kN m^{-3}), optimum water content (%), hydraulic conductivity (m s^{-1}), water capillary rise (mm) and thermal conductivity λ (W mK^{-1}) for the combined samples of each mineral fraction from the years 2013 and 2014.
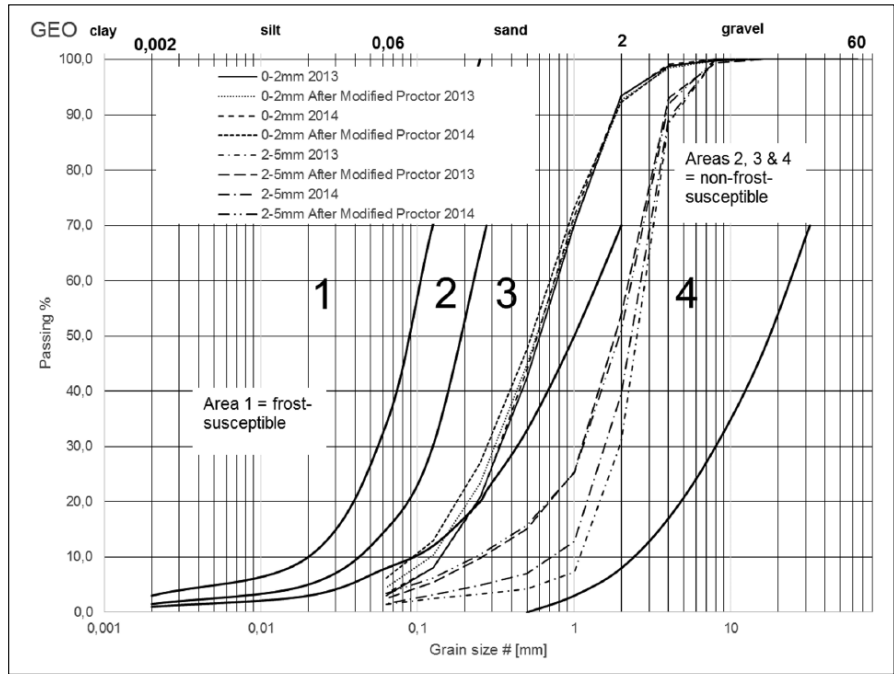
Figure 1. The grain size distributions of the combined samples for the 0–2 mm and 2–5 mm BA mineral fractions from the years 2013 and 2014 before and after the modified Proctor-compaction test compared with the frost susceptibility criteria published by Suomen Rakennusinsinöörien Liitto RIL ry (2013).

Figure 2. The grain size distributions of the combined samples for 5-12 mm and 12-50 mm bottom ash mineral fractions from the years 2013 and 2014 before and after modified Proctor-compaction test compared with the frost susceptibility criteria published by Suomen Rakennusinsinöörien Liitto RIL ry (2013).
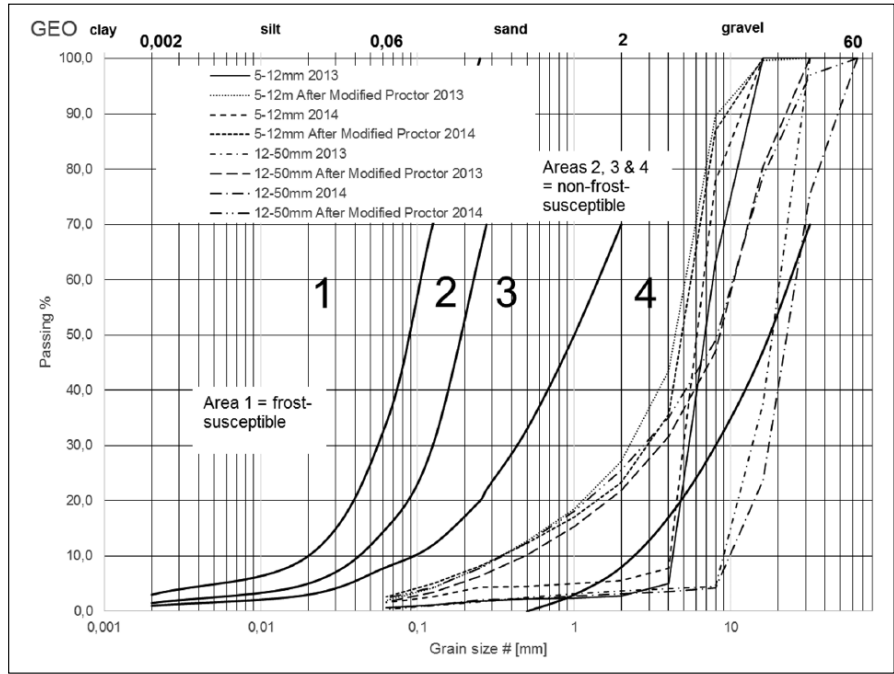
Table 5. A summary of the results from the technical analyses performed for the combined samples for all grain sizes (0–2 mm, 2–5 mm, 5–12 mm and 12–50 mm) of BA mineral fraction from the years 2013 and 2014.

	The BA mineral fractions							
	0–2 mm		2–5 mm		5–12 mm		12–50 mm	
	2013	2014	2013	2014	2013	2014	2013	2014
Maximum dry density (kN m^{-3})	13.58	13.72	15.49	15.12	16.2	16.1	16.14	16.57
Optimum water content (%)	25	28	17.5	18	10	15	9.9	11
Hydraulic conductivity k (m s^{-1})	1.7×10^{-6} –2.8×10^{-6}	2.3×10^{-6} –3.6×10^{-7}	1.3×10^{-5} –1.5×10^{-5}	3.6×10^{-6} –7.8×10^{-7}	1.3×10^{-5} –1.3×10^{-5}	1.4×10^{-5} –9.7×10^{-6}	NA	NA
Capillary rise of water (mm)	43	30	18	30	15	30	NA	NA
Thermal conductivity λ (W mK^{-1}) (T = +10 °C)	0.53	0.8	0.74	0.79	0.3	0.91	NA	NA
(T = −10 °C)	0.97	1.25	1.11	1.12	0.3	0.89	NA	NA

BA: bottom ash; NA: not analysed owing to materials' too large grain size for the particular test method.

The values of maximum dry density (kN m^{-3}) and optimum water content (%) were the same order of magnitude found by other researchers for MSWI BAs (Chandler et al., 1997; Hu et al., 2010; Izquierdo et al., 2001). Compared with the typical Finnish natural aggregates, the maximum dry densities, for example, for sand and gravel, are higher; approximately 21 kN m^{-3} for gravel and 20 kN m^{-3} for sand, whereas the optimum water content is lower for sand (10 %) and gravel (7%) (RTS, 2010), than it was for the BA mineral fractions (Table 5).

The hydraulic conductivities (m s^{-1}) of BA mineral fractions varied from 10^{-7} to 10^{-5} (Table 5). These are comparable with coarse and medium sand that have hydraulic conductivities of 10^{-6} to 10^{-2} and 10^{-6} to 10^{-3}, respectively, and are classified as good drainage materials (Lade, 2001). The water capillary rise of the BA mineral fractions varied from 15 to 43 mm (Table 5). For natural aggregates, such as coarse and fine sand, the capillary heights in compacted materials can be 40–150 mm and 400–3500 mm, respectively (Fagerström and Wiesel, 1972). The thermal conductivities (W mK^{-1}) of BA mineral fractions varied between 0.3–0.91 (T = +10 °C) and 0.3–1.25 (T = −10 °C) (Table 5). This can be compared with unfrozen sand that has thermal conductivities varying between 0.5–3.0 W mK^{-1} depending on its density and moisture content (Andersland and Anderson, 1978). The good drainage, the low capillary heights and the acquired thermal conductivities are all indicators of the favourable behaviour of BA mineral fractions against the frost action. In practice, this means that these properties, coupled with the lower maximum dry densities of BA mineral fractions, can allow the design of thinner and lighter road pavements with this treated BA than with natural aggregates. Regarding the management of road pavement settlements, this is very desirable in the local Finnish conditions, where the road pavements are normally constructed very thick in order to prevent the effects of frost from damaging the road structures. On the other hand, as frost behaviour is affected by many other factors as well (e.g. temperature and water availability), further testing is required in real conditions (e.g. test road) in order to fully understand the frost-behaviour of these BA mineral fractions.

Overall, when evaluating the differences of the technical properties between the four different BA mineral fractions (0– 2 mm, 2–5 mm, 5–12 mm, 12–50 mm), it can be concluded that the materials are to some extent very different (e.g. the grain size distributions, the maximum dry densities and the optimum water contents) and to some extent very similar (e.g. the rise of water capillary heights and the hydraulic and thermal conductivities). Based on their leaching properties, the larger fractions (i.e. >5 mm) may be more easily utilised in civil engineering structures. On the other hand, when the main aim is to reduce landfilling, the focus should be on finding utilisation options for the smaller fractions as well, as these constitute the main products in mass of the ADR process (see 'Sampling' section). With this comprehensive analysis of the technical and environmental properties of these BA mineral fractions, suitable applications for the different fractions with somewhat differing properties can be searched and studied further in the future.

Conclusions

This study comprehensively investigated the environmental and technical properties of the different size fractions of MSWI BA minerals (0–2 mm, 2–5 mm, 5–12 mm and 12–50 mm) generated from the advanced Dutch BA recovery process ADR. All these BA minerals had similarities, for example, in their potential to have favourable behaviour against the frost action, which was considered to be useful in Finnish conditions. From the environmental point of view, the leaching of hazardous substances was not problematic in most of the cases, especially for the larger fractions (>5 mm). The main exceptions can be antimony and Cl$^-$, which exceeded the Finnish emission boundary values for utilisation of other types of ashes in civil engineering structures. This, however, should be further tested in real conditions (e.g. test road) in order to acquire more information on the actual leaching potential of these elements. Overall, this study has shown that the novel BA recovering technique can be one solution to alleviate the utilisation of BA, and furthermore decrease its landfilling in Finland. In addition, the study provides

valuable information on the MSWI BA properties for the policy makers to evaluate more thoroughly whether the utilisation of MSWI BA could be further facilitated through changes in the national legislation.

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II

COMBINING MINERAL FRACTIONS OF RECOVERED MSWI BOTTOM ASH: IMPROVEMENT FOR UTILIZATION IN CIVIL ENGINEERING STRUCTURES

by

Sormunen, L.A., Kalliainen, A., Kolisoja, P. & Rantsi, R., 2016

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ORIGINAL PAPER

Combining Mineral Fractions of Recovered MSWI Bottom Ash: Improvement for Utilization in Civil Engineering Structures

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Abstract In real-life construction projects, the utilization of different types of waste derived aggregates can often be falsely considered as utilization, but in fact, it is merely dumping the potentially high value material from one site to another. For example, building highway noise barriers with waste derived aggregates cannot be considered as utilization. In this study, a more advanced approach was chosen in order to create aggregate like products from recovered municipal solid waste incineration (MSWI) bottom ash (BA) and thus potentially increase their value and image in civil engineering applications. MSWI BA from one waste incineration plant in Finland was first treated with a Dutch dry treatment technology called advanced dry recovery. This process separates non-ferrous and ferrous metals from MSWI BA and generates mineral fractions of different grain sizes. These mineral fractions may not be used separately, for example, in the unbound structural layers of roads due to the strict grain size distribution requirements of these civil engineering structures. Hence, different combinations were designed from these BA mineral fractions using the mathematical proportioning of aggregates. The aim was to create aggregate like products from this waste material for different structural layers (filtration, sub-base and base) of, for example, road and field structures. Three mixtures were chosen based on their correspondence to the grain size distribution requirements of natural aggregates and further analyzed in the laboratory

from their technical, mechanical and environmental point of view. The leaching of chrome (Cr) and chloride (Cl^-) exceeded the Finnish emission boundary values for utilization of certain types of ashes in civil engineering. On the other hand, the technical and mechanical properties of these mixed bottom ash products were considered suitable to be used, for example, in the unbound structural layers of the interim storage field in a waste treatment center. In such location, the leaching potential of harmful substances can be further studied and verified in a larger scale.

Introduction

The number of waste incineration plants has rapidly increased in Finland during the past decade. As a result, different parties from the Finnish waste sector have become interested in the treatment and utilization of the large amounts of municipal solid waste incineration (MSWI) bottom ash (BA). However, the utilization of MSWI BA in Finland is not that common as it is in many other European countries. For example, the utilization percent of MSWI BA in different applications (e.g. road construction and concrete products) can exceed up to 70–90 % in the Netherlands and Denmark [1, 2].

Several different reasons hinder the utilization of MSWI BA in Finland. One of the main reasons is that natural and crushed rock aggregates with good quality and reasonable prices are widely available in the whole country. In addition, the properties (e.g. technical,

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mechanical and leaching properties) of MSWI BA are not well known or tested in local conditions. This leads to the fact that contractors tend to use natural aggregates instead and also the Finnish policy makers hesitate to impose laws that would facilitate the utilization of MSWI BA in different applications. The annual amount of MSWI BA generated in Finland is estimated to be close to 300,000 tonnes in the end of year 2016 [3]. At the moment, most of it ends up in landfill sites, which means that high amounts of taxes should be paid for depositing this waste derived material (Finnish waste tax 70 € tonne^{-1} in the year 2016).

In real-life construction projects, the utilization of different types of waste derived aggregates can often be falsely considered as utilization, but in fact, it is merely dumping the potentially high-value material from one site to another. For example, building highway noise barriers with waste derived aggregates cannot be considered as utilization. In this study, a more advanced approach was chosen in order to create aggregate like products from recovered MSWI BA and thus potentially increase their value and also image in civil engineering applications. The study was part of a larger research project in which the utilization of recovered MSWI BA has been investigated thoroughly by starting from materials basic characterization and continuing into creating actual products from this potentially valuable waste derived aggregate.

The MSWI BA used in this study was first treated with a Dutch dry treatment technology called the advanced dry recovery (ADR) [4, 5]. The process separates non-ferrous and ferrous metals from MSWI BA and generates large amounts of mineral fractions with different grain sizes (75–80 % of treated BA). These mineral fractions may not be used separately, for example, in the unbound structural layers of roads due to the strict grain size distribution requirements of these civil engineering structures [6]. Hence, different combinations were designed from these BA mineral fractions using the mathematical proportioning of aggregates. The aim was to create aggregate like products from this waste derived material for different structural layers (filtration, sub-base and base) of, for example, road and field structures. At this point, three mixtures were chosen based on their correspondence to the grain size distributions of natural aggregates. These mixtures were then analysed in the laboratory in more detail from their technical and mechanical point of view. In addition, the leaching properties were investigated. Especially the study aimed to provide background data for a larger field scale study where these laboratory results have been verified and which results will be reported elsewhere.

Materials and Methods

MSWI BA and Its Treatment

The MSWI BA used in this study originated from a waste incineration plant in Mustasaari, Finland. The plant incinerates approximately 180,000 tonnes of mainly source-separated household waste using grate design for combustion (1000 °C). This yields to approximately 30,000 tonnes of BA in a year.

In the summer 2013, the annual amount of BA was treated in a waste treatment centre in Ilmajoki, Finland. The treatment process lasted for approximately 2 months. The MSWI BA was first screened with a drum screen to remove >50 mm fragments (see Fig. 1 for simplified process flowchart). The remaining fraction (<50 mm) was then fed into a dry treatment process where different sizes of screens, magnetic belts, eddy current separators and a patented ballistic separator ADR [4] recovered ferrous and non-ferrous metals from the BA (Fig. 1). The main residuals of this process were mineral fractions of different grain sizes (0–2, 2–5, 5–12, 12–50 mm), which accounted for 75–80 % of the total mass of treated BA. A more detailed description of the ADR technology can be found in the patent of Berkhout and Rem [4] and in, for example, de Vries and Rem [5].

MSWI BA Sampling

For the technical and mechanical analyses (see "Technical and mechanical analyses" section), the different BA mineral fractions were sampled representatively from the outdoor stockpiles 4 months after the BA treatment. An excavator was used to first remove the hardened surface (100–200 mm) and then to take the samples from different parts and depths of stockpiles. The total amount of each mineral fraction sample taken was approximately 300 kg.

For the leaching tests (see "Leaching tests" section), the samples were collected during the BA treatment at the end of the conveyor belt for each separate fraction. The samples (10 kg) were taken in every fourth day approximately two times a week. All together 12 subsamples were collected from each mineral fraction. The collected subsamples were further divided with the coning and quartering method [7] to smaller representative subsamples into 3 litre buckets. These subsamples were then used to generate composed samples for each mineral fraction size.

The sampling techniques were different for the technical/mechanical and leaching tests due to practical reasons. It is known that sampling technique and material aging can affect the results when different properties of MSWI BA are determined. In this study, the difference in sampling
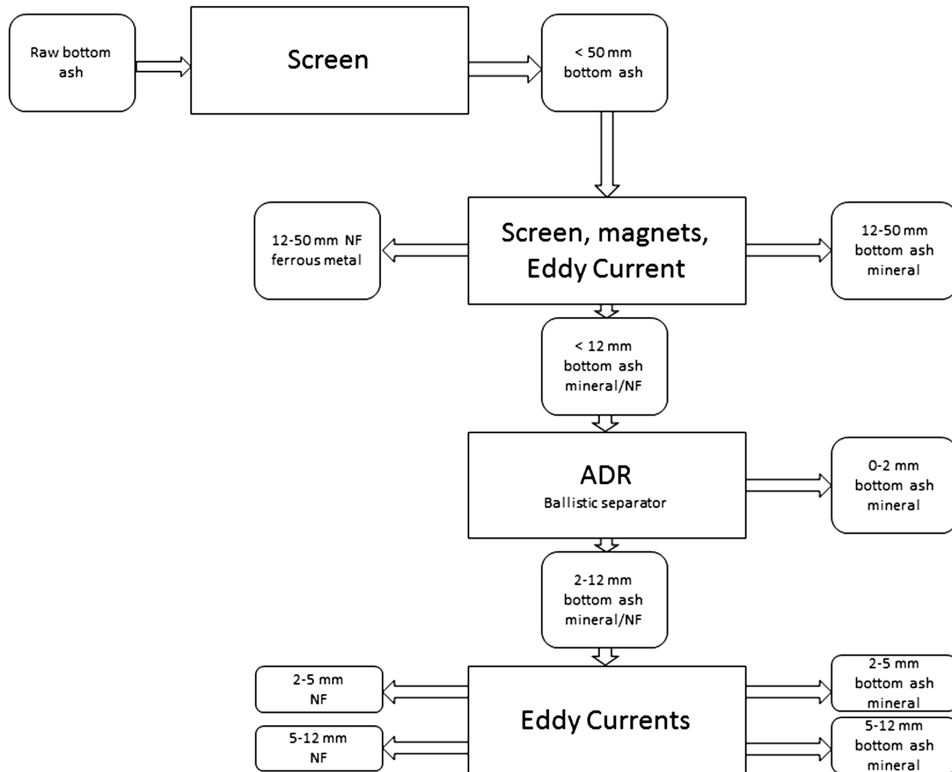
Fig. 1 A simplified flowchart of MSWI BA treatment process used in this study

techniques was not, however, seen relevant since the study aimed to gain information especially on the materials technical and mechanical properties, and not to compare these properties with the leaching test results of recovered MSWI BA. In addition, as intermediate storing is necessary in most real life scenarios, the technical and mechanical properties of recovered MSWI BA obtained in this study depict quite well the properties of MSWI BA that would actually end up for utilization in real-life construction projects.

MSWI BA Proportioning

The grain size distributions of separate MSWI BA mineral fractions (0–2, 2–5, 5–12, 12–50 mm) have been previously analysed by Sormunen and Rantsi [8]. The smallest MSWI BA mineral fraction (0–2 mm) was found to be suitable as filtration layer material when compared with the Finnish grain size distribution requirements for this unbound structural layer [6]. On the other hand, none of the MSWI BA mineral fractions were suitable as such for the unbound sub-base and base layers. Therefore, a

mathematical proportioning of aggregates was used to design aggregate like products from MSWI BA mineral fractions, whose grain size distributions fulfilled the corresponding requirements of these layers [6]. The mathematical proportioning is a simple tool commonly used, for example, in preparing suitable aggregates for asphalt mixtures [9]. The grain size distributions of aggregates of interest are simply combined and tested with different percentages until the wanted outcome, i.e. suitable grain size distribution, is obtained [9]. Several mixtures were tested and after finding the most suitable BA mixtures for sub-base and base layers based on their grain size distributions, the BA samples for each structural layer were prepared from the original BA mineral fractions accordingly for further analysis.

MSWI BA Analyses

The following analysis were performed for the three MSWI BA structural layer materials (filtration, sub-base and base) in order to obtain proper overview of materials technical, mechanical and leaching properties.

Technical and Mechanical Analyses

- The maximum dry densities and the optimum water contents (OWC, %) were analysed with a modified Proctor-test that was performed corresponding to SFS-EN 13286-2 standard [10].
- The grain size distributions were determined with a standardized wet sieving method (SFS-EN 933-1) [11] before and after the modified Proctor-test and after the plate loading test. This was done in order to find out how much MSWI BA particles crushed during the compaction. The amount of particle crushing was observed using the percentages passing sieve sizes <0.063 mm and 2 mm.
- The water contents (wt%, dry weight) were measured according to SFS-EN 1097-5 standard [12].
- The thermal conductivity was analysed with a thermal conductivity probe according to ASTM D5334-14 standard [13]. Thermal conductivity was analysed since it is a key material property when assessing the frost penetration depth in earth construction materials.
- The resistance to fragmentation was analysed with a standardized Los Angeles test (SFS-EN 1097-2) [14].
- The freeze–thaw durability was tested with a standardized freezing-and-thawing-test (SFS-EN 1367-1) [15] where the samples were exposed to 12 freeze–thaw cycles and after that the total loss of weight (%) was measured.
- The static bearing capacities (E1 and E2) were determined in a laboratory according to plate loading test as follows. The three different BA mixtures were first compacted into separate intermediate bulk containers (IBC) (Fig. 2) in approximately 250 mm thick layers. The size of IBC containers was 1200 × 1000 × 1165 mm (1 m^3). The total thickness

Fig. 2 Example of intermediate bulk container used for measuring the bearing capacities (E1 and E2) of different MSWI BA mixtures in the laboratory (© Envitop Oy)

of materials in each container was 700 mm when the plate loading tests were performed. A dial gauge was used to measure the amount of settlement (mm) under a metallic loading plate (d = 300 mm), while increasing the load in increments of 10 kN with a hydraulic jack up to 60 kN (848 kPa). A metal frame (Fig. 2) was used as a counterweight for the static loading. The measurement was done twice in order to calculate the bearing capacities (E1 and E2) for each BA mixture using the Eq. (1):

$$E_i = \frac{1.5 \times p \times a}{S_i} \tag{1}$$

where E_i = the bearing capacity determined in the ith loading cycle (E1 or E2, MPa); p = the maximum applied pressure (kPa); a = the radius of the loading plate (m); S_i = the total settlement of the loading plate in the ith loading cycle (mm).

- The flexible pavement for the interim storage field of the waste treatment centre was designed with the simplified (Odemark) elastic layer theory [e.g. 16]. This theory is commonly used for designing roads, streets and field structures in Finland [e.g. 17]. The calculation is based on the quantities illustrated in Fig. 3.

The bearing capacity on top of the upper layer (E_Y) is calculated based on the bearing capacity on top of the lower layer (E_A), the stiffness modulus (E) and the material thickness (h) of the upper layer. The calculation proceeds from the top of subsoil to the top of asphalt concrete pavement, and the structural layers are combined one by one with the Odemark equivalent Eq. (2):

$$E_Y = \frac{E_A}{\left(1 - \frac{1}{\sqrt{1+0.81\times\left(\frac{h}{a}\right)^2}}\right) \times \frac{E_A}{E} + \frac{1}{\sqrt{1+0.81\times\left(\frac{h}{a}\right)^2 \times \left(\frac{E}{E_A}\right)^{2/3}}}} \tag{2}$$

where E_Y = the bearing capacity on top of the upper layer (MPa); E_A = the bearing capacity on top of the lower layer (MPa); E = the stiffness modulus of the material in the upper layer (MPa); h = the material thickness of the upper
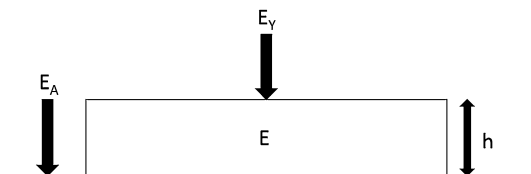

Fig. 3 The parameters used in calculation of bearing capacities according to the simplified (Odermark) elastic layer theory [16]

layer (m); a = the radius of the metallic loading plate used in the static plate load test (0.15 m).

The bearing capacities (E2) obtained from the laboratory scale plate loading tests for each BA mixture were used in the structural design of the interim storage field as the stiffness moduli (E) of the filtration, sub-base and base layers. The aim of the structural design was to obtain bearing capacities of 180 and 250 MPa on top of the base layer and the asphalt concrete pavement, respectively. In the design, the bearing capacity of the subsoil was estimated to be 20 MPa. This estimation was to some extent conservative value, since 20 MPa represents a bearing capacity of soft subsoil or moraine during thawing phase of seasonal frost [17]. It was considered appropriate also for the lightly compacted crushed concrete, glass and brick aggregates that were used below the structural layers as filling material.

Finally, since it was acknowledged that the distribution of stresses and strains under the plate loading test in the laboratory scale experiment could not take place as freely as in an ideal elastic half-space, a numerical simulation was performed on the confining effect of the IBC container walls (Fig. 2) using the Finite Element Method (FEM).

The model developed for the purposes of this study was created with a commercial software, PLAXIS 3D. It is a finite element software that has been developed especially for the analysis of deformation and stability problems in geotechnical engineering projects [18]. PLAXIS 3D software uses 10-node tetrahedral elements for soil layers and 6-node plate elements. The plate elements are based on Mindlin's plate theory [19]. The desired element mesh refinements are defined by the user and the program calculates the target element size based on the outer model geometry dimensions. In addition, the meshing procedure can be affected by defining the relative element size factor, polyline angle tolerance and surface angle tolerance [18]. In this study, the finest mesh at automatic meshing procedure was used; the relative element size was 0.5, the polyline tolerance angle was 30° and the surface angle tolerance was 15°.

A rather simple simulation was performed for the plate loading tests conducted in the laboratory. The loading plate element (diameter 300 mm, thickness 20 mm) had the material properties of steel (E′ = 210 MPa, ν = 0.3). The plate was loaded with evenly distributed pressure at 10 kN loading steps to the maximum load of 60 kN. In addition, an interface element was used between the loading plate and the MSWI BA layer to reduce friction. The MSWI BA layer was modelled as a single layer having different dimensions depending on the modelling conditions. Two different conditions were simulated to study the effect of boundary conditions in the plate loading tests performed in the laboratory:

- the unconfined conditions, when the total size of the model was 10 × 10 × 5 m
- the confined conditions, when the size of the model was similar to the IBC container in the laboratory, 1.2 x 1 x 0.7 m

The MSWI BA material layer was modelled using Hardening Soil (HS)-model. The HS-model is an advanced model for the simulation of soil behaviour [18]. It has been successfully used and verified with field data in other types of civil engineering applications with natural and crushed rock aggregates [e.g. 20, 21]. Limiting states of stresses are described by the means of friction angle (φ'), cohesion (c'), and dilatancy angle (ψ). The material stiffness is described by using three different input stiffness's: the triaxial loading stiffness (E_{50}), the triaxial unloading stiffness (E_{ur}) and the oedometer loading stiffness (E_{oed}). All these stiffnesses relate to a reference stress 100 kPa that was used in this study. The hardening rules can be divided into two main types of hardening: shear and compression hardening. The shear hardening is used to model plastic strains due to primary deviatoric loading. The compression hardening is used to model irreversible strains in oedometric and isotropic loading. Therefore, the stiffnesses of MSWI BA material layers are more appropriate on both sides of the yield surface i.e. when subjected to deviatoric loading the material stiffness decreases simultaneously with the development of irreversible strains [18].

The material parameters for MSWI BA layers in the model were estimated using the results of previous studies [e.g. 20–22]. The parameters were chosen to represent the probable range of material stiffnesses and strengths of natural or crushed rock aggregates having similar grain size distributions as the MSWI BA materials presented in Fig. 4. The model parameters used for the different simulated MSWI BA materials are presented in Table 1.

Leaching Tests

The leaching properties of mixed MSWI BA sub-base and base layer material samples were analysed with a standardized percolation test (CEN/TS/14405) [16]. This test provides information on the short and long term leaching behaviour and the characteristics of waste materials [23]. For different parameters, the percolation test filtrates (seven per each sample) were analysed as follows:

- Mercury with cold vapour atomic fluorescence spectroscopy (CVAFS)
- Other elements (arsenic, barium, cadmium, cobalt, chromium, copper, molybdenum, nickel, lead, antimony, selenium, vanadium and zinc) with inductively coupled plasma mass spectrometer (ICP-MS)

Fig. 4 The grain size distributions of the bottom ash (BA) mixtures for the filtration, sub-base and base layers. The limit values of respective structural layers are given as well [14]
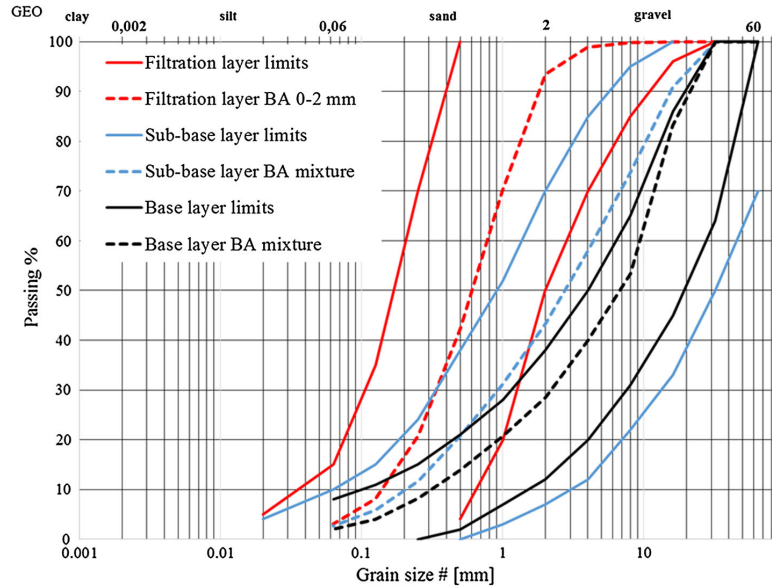

Table 1 The material parameters used in the FEM simulations

Parameter	c' (kPa)	φ' (°)	ψ (°)	E_{50}^{ref} (kPa)	E_{oed}^{ref} (kPa)	E_{ur}^{ref} (kPa)	v_{ur}	m	p^{ref} (kPa)	K_0^{nc}	R_f
Base	10	45	15	250	210	500	0.2	0.5	100	0.300	0.9
Sub-base	10	45	15	150	150	300	0.2	0.5	100	0.330	0.9
Filtration	5	38	8	80	80	160	0.2	0.5	100	0.3843	0.9

c' = effective cohesion, φ' = effective angle of internal friction, ψ = angle of dilatancy, E_{50}^{ref} = secant stiffness in standard drained triaxial test, E_{oed}^{ref} = tangent stiffness for primary oedometer loading, E_{ur}^{ref} = unloading–reloading stiffness, v_{ur} = Poisson's ratio for unloading–reloading, m = power for stress-level dependency of stiffness, p_{ref} = reference stress for stiffnesses, K_0^{nc} = K_0-value for normal consolidation, R_f = failure ratio $q_f q_a^{-1}$

- Chloride, fluoride and sulphate with ion chromatography (IC)
- Dissolved organic carbon with a standardized test method SFS-EN1484 [24] using infrared detector (IR).

The measurement uncertainty of these analyses varied from ±10 to 30 % depending on the element and the sample. In addition, the pH, the electrical conductivity (EC) and the redox potential of each sample were analysed. The leaching test results for filtration layer material (i.e. 100 % <2 mm mineral fraction) were obtained from Sormunen and Rantsi [8].

The leaching of different elements were then compared with the Finnish emission boundary values set for assessing the utilization possibility of waste derived materials in civil engineering structures [25]. The emission boundary values for evaluating the utilization possibility of MSWI BA from other European countries were also used as Ref. [26, 27]. It should be noted that the Finnish emission boundary values are defined for the utilization of fly and bottom ashes from

coal, wood- and peat-burn facilities in structures covered with asphalt pavements. They were used as references since, at the moment, the national legislation in Finland has not set any emission boundary values particularly for the utilization of MSWI BA in civil engineering applications and the MSWI BA in this study was aimed to be used in asphalt concrete covered field structure. On the other hand, it should be mentioned that this national decree on waste utilization is, at the time of writing, under renewal and MSWI BA is considered to be included within the decree by the authorities.

Results and Discussion

Table 2 summarizes the amount (%) of BA mineral fractions (0–2, 2–5, 5–12 and 12–50 mm) in the BA mixtures for the filtration, sub-base and base layers obtained with the mathematical proportioning of aggregates. These amounts

yielded the most proper results for the grain size distributions of respective structural layers if compared with the upper and lower limits of the grain size distributions for the respective structural layers given by RTS [6]. This is further illustrated in Fig. 4 where the analysed grain size distributions of each BA structural layer material are given. The amount of coarsest BA mineral fraction (12–50 mm) was the highest (55 %) in the base layer material, whereas the grain size distribution of 0–2 mm BA mineral fraction was suitable as such for the filtration layer (Table 2; Fig. 4). The amount of different BA mineral fractions varied from 15 to 35 % for the sub-base layer material (Table 2).

Technical and Mechanical Analyses

Table 3 summarizes the bearing capacities (E1 and E2, MPa), the maximum dry densities (kN m^{-3}), the optimum water contents (%), the actual water contents (%), the loss of weights (%) and the thermal conductivities λ (W mK^{-1}) of three BA mixtures for the filtration, sub-base and base layers.

The maximum dry densities of the three BA mixtures (12.5–16.8 kN m^{-3}) (Table 3) were lower than the corresponding values of typical Finnish natural sands (approximately 20 kN m^{-3}) and gravels (approximately 21 kN m^{-3}) [6]. In addition, the thermal conductivities (0.6–1.0 W mK^{-1}) were to some extent lower (Table 3) when compared to the thermal conductivity of, for example, unfrozen sand: 0.5–3.0 W mK^{-1} depending on its density and moisture content [28]. The optimum water contents (OWC) for sub-base (9.8 %) and base (10 %) layer materials (Table 3) were similar to the OWCs of corresponding natural aggregates [6]. The OWCs of MSWI BA materials obtained in this study were, however, lower than the values that have been obtained in the further studies for these particular materials (sub-base 15.0–16.5 % and base 16.5–18.5 %, unpublished). Based on this, the actual OWC values for sub-base and base materials are most likely higher than the values given in Table 3.

The Los Angeles test was noticed unsuitable for these materials due to the amount of particle crushing especially during the modified Proctor test (see Table 4). It should, however, be noted that the values describing the crushing of MSWI BA particles given in Table 4 can only be used for illustrative purposes, since exactly the same sample cannot be used for testing the particle size distribution after each compaction test. This affects the sample representativeness and the obtained passing values (i.e. it is not possible that, for example, the amount of fines (<0.063 mm) is less after the compaction than it was before the test) (Table 4).

The bearing capacities (E2, MPa) of BA mixtures (90–320 MPa) determined in the laboratory were higher (Table 3) than the expected bearing capacities of natural aggregates in the corresponding structural layer in the field; filtration layer 70 MPa, sub-base layer 150 MPa and base layer 200 MPa [29]. This result should, however, be evaluated with caution, since the bearing capacities of BA mixtures were acquired in a confined system, where the distribution of stresses and strains under the plate loading test could not take place as freely as in an ideal elastic half-space. This confining effect was therefore modelled with FEM. The simulation results obtained with the base layer material clearly indicated that in confined conditions the material is stiffened by the boundary effects as the load-settlement curve shows hardening behaviour at higher loads (Fig. 5). In unconfined conditions the soil softens instead and the incremental deflection increases as the load increases (Fig. 5). Similar behaviour was obtained for the sub-base material. For the filtration layer material, softening behaviour was observed both in the confined and unconfined conditions, but a marked reduction in the amount of deflection was observed in the simulation of confined conditions (Fig. 5).

The simulated plate loading test results were also converted as moduli values (E1 and E2) in the same way as was done with the actual laboratory tests. Table 5 summarizes the moduli values E1 and E2 for each MSWI BA material determined based on the laboratory plate loading tests together with those obtained with the FEM simulations. The ratio of moduli values in unconfined and confined model conditions are also given. In general, the simulated moduli values were of the same order of magnitude as those obtained from the laboratory tests (Table 5). On the other hand, the E1 and E2 values were up to 25–35 % higher in the confined simulations than they were in the unconfined simulations (Table 5). Even though these values indicate the maximum confinement effect in the moduli values determined in the laboratory, it is clear that the plate loading tests made in the intermediate bulk containers (Fig. 2) overestimate the actual material stiffnesses at least to some extent.

Table 2 The amount of different bottom ash mineral fractions (%) in the mixtures for the filtration, sub-base and base layers calculated with the mathematical proportioning of aggregates

Layer	Bottom ash mineral fractions (%)			
	0–2 mm	2–5 mm	5–12 mm	12–50 mm
Filtration	100	–	–	–
Sub-base	35	25	25	15
Base	15	15	15	55

Table 3 A summary of technical and mechanical properties of the three bottom ash mixtures intended to be used in the unbound filtration, sub-base and base layers

Analyses	Bottom ash mixtures		
	Filtration layer	Sub-base layer	Base layer
Maximum dry density (kN m^{-3})	12.5	16.0	16.8
Optimum water content (%)	27	9.8	10
Water content (%)	23–27	14–17	12–15
Loss of weight (%)	+1	+1	+1
Thermal conductivity, λ (W mK^{-1})			
(T = +10 °C)	0.6	0.6	0.4
(T = −10 °C)	1.0	0.8	0.6
Bearing capacity (MPa)			
E1	50	130	140
E2	90	270	320

Table 4 The passing (%) in sieve sizes <0.063 mm and 2 mm before and after the modified Proctor test and the plate loading test (PLT) for the bottom ash mixtures intended to be used in the unbound filtration, sub-base and base layers

Layer	Passing (%)	
	<0.063 mm	2 mm
Filtration		
Before tests	3.1	93.4
After proctor	8.2	93.4
After PLT	10.1	93.3
Sub-base		
Before tests	2.7	43.3
After proctor	6.1	55.9
After PLT	1	51.0
Before tests	2	28.5
After proctor	13.3	45.9
After PLT	4.6	54.8

Table 6 provides the structural design for the interim storage field calculated with the simplified Odemark elastic layer theory. In the design, the total thickness of filtration layer was 500 mm and it was divided into two sublayers as recommended by the Odemark elastic layer theory [e.g. 16]. Furthermore, an additional base layer of rock aggregate (#0–32, 300 mm) was used to reduce the intensity of traffic induced dynamic loading on the MSWI BA materials that can be prone to particle crushing as was illustrated in Table 4 and also in previous studies by other researchers [e.g. 30]. With the current design, also the target bearing capacities 180 and 250 MPa on top of the base layer and the pavement, respectively, were well exceeded (Table 6). These calculated bearing capacities should, however, be verified in the field during the construction due to the uncertainties of laboratory plate load tests that were demonstrated with the FE-model (Fig. 5; Table 5).
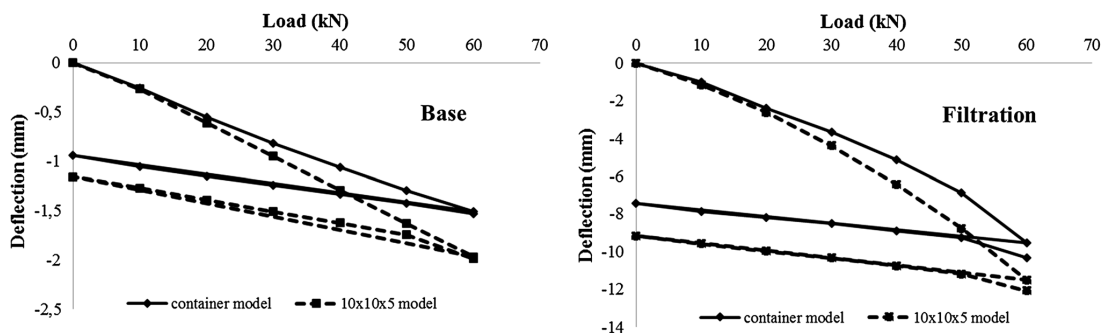

Fig. 5 The simulated load–deflection curves for the base (*left*) and filtration (*right*) layer MSWI BA materials

Table 5 The moduli values (MPa) determined from the laboratory tests and obtained from the FEM simulations

Layer	Laboratory tests		Confined model		Unconfined model		Ratio unconfined/confined	
	E1	E2	E1	E2	E1	E2	E1	E2
Base	140	320	124	340	93	272	1.33	1.25
Sub-base	130	270	81	208	61	167	1.33	1.25
Filtration	50	90	23	88	17	81	1.35	1.09

Table 6 The interim storage field structural design calculated with the simplified Odemark elastic layer theory

Layer Material	Filtration BA 0–2 mm	Filtration BA 0–2 mm	Sub-base BA mixture	Base BA mixture	Base Aggregate #0-32	Pavement ABT
E_A (MPa)	20	42	63	142	230	260
h (mm)	250	250	300	300	300	110
E (MPa)	90	90	270	320	280	2500
E_Y (MPa)	42	63	142	230	260	435

E_A = the bearing capacity (MPa) under the dimensioned layer, E = the E-modulus (MPa) of the material used in the dimensioned layer, E_Y = the bearing capacity (MPa) on top of the dimensioned layer, h = the thickness of the layer (mm)

BA bottom ash, *ABT* asphalt concrete (water tight)

Leaching Tests

The results of percolation tests are compared with the emission boundary values of different countries in Table 7. The Finnish and French emission boundary values for chromium (Cr) was exceeded by the BA (0–2 mm) aimed to be used as filtration layer [8], while the boundary value for chloride (Cl^-) was exceeded by the BA materials intended to be used as filtration and base layers (Table 7). All the other elements were below the emission boundary values of all reference countries also when the measurement uncertainties of analyses (±10–30 %) were taken into account.

The excessive leaching of chromium in filtration layer material (i.e. MSWI BA mineral fraction 0–2 mm) has been discussed by Sormunen and Rantsi [8]. The authors concluded that chromium leaching is not common for the MSWI BA minerals treated with the ADR technology since excessive leaching of chromium was found only in a few samples during the treatment process in the years 2013–2014. On the other hand, the extensive leaching of highly soluble chloride from MSWI BA is a well-known matter and has been demonstrated both in the laboratory and field scale studies [e.g. 3, 8, 31–34].

If the current Finnish decree on utilization of waste derived materials in civil engineering structures is considered, the leaching of hazardous elements from the studied BA structural layer materials is mainly not problematic based on the obtained laboratory results. On the other hand, since these emission boundary values are not yet applicable for the MSWI BA, further studies should be conducted in a larger scale in order to properly evaluate the leaching

behaviour of hazardous substances from these BA materials. One such study has been conducted with the interim storage field designed in this paper and the obtained results will be published in the near future.

Conclusions

In this paper, a novel case study was presented in which MSWI BA mineral fractions were combined using mathematical proportioning of aggregates in order to create aggregate like products from ADR recovered MSWI BA. The study was part of a larger research project in which the utilization of recovered MSWI BA has been investigated thoroughly by starting from materials basic characterization into creating actual products from this potentially valuable waste derived aggregate. The following conclusions can be drawn from this study:

- A simple tool, such as the mathematical proportioning of aggregates can be used for combining MSWI BA mineral fractions to create aggregate like BA mixtures for the unbound structural layers of, for example, road and field structures. Even though this type of approach requires additional mixing of materials that cause some extra material handling costs, it is yet much cheaper than the depositing of MSWI BA minerals in landfill sites with waste taxes as high as 70 €/tonne in Finland (in the year 2016).
- At this stage, the suitability of MSWI BA mixtures was evaluated based on the requirements given for natural aggregates. In future studies, it would be interesting to test other grain size distributions based on, for example,

Table 7 The results of standardized percolation test (mg kg^{-1}, dw L S^{-1} 10) for the different bottom ash materials intended to be used in unbound filtration, sub-base and base layers

| | Bottom ash mixtures Standardized percolation test (mg kg^{-1} dw L S^{-1} 10) | | | Emission boundary values (mg kg^{-1} dw L S^{-1} 10) | | |
	Filtration layer[a]	Sub-base layer	Base layer	Finland[b]	The Netherlands[c]	France[d]
pH[e]	11.2–12.0	9.9–11.3	9.6–11.2	–	–	–
EC (mS/m)[e]	51–1740	31–1651	27–1543	–	–	–
Redox (mV)[e]	261–338	297–362	287–366	–	–	–
As	0.02	0.01	0.01	**1.5**	2	0.6
Ba	1.1	0.33	0.3	**60**	100	56
Cd	<0.01	<0.01	<0.01	**0.04**	0.06	0.05
Co	<0.01	<0.01	<0.01	–	2.4	–
Cr	**6.5**	0.87	1.4	**3**	7	2 (total Cr)[f]
Cu	2.9	0.79	1.2	**6**	10	50
Mo	1.7	0.77	0.94	**6**	15	5.6
Ni	0.04	0.02	0.02	**1.2**	2.1	0.5
Pb	<0.01	<0.01	<0.01	**1.5**	8.3	1.6
Sb	0.14	<0.1	0.14	**0.18**	0.7	0.7
Se	0.03	0.01	0.02	**0.5**	3	–
V	0.25	0.13	0.16	**3**	20	–
Zn	0.19	0.06	0.08	**12**	14	50
F$^-$	8.4	<1.0	<1.0	**50**	1500	60
Cl$^-$	**4800**	2300	**2900**	**2400**	8800	10,000
SO$_4^{2-}$	3300	2600	3000	**10,000**	20,000	10,000
Hg	<0.0002	0.002	0.004	**0.01**	0.08	0.01
DOC	220	84	110	**500**	–	–

EC electrical conductivity, DOC dissolved organic carbon, dw dry weight

[a] Sormunen and Rantsi [22]

[b] Finnish emission boundary values for assessing the utilization potential of fly and bottom ashes from coal, wood and peat burn facilities in civil engineering structures with asphalt pavements [8]

[c] The Dutch emission boundary values for utilization of MSWI BA in isolated conditions [26]

[d] The French emission boundary values for MSWI BA utilization in non-shaped structures covered by bitumen coatings [27]

[e] Given as a range of seven solution obtained in the test unlike the analysis results for harmful substances

[f] Both chromium-6 and chromium-3 should be analyzed

the amount of different BA mineral fractions generated from the treatment process in order to increase their utilization in relation to production. When considering the differences of studied BA mixtures and natural aggregates, it should be borne in mind that the BA mixtures are prone to crushing both during compaction and subsequent heavy traffic loading. It is thus recommended, that an additional aggregate layer or a thicker asphalt pavement should be considered on top of BA base layer in order to meet the durability requirements of road and field structures. Furthermore, it is necessary to emphasize that appropriate compaction equipment and methods should be used for compacting these BA mixtures in order to prevent BA particles from

extensive crushing in the field. During the construction, the bearing capacity requirements obtained for the BA structural layers in this study should also be verified as the FEM-modelling illustrated that the bearing capacities in confined laboratory conditions can be overestimated up to 35 %.

- Finally, from the environmental point of view, the leaching of chromium and chloride exceeded the Finnish emission boundary values given for assessing the utilization possibility of other types of ashes in civil engineering structures. These boundary values are not directly set for the utilization of MSWI BAs, but they were used as reference since other limit values do not exist for this particular material in national legislation.

Nevertheless, as the leaching properties of BA mixtures were obtained in the controlled environment in laboratory, further studies have already been conducted to evaluate the leaching of hazardous substances from the BA mixtures in the field as well. These results will be reported in the near future. In addition, it should be mentioned that the national waste utilization decree [25] is, at the time of writing under renewal and MSWI BA is considered to be added within this decree. This, and the forthcoming studies are providing valuable information for the authorities to evaluate the potential risks related to the utilization of this waste derived aggregate.

Compliance with Ethical Standards

Conflicts of interest Authors Sormunen and Rantsi are employed by Suomen Erityisjäte Oy, which is the responsible leader of the joint research project.

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III

MECHANICAL PROPERTIES OF RECOVERED MUNICIPAL SOLID WASTE INCINERATION BOTTOM ASH: THE INFLUENCE OF AGING AND CHANGES IN MOISTURE CONTENT

by

Sormunen, L.A., & Kolisoja, P. 2016

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Published online: 13 Nov 2016.

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Mechanical properties of recovered municipal solid waste incineration bottom ash: the influence of ageing and changes in moisture content

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The scarcity of non-renewable natural resources and the demand for waste recycling and utilisation steer towards increased use of waste-derived materials in civil engineering structures. However, as the quality of different waste-derived materials can vary depending on input materials and processes in which they are generated, the utilisation of these materials in civil engineering may be risky and cumbersome unless their properties are well known. In Finland, due to the recently increased number of waste incineration plants, nearly 300,000 t of municipal solid waste incineration bottom ash (MSWI BA) is generated annually in the country. As the material is mainly landfilled or used in landfill site structures at the moment, the utilisation of MSWI BA in different civil engineering applications could be increased, if the essential properties of the material were properly understood. In this study, the mechanical properties of recovered MSWI BA were investigated with cyclic load and static triaxial tests. The study focused especially on the influence of changes in moisture content and its relation to the development of recovered MSWI BA stiffness and strength properties over time. The obtained results showed that the stiffness of recovered MSWI BA was highly affected by the changes in moisture content over time but also the material ageing had an influence. The resilient modulus, M_r, was at least doubled during the two months' storage of test specimens. Furthermore, when the MSWI BA material dried out and the moisture content decreased 5–7%, the resilient modulus, M_r, of the material was even quadrupled.

Keywords: recovered municipal solid waste incineration bottom ash; advanced dry recovery; mechanical properties; cyclic; static; triaxial test; ageing; moisture content

1. Introduction

The need for recycling and utilisation of different types of waste materials has gradually increased in Europe (EC, 2016). Especially the use of alternative waste materials as a replacement of natural aggregates in construction is continuously growing, since the unrenewable natural aggregates are usually scarce in locations, where most of construction takes place (Reid et al., 2001). The different types of political and economic drivers, such as the recently published Circular Economy Package of European Commission (EC, 2015) and the increased waste taxes for landfilling in many European countries (e.g. 70 euro/t in Finland in the year 2016 according to the Finnish Waste Tax Act 1126/2010; Finnish Parliament, 2010) already steer towards waste recycling and utilisation instead of landfilling.

In civil engineering, the utilisation of waste-derived materials is particularly interesting and beneficial since large volumes of materials are required in different types of applications (Prezzi,

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Bandini, Carraro, & Monteiro, 2011). However, regardless of their origin, the durability of construction materials is of utmost importance in order to assure that the structures built now will last tens of years ahead. The waste-derived aggregates are generated in many different types of processes using various input materials, which means that these materials can be very heterogeneous and, hence, their durability properties can also vary. Due to this, the properties of waste-derived materials should be investigated thoroughly in order to steer their use into structures that are suitable for their properties. The attractiveness of these materials among the construction companies and constructors could be further increased if their strengths and weaknesses were well known.

In this study, the aim was to investigate the mechanical properties of recovered municipal solid waste incineration bottom ash (MSWI BA). The MSWI BA is produced in large quantities in Europe (Confederation of European Waste-to-Energy Plants, 2011), and in Finland alone, nearly 300,000 t of BA is estimated to be annually generated from the year 2017 onwards (Ministry of Environment, 2008). Even though MSWI BA is commonly used in different types of civil engineering applications in many European countries, such as the Netherlands and Denmark (Astrup, 2007; International Solid Waste Association, 2006), the mechanical properties of MSWI BA are mainly based on empirical studies and still remain inadequately known (Becquart, Bernard, Abriak, & Zentar, 2009).

In the literature, some studies have investigated the mechanical properties of MSWI BA with different types of test procedures. For example, Becquart et al. (2009) used unconfined compression tests and static triaxial tests to determine the stiffness, compressibility and friction angle of treated MSWI BA. Chimenos, Fernandez, Miralles, Rosell, and Navarro Ezquerra (2005) studied the relationship between natural weathering of MSWI BA and its compressive strength with unconfined uniaxial compression tests, and Wiles and Shepherd (1999) compared the differences in strength properties of MSWI BA from two types of incineration plants using a static triaxial test procedure. Furthermore, Weng, Lin, and Ho (2010) studied artificially produced MSWI BA using direct shear tests in order to understand the influence of MSWI BA's chemical composition on its mechanical properties. In Sweden, Arm (2003, 2004) used cyclic load triaxial tests to investigate the effects of locational and seasonal variations in the deformation properties of MSWI BA, and with the same test procedure, Bendz et al. (2006) studied the stiffness of MSWI BA samples cored from an existing test road. Some studies have also focused on the mechanical properties of MSWI BA blended with, for example, limestone and enzymes (Ahmed & Khalid, 2009, 2011) in foundation layers and with fly ash (Muhunthan, Taha, & Said, 2004) as backfill material or lightweight embankment material.

When testing the stiffness properties of granular materials in civil engineering applications, one of the most essential and widely used test methods for various types of unbound aggregates is the cyclic load triaxial test (e.g. Brown, 1978; Sweere, 1990; Thom, 1988). It has also been a standardised test procedure for a long time both in the U.S. (AASHTO, 1992) and in Europe (CEN-EN 13286-7, Suomen Standardisoimisliitto [SFS], 2004a). The cyclic load triaxial test simulates the physical conditions and stress states of granular materials used in unbound pavement layers that are subjected to moving loads (SFS, 2004a). Already in the beginning of 2000s, Reid et al. (2001) concluded that more performance-related tests, such as cyclic load triaxial tests should be conducted on alternative materials used in civil engineering as well. However, the cyclic load triaxial test has only been used in a few studies to investigate the stiffness properties of MSWI BA without any possibly strengthening additives (e.g. Arm, 2003, 2004; Bendz et al., 2006). Due to this, the cyclic load triaxial test was chosen as the primary test method for the current study. In addition, static triaxial tests were used in order to determine the strength and stiffness properties of recovered MSWI BA.

It should be further noted that in this research, the MSWI BA was first recovered with an advanced dry treatment technology called advanced dry recovery (ADR), which has been

developed in the 2000s in the Netherlands (de Vries & Rem, 2013). The changing quality of waste ending up in waste incineration plants due to increased recycling efforts, and also the development of treatment technologies for MSWI BA in order to remove ferrous (F) and non-ferrous (NF) metals from the MSWI BA minerals have been rapid for the past decade. Therefore, the quality of MSWI BA minerals utilised in civil engineering applications today can be very different from what they were, for example, 10 years ago, when some of the before-mentioned studies on mechanical properties of MSWI BA were conducted (e.g. Arm, 2003, 2004; Bendz et al., 2006).

Finally, it is well known that the deformation properties of granular materials can be considerably affected by, for example, moisture content (e.g. Rada & Witczak, 1981; Sweere, 1990; Thom, 1988). This has been later demonstrated also by Kolisoja, Saarenketo, Peltoniemi, and Vuorimies (2002), who studied the suction and deformation properties of crushed rock base course aggregates in situations that simulated varying seasonal conditions. The origin, chemical properties and also porosity of MSWI BA are different from those of natural rock aggregates (Chandler et al., 1997). As a result, the MSWI BA can behave very differently in changing moisture conditions than normal unbound aggregates. Therefore, this study aimed to investigate especially the changes of recovered MSWI BA moisture content over time and its influence on the material's mechanical properties (i.e. stiffness and strength) in controlled laboratory conditions. This matter is important to understand in order to use this material in a proper way and also to steer its use into structures, which are suitable to its mechanical properties.

2. Materials and methods

2.1. *MSWI BA and its recovery*

In this study, the MSWI BA originated from a waste incineration plant located in the western part of Finland. The grate incinerator (1000°C) generates approximately 30,000 t of BA in a year using mainly pre-sorted household waste (180,000 t/year) for combustion. The annual amount of MSWI BA was treated with a Dutch dry treatment technology (ADR) in the year 2015. During this recovery process, F and NF metals were separated from the MSWI BA minerals with screens, magnets, eddy currents and a ballistic separator (i.e. the ADR).

The MSWI BA minerals yield approximately 75–80% of the treated BA coming out from the process in four different size fractions (0–2, 2–5, 5–12, 12–50 mm). They consist mainly of glass, ceramics, sand, etc. These mineral fractions were combined into aggregate products, which, based on their grain size distribution, were suitable to be used in filtration layer (FL), sub-base layer (SBL) and base layer (BL) of, for example, roads and field structures. The quality requirements given by the general quality criteria for infrastructure construction in Finland (Rakennustietosäätiö (RTS) InfraRYL, 2010) were used as reference as described in Sormunen, Kalliainen, Kolisoja, and Rantsi (2016). A more detailed description of the ADR treatment process can be found, for example, in de Vries and Rem (2013) and the typical technical properties, such as the grain size distributions of separate MSWI BA mineral fractions, are given in Sormunen and Rantsi (2015).

2.2. *Laboratory test series*

The mechanical properties (stiffness and strength) of recovered MSWI BA mineral fraction mixtures were studied in the laboratory scale using the cyclic load and static triaxial tests. The cyclic load triaxial test is a widely accepted test method for investigating the stiffness properties of unbound natural aggregates (AASTHO, 1992; SFS, 2004a). The test allows to study the deformation properties of granular materials under various loading paths that simulate traffic
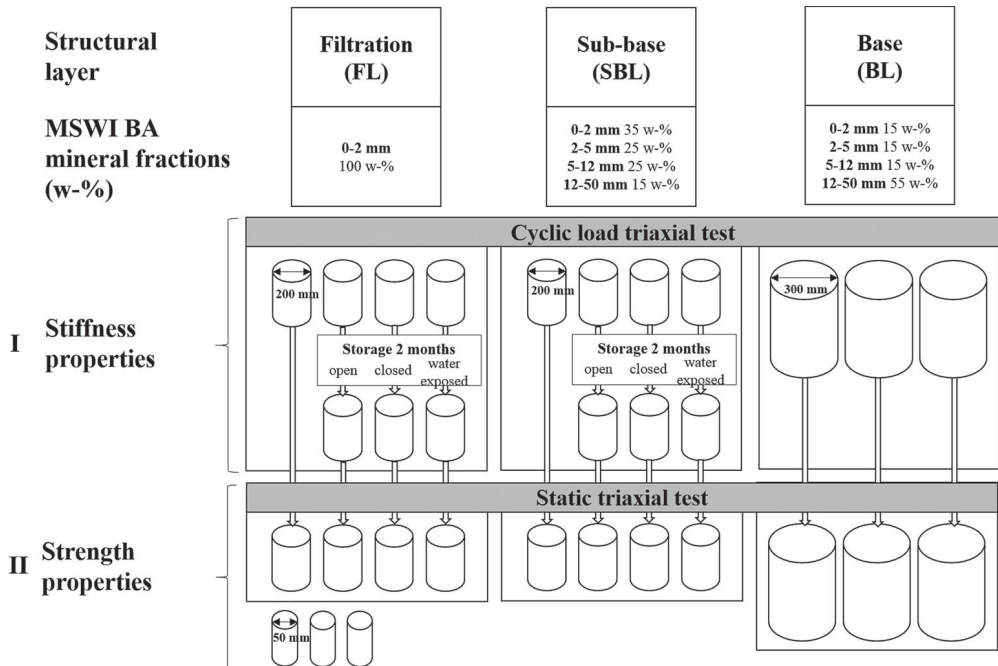
Figure 1.   The structure of laboratory test series (MSWI BA: municipal solid waste incineration bottom ash; w%: weight%).

conditions (Arm, 2004; Becquart et al., 2009), and to further assess whether a granular material can be used in unbound road layers (SFS, 2004a). Figure 1 illustrates the structure of laboratory test procedures performed in this study. A more detailed description of sampling, test specimen preparation and laboratory test series is given in the subsequent chapters.

2.2.1.   *Sampling and test specimen preparation*

For testing the mechanical properties of recovered MSWI BA mixtures in the laboratory, the mineral fractions were first sampled separately from the stock piles using a stratified random sampling method (Gy, 1979). The size of each combined mineral fraction sample was approximately 300 kg.

For each test specimen, the separate MSWI BA mineral fractions were weighed and mixed with a concrete mixer in the laboratory according to the mixing ratios of different structural layer materials (FL, SBL, BL, weight %) given in Figure 1.

A constant compaction effort was used in order to obtain a degree of compaction (DoC) that, according to earlier experiences, corresponded well to a compacted structural layer material in the field (Kolisoja, 1997). The compaction of each test specimen was made with a vibratory compaction device weighing 1 kN. The compaction was made in 50 mm layers for all the other test specimens, except the first test specimen of filtration layer material (FL_1) that was compacted in a 100 mm layer. It was noticed that the compaction in 100 mm layers was not efficient enough to obtain sufficient DoC for MSWI BA test specimens as can be seen from Table 1 (see Section 3.1). Previously analysed maximum dry densities, ρ_{max}, and optimum water contents, OWC%, for each MSWI BA mixture were used as reference (Sormunen & Kolisoja, 2016). It should be noted that the achieved DoCs for recovered MSWI BA were to some extent lower

Table 1. The dry densities (ρd), the water contents (w) and the degrees of compaction (DoC) for each test specimen and the average TOC% in the laboratory test series.

Layer	Test specimen ID	Previously analysed[a]		Before the test			After the storage/test				TOC (%)	Storage condition
		ρ_{max} (kg/m^3)	OWC (%)	ρ_d (kg/m^3)	DoC (%)	w (%)	w upper (%)	w middle (%)	w lower (%)	w average (%)		
FL	FL_1[b]	1.50	27.7	1.19	79.3	27.7	27.0	27.2	28.7	27.7	0.7	−
	FL_2			1.31	87.7	30.7	31.5	30.0	30.7	30.7		Closed
	FL_3			1.29	86.3	30.7	23.7	23.2	23.3	23.4		Open
	FL_4			1.26	84.2	30.7	32.6	34.0	29.2	31.9		Water exposed
SBL	SBL_1	1.75	17.5	1.56	88.9	17.6	16.6	17.4	18.8	17.6	0.6	−
	SBL_2			1.56	88.7	17.5	15.5	15.6	17.2	16.1		Closed
	SBL_3			1.57	89.6	17.5	12.1	12.2	12.3	12.2		Open
	SBL_4			1.56	88.9	17.5	17.7	19.3	16.9	17.9		Water exposed
BL	BL_1	1.83	15.7	1.56	85.1	13.5	14.4	14.6	12.0	13.7	0.5	−
	BL_2			1.58	85.9	14.7	14.7	14.2	13.7	14.2		−
	BL_3[c]			1.68	91.4	14.7	15.3	15.3	14.3	15.0		−

Note: The previously analysed maximum dry densities (ρ_{max}) and OWC for each MSWI BA material are given as well.
ρ_{max}: maximum dry density; OWC: optimum water content; TOC: total organic carbon.
[a]Sormunen and Kolisoja (2016).
[b]Compacted in 100 mm layers unlike other specimens that were compacted in 50 mm layers.
[c]The specimen softened during the compaction and started to gush on top of the compaction plate.

than the typical DoCs for natural aggregates due to particle crushing that takes place during the Proctor compaction method (Sormunen & Kolisoja, 2016). The height of each compacted triaxial test specimen was approximately 400 mm for the FL and SBL materials and 600 mm for the BL material. The diameter was 200 mm for the FL and SBL material specimens and 300 mm for the BL material specimens as was required by the larger maximum grain size of the BL material.

2.2.2. *Cyclic load triaxial test*

In the first part of the study (I, Figure 1), the stiffness properties of each MSWI BA layer material (FL, SBL, BL) were studied under repeated loading with cyclic load triaxial tests according to a standardised test method SFS-EN 13286-7 (SFS, 2004a). The possible changes in stiffness properties due to storage time (i.e. ageing) and the variation of moisture content were studied as well, as described in the following paragraphs.

The low stress level test method B up to the confining pressure level of 70 kPa (i.e. 19 cyclic load series each consisting of 100 load cycles) was followed in the cyclic load triaxial test (SFS, 2004a). This low stress level option was used, since it is known that the MSWI BA minerals are prone to crushing (Bendz et al., 2006; Sormunen et al., 2016), and the current MSWI BA mixtures are most likely to be used either under a thick asphalt concrete surfacing or in lower structural layers where lower stress levels occur. Figure 1 provides the number of test specimens for each MSWI BA material in the cyclic load triaxial tests.

After the first loading phase, three test specimens of FL and SBL materials were stored indoors for two months in different conditions: (1) *open*, in which the specimen was allowed to dry out freely by keeping the top of the test specimen open, (2) *closed*, in which the aim was to keep the moisture content of the test specimen constant by sealing the specimen tightly with a plastic film, and (3) *water exposed*, in which unrestrained water supply was provided to the bottom level of the test specimen. Figure 2 illustrates the state of the test specimens during storage.

After the storage, the cyclic load triaxial tests were performed for all the specimens in the same way as described previously in order to investigate whether the ageing (i.e. storing) and the changes in moisture content had an effect on the resilient deformation properties of MSWI

Figure 2.   Test specimen's storage types (open, closed, water exposed).

BA FL and SBL materials. The cyclic load triaxial test was performed for the BL material only with the three fresh test specimens, since it was not possible to move the 300 mm diameter test specimen out from the triaxial test cell for storage with the available testing arrangement.

2.2.3. *Static triaxial test*

In the second phase of the study (II, Figure 1), the strength properties of the MSWI BA structural layer materials were investigated with the static triaxial tests. The static triaxial test is a commonly used test method for determining the strength properties of different types of granular materials including those intended to be used in infrastructure construction. The chosen study scale was sufficient enough for the given grain size distributions of the tested MSWI BA materials (Sormunen et al., 2016). As illustrated in Figure 1, the static triaxial test was performed for the one fresh and the three stored specimens of both FL and SBL materials. For the BL material, each of three fresh test specimens was tested right after the cyclic load triaxial test.

The static triaxial tests were conducted under constant confining pressure conditions using a multi-stage testing approach, since it is a time-saving method and can be conducted with one single test specimen using incrementally increasing confining pressure (Kolisoja, 2013). This means that specimen testing was started at the lowest confining pressure (20 kPa) and when the specimen started to yield under a constant axial load, the monotonously increasing axial loading was suspended. After the axial load was removed, the confining pressure was increased to a next level (40 kPa) and the application of axial load was repeated. All together four confining pressures were used: 20, 40, 70 and 130 kPa. For the FL material, three additional test specimens with diameter of 50 mm were tested with a conventional consolidated drained triaxial test method (SFS, 2004b). In this test method, three identical test specimens were prepared and then exposed to a monotonously increasing axial load until failure under the different confining pressures (25, 50, 100 kPa) within the test chamber. This was made in order to compare the results of this conventionally performed triaxial test with the results obtained from the multi-stage static triaxial test.

2.2.4. *Grain size distributions, water contents and total organic carbon*

After all the tests were performed, the test specimens were divided into three parts (bottom, middle and top) and the grain size distributions of these sub-divided samples were analysed with a standardised wet sieving method (SFS, 2012). This was done in order to see whether the compaction had an effect on the particle size distributions of test specimens. The water contents (w%) were also determined for these samples according to a standardised test method (SFS, 2008). According to Arm (2004), the organic matter can decrease the resilient modulus of MSWI BA. Therefore, the total organic carbon (TOC) contents (%) were also analysed according to a standardised test method (SFS, 2011) for one combined sample of each BA structural layer material.

2.3. *Modelling of resilient modulus values (M_r)*

The resilient modulus (M_r) is commonly used to represent the recoverable deformation properties of unbound granular materials. The stress-dependent resilient modulus values determined with the cyclic load triaxial tests can be described with different types of non-linear empirical models, such as the classical $K–\theta$ model (Brown & Pell, 1967) or its modifications, such as the so-called universal model that explicitly takes into account the effect of deviator stress (q) as well (Uzan, Witczak, Schullion & Lytton, 1992).

The K–θ model introduced by Brown and Pell (1967) was chosen for the current study, since it explained the obtained results for MSWI BA mixtures as well as the universal model suggested by Uzan et al. (1992). In addition, it enables straightforward comparison of the obtained test results to those abundantly available for normal unbound aggregates. A dimensionally consistent version of Brown and Pell (1967) model was, however, used in this study

$$M_{\mathrm{r}} = K_1 \theta_0 \left(\frac{\theta}{\theta_0} \right)^{K_2}, \tag{1}$$

where M_{r} = resilient modulus, K_1 = material parameter ('modulus value'), K_2 = material parameter ('stress exponent'), θ = the sum of principal stresses (i.e. three times the mean principal stress p), θ_0 = reference stress 100 kPa.

3. Results and discussion

3.1. *Cyclic load triaxial test*

Figure 3 summarises the results of the cyclic load triaxial test for the three recovered MSWI BA materials intended to be used in the FL, the SBL and the BL of, for example, roads and field structures. The values of resilient modulus (M_{r}, MPa) are given as a function of the corresponding sum of principal stresses (kPa). The M_{r} values after the storage are also presented in Figure 3 for the FL and SBL materials. Figure 4 illustrates examples of grain size distributions for the three MSWI BA materials analysed from the divided test specimens in the end of laboratory test series. The grain size distributions are compared with the general quality criteria for infrastructure construction in Finland (RTS, 2010). The dry densities (ρ_{d}) water contents (w) and the degrees of compaction (DoCs) of each specimen before and after the tests are given in Table 1. The maximum dry densities (ρ_{max}) and the OWC% from Sormunen and Kolisoja (2016) and the TOC% for each MSWI BA material analysed in this study are given in Table 1 as well.

The resilient modulus, M_{r}, of fresh MSWI BA specimens at the tested stress levels was the smallest for the FL material (50–150 MPa) and the highest for the BL material (100–400 MPa) (Figure 3). This is a logical phenomenon as the grain size distribution of BL material was clearly coarser than it was for the FL material (see Figure 4). The M_{r} values also increased nearly linearly with the principal stress (Figure 3), which was not fully in accordance with the typical behaviour of natural hard rock aggregates (Kolisoja, 1997). The grain size distributions of each MSWI BA material were within the quality criteria given by RTS (2010), and the compaction mainly had an effect on the larger grains of SBL and BL materials, as can be seen in Figure 4. The average TOC varied from 0.5% to 0.7% for the tested MSWI BA materials (Table 1). This result was expected as currently the amount of organic matter, measured as TOC%, in MSWI BA should be less than 3% (EU, 2010), and most of the modern facilities can reach below 1% TOC. It is thus unlikely that the TOC% in the studied MSWI BA materials had an effect on the obtained resilient modulus values in this research.

Figure 3 indicates further that the M_{r} values obtained with the cyclic load triaxial test increased for the FL and SBL materials when the test specimens were stored for two months indoors in different conditions (*open*, *closed*, *water exposed*). During the storage, the water content of specimens changed especially in cases where it was expected; for the *open* specimens, the moisture content decreased 7.3% and 5.3% for the FL and SBL materials, respectively; for the *water exposed* specimens, the moisture content increased 1.2% and 0.4%; and for the *closed* specimens, the moisture content remained at the same level with the FL material but decreased by 1.4% with the SBL material (Table 1). This result may be due to imperfect encapsulation of the test specimen during the storage period.
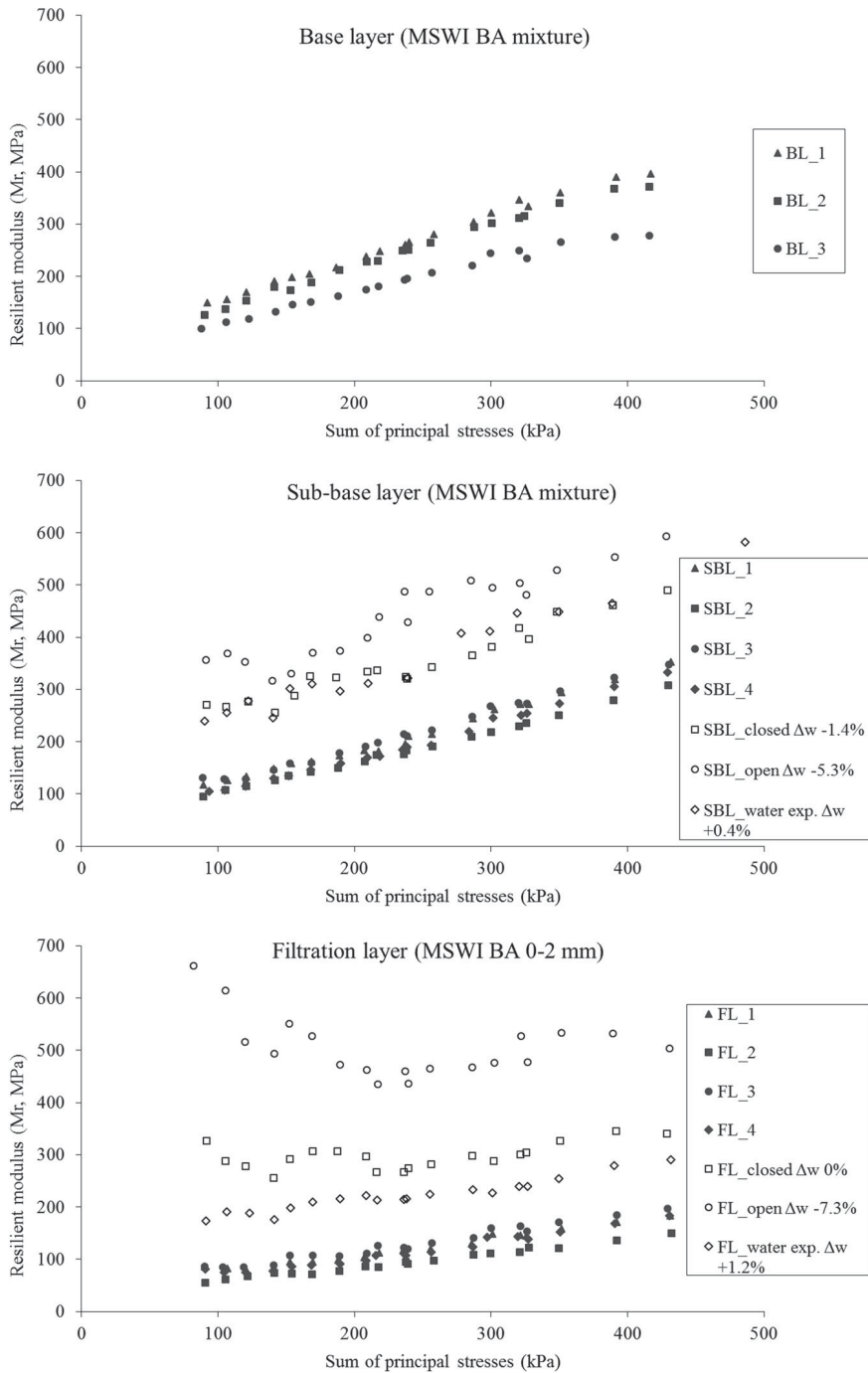
Figure 3.   A summary of the results from the cyclic load triaxial tests for the three recovered MSWI BA structural layer materials (bottom: FL; middle: SBL; up: BL).
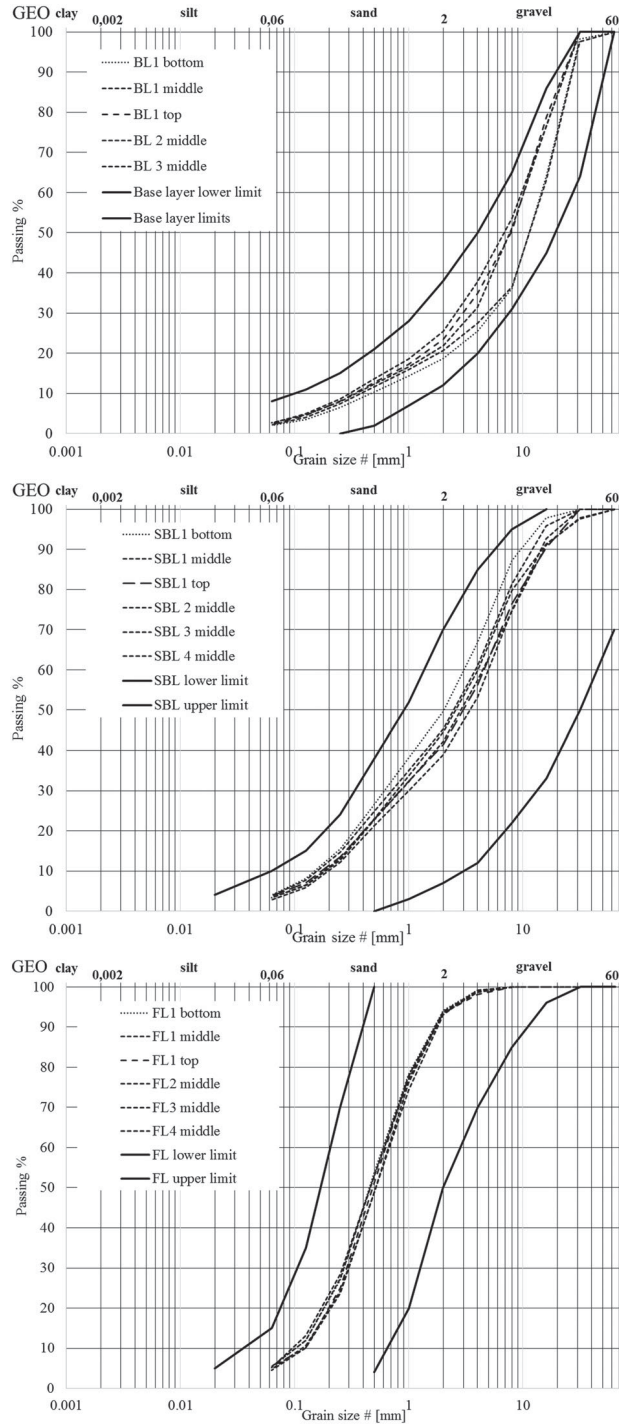
Figure 4.   The examples of grain size distributions of MSWI BA structural layer materials: BL (top), SBL (middle) and FL (bottom). The limit values for respective structural layers given by RTS (2010) are shown as well.

The highest M_r values were obtained for the *open* FL test specimens in the very beginning of the cyclic load triaxial test (Figure 3). Thereafter, the M_r values decreased to some extent before they started to increase again when the sum of principal stresses increased from approximately 200 kPa onwards. It is assumed that this phenomenon is related to the different chemical reactions taking place during the MSWI BA ageing and that can affect the materials' mechanical properties (Reichelt, 1996). These chemical reactions most likely create some type of bondages between MSWI BA particles, but are not permanent and partly break down rather quickly under the applied loading as can be seen in Figure 3. Nevertheless, the obtained results showed that the stiffness of all tested MSWI BA specimens increased over time regardless of their storage condition. The most predominant, up to quadruple, increase in stiffness values was obtained for the test specimens that were allowed to dry out freely and whose moisture content decreased approximately 5–7% (Figure 3). Conversely, as the various chemical reactions due to MSWI BA ageing can also influence the development of materials mechanical properties, this should be further studied with a different type of test set-up in order to understand how much the increase of resilient modulus over time is affected by the changes in moisture content, and what the role of different types of chemical reactions is.

Finally, one observation made during the preparation of test specimens was that the recovered MSWI BA materials were to some extent sensitive to water. For example, the last test specimen of BL material (BL_3) started to soften during the compaction when the water content of the test specimen was not even in its OWC (15.7%) (Table 1). Therefore, the appropriate use of water with MSWI BA during construction is of utmost importance in order to obtain sufficient DoC without, however, softening the material with excessive water.

3.2. *Modelling the values of resilient modulus (M_r)*

Table 2 summarises the K–θ model parameters, K_1 and K_2, and the respective values of resilient modulus, M_r, at the sum of principal stress values 100, 200 and 300 kPa, for the tested MSWI BA materials (FL, SBL, BL).

The M_r values obtained with the fresh MSWI BA test specimens in this study were of the same order of magnitude as those obtained by Arm (2003, 2004), Bendz et al. (2006) and Sweere (1990) for MSWI BA in previous studies. For example, according to Arm (2003) and Bendz et al. (2006), the resilient modulus of MSWI BA varied approximately 110–225 MPa with the sum of principal stresses 90–225 kPa. This implies that using novel technologies, such as ADR, for MSWI BA treatment does not improve the materials' mechanical properties as such, but the advantages of such technologies are more related to, for example, the increased recovery rate of valuable metals. However, the recovered MSWI BA is mechanically suitable especially for the lower structural layers of roads and field structures, as concluded by other researchers as well (e.g. Arm, 2003; Bendz et al., 2006).

When the M_r values obtained for the MSWI BA materials were compared to those of well-compacted normal Finnish unbound natural gravel and crushed rock aggregates used in road structures, the moduli values of the MSWI BA materials were observed to be of the order of 50–60% of those typically determined for unbound aggregates with a similar grain size distribution (Kolisoja, 1994, 1997).

3.3. *Static triaxial test*

Table 3 summarises the strength parameters; friction angle, φ', and cohesion, c', of the recovered MSWI BA materials. In addition, Table 3 presents the stiffness values determined as a secant modulus up to 50% of peak deviator stress (E_{50}). Figure 4 illustrates an example of static triaxial

Table 2.   The K–θ model parameters, K_1 and K_2, and the respective resilient modulus, M_r, at the sum of principal stress values; $\theta = 100$, 200 and 300 kPa, for the tested MSWI BA materials.

Test specimen	K_1	K_2	Resilient modulus, M_r (MPa)		
			$\theta = 100$	$\theta = 200$	$\theta = 300$
FL					
FL_1_fresh	709.3	0.620	70.9	109	140
FL_2_fresh	540.5	0.664	54.0	85.5	112
FL_3_fresh	758.8	0.631	75.8	117	152
FL_4_fresh	635.5	0.688	63.5	102	135
FL_fresh_combined	661.8	0.648	66.1	104	135
FL_2_closed	2801	0.074	280	295	304
FL_3_open	5058	0.000	506	506	506
FL_3_open[a]	3630	0.263	363	436	485
FL_4_water exposed	1724	0.308	172	213	242
SBL					
SBL_1_fresh	1085	0.781	108	186	256
SBL_2_fresh	944.0	0.781	94.4	162	223
SBL_3_fresh	1141	0.751	114	192	260
SBL_4_fresh	930.5	0.854	93.0	168	238
SBL_fresh_combined	1024	0.791	102	177	244
SBL_2_closed	2414	0.446	241	329	394
SBL_3_open	3157	0.407	316	419	494
SBL_3_open[b]	2867	0.496	287	404	494
SBL_4_water exposed	2322	0.512	232	331	407
BL					
BL_1_fresh	1451	0.712	145	238	317
BL_2_fresh	1321	0.741	132	221	298
BL_3_fresh	1061	0.703	106	173	230
BL_fresh_combined	1277	0.720	128	210	282

[a]Cell pressures 50 and 70 kPa only.
[b]Cell pressures 35, 50 and 70 kPa only.

test results of the SBL material in different storage conditions: *fresh*, *open*, *closed* and *water exposed*. The results indicate the development of deviator stress (kPa) as a function of axial strain (%) under the confining pressures of 20, 40, 70 and 130 kPa, respectively.

The friction angles (φ') obtained for MSWI BAs in other studies varied from 30° to 50° depending on the grain size distributions and the DoCs of the tested MSWI BAs (Becquart et al., 2009; Wiles & Shepherd, 1999). Similar friction angle values were obtained for the recovered MSWI BA materials in this study (Table 3). Wiles and Shepherd (1999) obtained cohesion values from 13.8 to 27.6 kPa for the MSWI BA with grain size < 4.75 m. The cohesion values obtained in the current study were clearly higher especially for the stored MSWI BA test specimens as can be seen from Table 3. This difference is most likely related to the ageing effects that have taken place in the tested MSWI BA materials during the storage period.

When comparing the obtained strength parameters with those of well-compacted crushed rock aggregates with medium or good quality (φ': 45–50° and c': 5–25 kPa) (Kolisoja, 2013), the friction angle values for SBL and BL materials were in the same level, but the cohesion values were clearly higher even for the fresh MSWI BA specimens (c': 57.8–65.5 kPa). This difference is most likely related to the chemical properties of MSWI BA that cause stronger cohesive forces between MSWI BA particles and thus higher cohesion values than the ones normally obtained for natural aggregates.

Table 3.   A summary of static triaxial test results for the tested MSWI BA materials.

Test specimen	φ' (°)	c' (kPa)	E_{50} (MPa) at 20 kPa	E_{50} (MPa) at 40 kPa	E_{50} (MPa) at 70 kPa	E_{50} (MPa) at 130 kPa
FL						
FL_1_fresh	34.1	64.5	83.0	98.0	112	139
FL_2_closed	43.6	98.6	126	121	131	162
FL_3_open	41.7[a]	108[a]	315	83.0[a]	114[a]	149[a]
FL_4_water exposed	37.0	81.2	157	147	165	189
50 mm diameter test series	44.6	47.7				
SBL						
SBL_1_fresh	49.6	65.5	194	215	236	290
SBL_2_closed	47.9	144	271	278	263	309
SBL_3_open	52.1	194	197	419	383	446
SBL_4_water exposed	47.5	139	274	258	260	298
BL						
BL_1_fresh	39.5	57.8	184	203	216	287
BL_2_fresh	40.3	56.8	175	174	202	259
BL_3_fresh[b]	35.8	50.1	112	124	142	193
BL_fresh_average	39.8	50.2	157	167	187	246

Notes: φ: friction angle; c: cohesion; E_{50}: secant modulus values determined at 50% of the peak of deviator stress in the different confining pressures (20, 40, 70, 130 kPa).
[a]The values are not comparable due to a sudden axial strain increment of about 2% that took place as a result of equipment malfunction after 20 kPa confining pressure loading cycle.
[b]Test specimen softened during compaction due to excessive amount of water.

The values of secant modulus (E_{50}) of recovered MSWI BA materials were the lowest for the FL material and within the same level with the fresh SBL and BL materials in most of the test specimens (Table 3). This was expected, since normally the stiffness of aggregates increases with increasing grain size (Kolisoja, 1997). On the other hand, the last test specimen of BL material (BL_3) had clearly lower stiffness values (112–193 MPa) than the other two BL test specimens (175–287 MPa) (Table 3). This was most likely related to the water-induced softening of this specimen that was noticed during the test preparation (Table 1).

Figure 5 illustrates the analogous phenomena as noticed for the stored test specimens of FL and SBL materials in the cyclic load triaxial tests. The shear strength of the SBL material increased to some extent regardless of storage type, and the most prominent increase was noticed for the test specimens that were allowed to dry out freely (SBL_open, Figure 5). The same effect can be seen with the FL material from the strength properties given in Table 3.

The results of the multi-stage static triaxial test for the FL material were also compared to those obtained in the series of conventionally drained triaxial tests performed with the test specimens having a diameter of 50 mm and using confining pressures of 25, 50 and 100 kPa (friction angle, $\varphi' = 44.6\%$; cohesion, $c' = 47.7$ kPa; Table 3). In terms of shear strength, it can be calculated that the values obtained from the multi-stage triaxial test were approximately 10–20% lower on the normal stress range of 100–300 kPa. Partly this difference can be attributed to the higher DoC in the 50 mm diameter test specimens (82.4% vs. 79.3%) and partly to the difference in the applied test procedures. In a multi-stage triaxial test the absolute peak value of deviator stress at each confining pressure is not necessarily reached before the load application is interrupted, since it is attempted to limit the total accumulated axial strain of the test specimen during the whole test procedure in the range of 1.0–1.5% (Figure 5). Therefore, somewhat lower values of shear strength can be expected in the multi-stage triaxial test than in the conventional drained triaxial test.
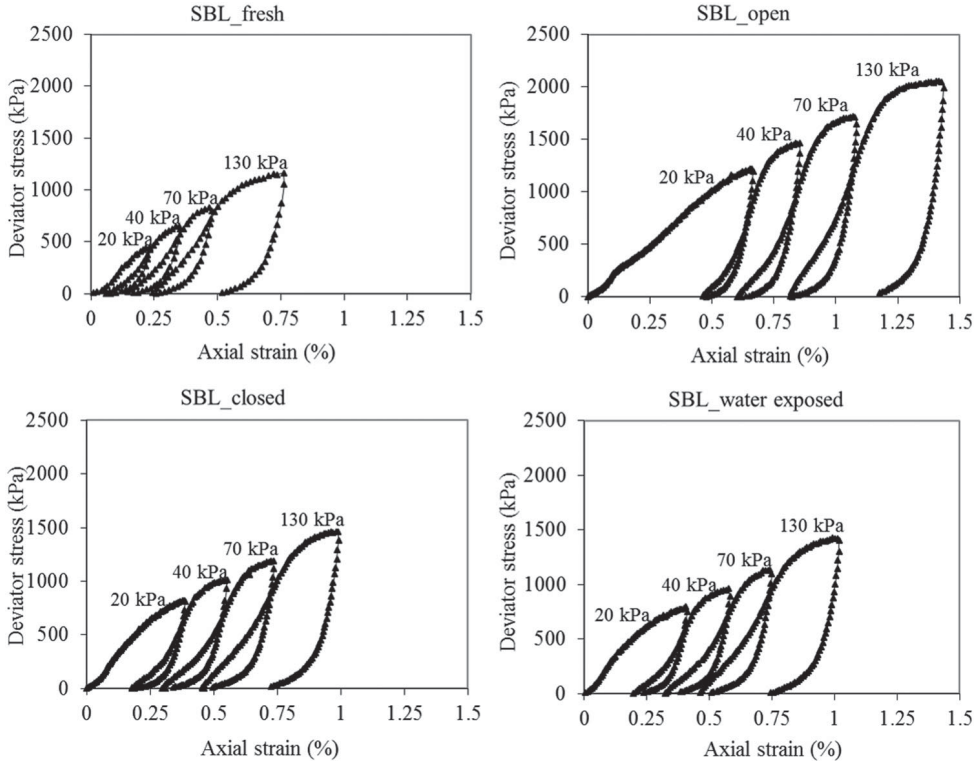
Figure 5.   An example of the results from the static triaxial test with the recovered MSWI BA SBL material (up left: fresh; up right: open; bottom left: closed; bottom right: water exposed test specimen).

3.4.   *Comparison of cyclic load and static triaxial test results*

Figure 6 illustrates a comparison of secant modulus values (E_{25}, E_{50} and E_{75}) determined from the static triaxial tests at 25%, 50% and 75% of the peak deviator stress, respectively, and the resilient modulus (M_r) values of cyclic load triaxial test obtained under different confining pressures during each test. All the modulus values are again given as a function of a sum of principal stresses (kPa). The comparison is shown only for the first fresh test specimen of each tested MSWI BA material (i.e. FL_1, SBL_1 and BL_1), but basically similar behaviour was observed for all the tested specimens.

When comparing the resilient and secant moduli values it is important to note that the deviator stresses to the confining pressure ratios were not consistent. In the cyclic load triaxial test the applied load series corresponded to the ratios of about 1–3 while in the multi-stage static triaxial tests the stress ratios corresponding to the given secant modulus values depended on the confining pressure (see Figure 6). For example, at 20 kPa confining pressure, the stress ratio values varied from approximately 4 (E_{25}) to more than 10 (E_{75}) while at 130 kPa confining pressure the respective range was only approximately 1–3 for the FL material and 2–6 for the SBL and BL materials. Nevertheless, an obvious conclusion from Figure 6 is that the difference between resilient and secant moduli values of tested MSWI BA materials is getting larger when the level of applied stresses increases. Most likely this is related to the crushing of MSWI BA particles that starts to take place under high stress levels. As a result, the deformations in MSWI BA materials develop faster than, for example, in normal unbound aggregates under comparable values of confining pressure and axial load.
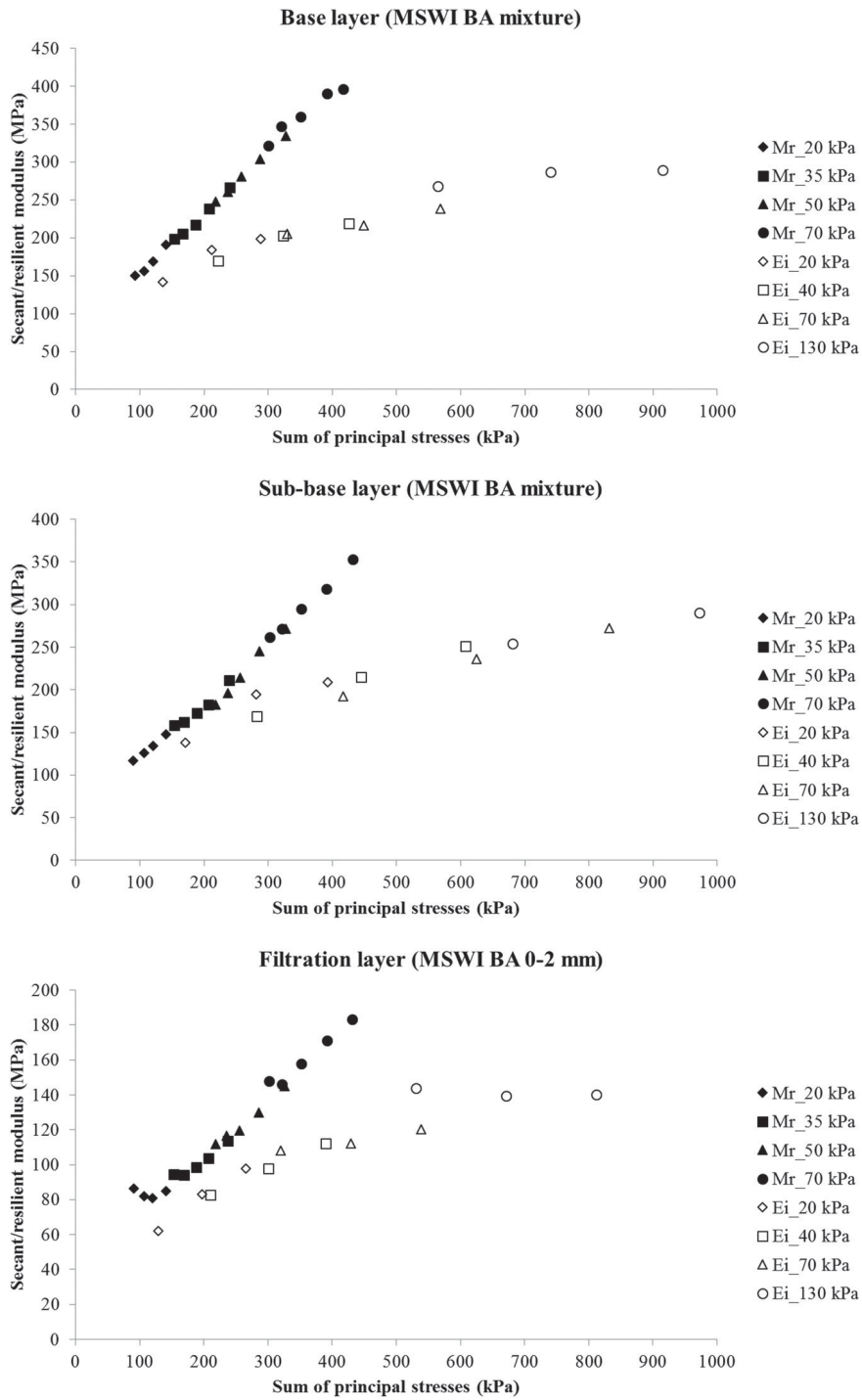
Figure 6. The comparison of secant modulus, Ei, values determined from the static triaxial test and the obtained resilient modulus, Mr, values of cyclic load triaxial test in different confining pressures for the three tested MSWI BA materials.

4.   Conclusions

The aim of this study was to investigate the mechanical properties of MSWI BA recovered with a novel ADR technology. Furthermore, the study focused especially on the influence of changes in moisture content and its relation to the development of recovered MSWI BA stiffness and strength properties over time. Based on the results obtained in this study, the following conclusions can be drawn:

- The stiffness and strength properties of ADR recovered MSWI BA were the same order of magnitude as those obtained in previous studies for MSWI BA more than 10 years ago when, for example, the treatment processes of MSWI BA were different. This implies that the use of novel technologies, such as ADR, does not improve the materials' mechanical properties as such, but the advantages of using such technologies are more related to, for example, the increased recovery rate of valuable metals. However, the recovered MSWI BA is mechanically suitable especially for the lower structural layers of roads and field structures.
- The stiffness and strength properties of recovered MSWI BA improve over time regardless of changes in materials' moisture content (i.e. whether it slightly increases, decreases or remains the same). However, the most prominent increase in shear strength and resilient modulus was found for the stored MSWI BA test specimens that were allowed to dry out freely and in which the respective loss of moisture content was 5–7%. Thus, it can be concluded that moisture content has an effect on the development of mechanical properties of recovered MSWI BA materials. On the other hand, it is possible that the different chemical reactions that take place during the ageing of MSWI BA can affect the materials' mechanical properties as well. Therefore, it should be further studied how much the increase in resilient modulus and shear strength of recovered MSWI BA is affected by the changes in moisture content and what the role of chemical reactions is.
- The recovered MSWI BA minerals were sensitive to water. This was noticed during the compaction of test specimens: the material started to soften under the compaction plate when the water content was too high, and also, if the amount of water was too much below the materials' OWC%, a sufficient DoC was not obtained. Therefore, appropriate use of water in real-life applications is of utmost importance in order to obtain sufficient DoC during construction with this waste-derived aggregate.
- Finally, at high stress levels the stiffness of the recovered MSWI BA material does not increase proportionally with increasing stresses, which differs from the behaviour of unbound natural aggregates. This was most likely related to the crushing of MSWI BA particles that takes place under high stress levels. Therefore, the recovered MSWI BA minerals are not recommended to be used in structural layers (i.e. BL) where high stress levels occur.

Disclosure statement

No potential conflict of interest was reported by the authors.

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IV

CONSTRUCTION OF AN INTERIM STORAGE FIELD USING RECOVERED MUNICIPAL SOLID WASTE INCINERATION BOTTOM ASH: FIELD PER-FORMANCE STUDY

by

Sormunen, L.A., & Kolisoja, P. 2017

Construction of an interim storage field using recovered municipal solid waste incineration bottom ash: Field performance study

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A B S T R A C T

The leaching of hazardous substances from municipal solid waste incineration (MSWI) bottom ash (BA) has been studied in many different scales for several years. Less attention has been given to the mechanical performance of MSWI BA in actual civil engineering structures. The durability of structures built with this waste derived material can have major influence on the functional properties of such structures and also the potential leaching of hazardous substances in the long term. Hence, it is necessary to properly evaluate in which type of structures MSWI BA can be safely used in a similar way as natural and crushed rock aggregates. In the current study, MSWI BA treated with ADR (Advance Dry Recovery) technology was used in the structural layers of an interim storage field built within a waste treatment centre. During and half a year after the construction, the development of technical and mechanical properties of BA materials and the built structures were investigated. The aim was to compare these results with the findings of laboratory studies in which the same material was previously investigated. The field results showed that the mechanical performance of recovered BA corresponds to the performance of natural aggregates in the lower structural layers of field structures. Conversely, the recovered MSWI BA cannot be recommended to be used in the base layers as such, even though its stiffness properties increased over time due to material aging and changes in moisture content. The main reason for this is that BA particles are prone for crushing and therefore inadequate to resist the higher stresses occurring in the upper parts of road and field structures. These results were in accordance with the previous laboratory findings. It can thus be concluded that the recovered MSWI BA is durable to be used as a replacement of natural aggregates especially in the lower structural layers of road and field structures, whereas if used in the base layers, an additional base layer of natural aggregate or a thicker asphalt pavement is recommended.

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1. Introduction

The potential leaching of hazardous substances from municipal solid waste incineration (MSWI) bottom ash (BA) has been studied in different scales by many researchers; varying from smaller scale laboratory studies (e.g. Dijkstra et al., 2006; Ecke and Åberg, 2006; Forteza et al., 2004) into large-scale field studies (e.g. Dabo et al., 2009; De Windt et al., 2011; Hjelmar et al., 2007; Lidelöw and Lagerkvist, 2007). The technical properties of MSWI BA are also well known (e.g. Chandler et al., 1997; Hu et al., 2010; Izquierdo et al., 2002), whereas less data is available on the mechanical performance of actual civil engineering structures constructed with MSWI BA. Some researchers have investigated the stiffness and strength properties of MSWI BA in the laboratory (e.g. Arm, 2004; Becquart et al., 2009; Sweere, 1990; Wiles and Shepherd, 1999), while only a few large scale studies have been conducted on the mechanical performance of MSWI BA in actual field structures (Arm, 2003; Bendz et al., 2006; Hartlén et al., 1999; Reid et al., 2001). In general terms, the durability of structures built with this waste derived material can also have major influence on, for example, the potential leaching of hazardous substances and the functionality of civil engineering structures in the long term. Hence, it is necessary to properly evaluate in which type of structures MSWI BA can be safely used in a similar way as natural and crushed rock aggregates.

This paper describes the construction of an interim storage field within a waste treatment centre, where recovered MSWI BA was used in the different structural layers of the field, and reports the mechanical quality control measurements taken during and half a year after the construction. The MSWI BA used in this study was treated with a Dutch dry treatment technology called ADR (Advanced Dry Recovery). Up to now, no large scale field studies have been published on the mechanical performance of MSWI BA

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recovered with this particular technology. The ADR technology was developed in the Netherlands in the 2000s. It improves the recovery of especially non-ferrous metals from the BA due to removal of fines with a ballistic separator (de Vries and Rem, 2013). Therefore, the quality, and thus the properties of recovered BA can be different from what they were, for example, ten years ago when the latest studies on the mechanical performance of recovered MSWI BA in actual field structures were conducted (Arm, 2003; Bendz et al., 2006; Hartlén et al., 1999; Reid et al., 2001).

The main aim of this study was to evaluate whether the mechanical performance of structures built with this recovered BA corresponds to the performance of natural aggregates, and thus fulfils the target values set for these structures. In addition, the development of mechanical properties over time was investigated in the field scale, since recently conducted laboratory experiments have shown that the mechanical behaviour of recovered MSWI BA is greatly dependent on materials aging and the changes in materials moisture content (Sormunen and Kolisoja, 2016).

2. Materials and methods

2.1. MSWI BA and its recovery

The MSWI BA used in this study originated from a waste incineration plant in Mustasaari, Finland. The plant uses grate design for waste combustion (1000 °C). The input waste material (approximately 180 000 t/year) is source-separated waste from 50 municipalities and over 400 000 inhabitants. Approximately 30 000 t of BA is generated in the plant annually. The BA is quenched with water before transported into a waste treatment centre (Ilmajoki, Finland), where it is treated.

The annual amount of MSWI BA was treated in the year 2013, in order to recover ferrous (F) and non-ferrous (NF) metals from the BA. The treatment was performed with a Dutch dry treatment technology called the ADR. In brief, using dry screens, magnets, wind sifters, eddy current separators and a ballistic separator (i.e. the ADR), the process separates F and NF metals from the BA (Sormunen et al., 2016). The remaining fractions are BA minerals of different grain sizes (0–2 mm, 2–5 mm, 5–12 mm and 12–50 mm). They consist mainly of glass, sand, and ceramics and are the most abundant materials from the process, accounting for approximately 75–80% of the total mass of treated BA (Sormunen and Rantsi, 2015). The principle behind the ADR technology has been described in more detail in the patent of Berkhout and Rem (2009) and, for example, in de Vries and Rem (2013).

2.2. Interim storage field

2.2.1. Preparation of construction materials

The starting point for preparing construction materials from MSWI BA mineral fractions was based on their grain size distributions. The grain size distributions of different BA mineral fractions (0–2, 2–5, 5–12, 12–50 mm) reported by Sormunen and Rantsi (2015) did not, as such, fulfil the strict grain size distribution requirements for the sub-base and base layer materials that are given by the general quality criteria for infrastructure construction in Finland (RTS, 2010). Therefore, a mathematical proportioning of aggregates was used to design construction materials from recovered MSWI BA, whose grain size distributions fulfilled the aforementioned requirements for these two structural layers. A more detailed description of the material design is given in Sormunen et al. (2016). Table 1 summarizes the amounts of different BA mineral fractions (%) used in the BA aggregate mixtures for the sub-base and base layers of the interim storage field (Sormunen et al., 2016). For the filtration layer, a mixture was not necessary

since the grain size distribution of 0–2 mm BA mineral fraction fulfilled the requirements given by RTS (2010) for the materials intended to be used in filtration layers (Sormunen et al., 2016).

The mixing of BA mineral fractions into aggregate mixtures was performed with a drum sieve and the grain size distributions of each BA mixture were analysed as described in Section 2.2.4. In addition, the technical and mechanical properties of these chosen BA mixtures were investigated in the laboratory before designing the interim storage field structure. The results of these analyses can be found in Sormunen et al. (2016).

2.2.2. Structural design of the interim storage field

The structural design of a flexible pavement for the interim storage field was made with the simplified (Odemark) elastic layer theory. It is commonly used theory in the structural design of road, field and street structures in Finland (Tiehallinto, 2004). The principle behind this theory is described in more detail by Ullidtz (1998) and its mathematical Eq. (1) is given as follows:

$$E_Y = \frac{E_A}{\left(1 - \frac{1}{\sqrt{1 + 0.81 \times \left(\frac{h}{a}\right)^2}}\right) \times \frac{E_A}{E} + \frac{1}{\sqrt{1 + 0.81 \times \left(\frac{h}{a}\right)^2 \times \left(\frac{E}{E_A}\right)^{2/3}}}} \qquad (1)$$

where,

E_Y = the bearing capacity on top of the upper layer (MPa).
E_A = the bearing capacity on top of the lower layer (MPa).
E = the E-modulus (stiffness) of the material in the upper layer (MPa).
h = the material thickness of the upper layer (m).
a = the radius of metallic loading plate used in the static plate load test (0.15 m).

The subsoil underneath the field structure varied from solid rock to stiff moraine. Crushed concrete, brick and glass was used as filling material below the actual structural layers. In the field design calculations, an E-modulus value of 20 MPa was used for the subgrade. This somewhat cautious estimate was considered appropriate due to the fragile nature of filling materials and since these materials would not be heavily compacted during the construction. A more detailed description of the field design process can be found in Sormunen et al. (2016). A principal cross-section of the field structure is given in Fig. 1. The bearing capacity requirements (E2) set during the structural design of the field were: 63 MPa for the MSWI BA filtration layer, 142 MPa for the MSWI BA sub-base layer, 230 MPa for the MSWI BA base layer and 260 MPa for the base layer made of crushed rock aggregate (Sormunen et al., 2016).

2.2.3. Construction of the interim storage field

The interim storage field was built between July and October in the year 2014. The size of the field was approximately 10 000 m^{-2}. As mentioned in Section 2.2.2, the BA materials were used in the filtration, sub-base and base layers. The total amount of BA minerals used in construction was approximately 15 400 t (dry weight = dw). An additional base layer of crushed rock aggregate (#0 … 32 mm) was built on top of BA layers, since the BA mineral particles were observed to be prone for crushing (Sormunen et al., 2016). In addition, sub-surface drains and an LDPE-film (thickness 0.5 mm) was placed underneath the BA layers in order to collect and analyse the quality of leachate. The results of leachate quality are not discussed in this paper but will be reported elsewhere.

The BA structural layers were first watered in order to improve the compaction of structural layers. Each structural layer was then

Table 1
The amount of different bottom ash (BA) mineral fractions (%) used in the structural layers (base, sub-base and filtration) of the interim storage field.

Structural layer	The amount of BA mineral fractions (%)			
	0–2 mm	2–5 mm	5–12 mm	12–50 mm
Base	15	15	15	55
Sub-base	35	25	25	15
Filtration	100	–	–	–

First reported in Sormunen et al. (2016).
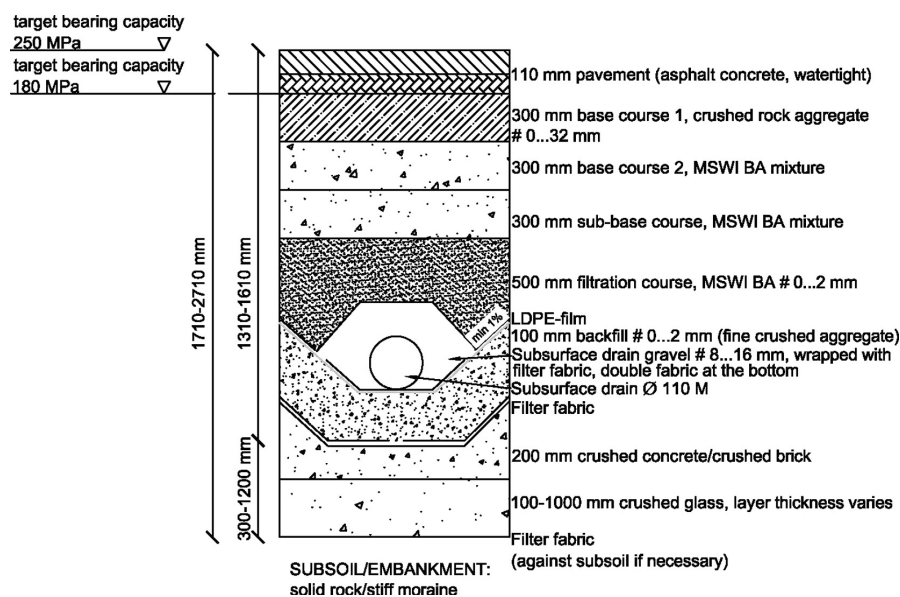
Fig. 1. The cross-section of the interim storage field in which recovered municipal solid waste incineration bottom ash (MSWI BA) was used (© Lakeuden Etappi oy).

compacted using a wheel vibrator roller (Amman AC 110). The number of required roller overruns and the thickness of compaction layers for each BA material was tested with a smaller test field (20 × 20 m) that was constructed within the interim storage field. The degree of compaction (DoC) for each structural layer material in the test field was followed after each overrun with a nuclear density gauge (NDG, Troxler 3440) until the DoCs no longer improved. The operating principle of NDG is explained in more detail in Section 2.2.4. The obtained number of required overruns with the roller were six (6) for the filtration and the sub-base layers and twelve (12) for the base layer. Each layer was compacted with its full layer thickness at once (thicknesses of each layer are given in Fig. 1). The test field was left as part of the field structure after the tests were performed.

2.2.4. Quality control during construction

Table 2 summarizes the test methods used in this study for the quality control during and half a year after the field construction. Further explanation of the test methods are given in the subsequent paragraphs and in Sections 2.2.5 and 2.3.

The grain size distributions of each BA structural layer material (n = 4/material) were analysed with a standardized wet sieving method (SFS, 2012). The maximum dry densities (ρ_{dmax}) and the optimum water contents (OWC) of each BA structural layer material (n = 3/material) were analysed with the modified Proctor compaction test (SFS, 2013).

The density measurements for the BA structural layers were made using the NDG. The gauge measures and reports the water content (%), the wet density (kg m^{-3}) and the dry density (kg m^{-3}) of a material using radioactive radiation and its backscattering. The degree of compaction (%) can then be calculated using Eq. (2).

$$DoC = \frac{\gamma d}{\gamma d_{max}} * 100\%$$
(2)

where,

DoC = Degree of compaction (%).
γd = Measured dry density (kg m^{-3}).
γd_{max} = Maximum dry density (kg m^{-3}).

The NDG was first calibrated according to the instructions given by the supplier. The measurements were made from different depths (100–300 mm) depending on the thickness of each structural layer and the extent of measuring rod of the NDG. The filtration layer was measured up to the depth of 300 mm whereas the sub-base and base layers were measured up to the depth of 200 mm. The number of density measurement points on top of each structural layer is given in Table 3. At each measurement point, the measurement was repeated four times by rotating the equipment 90 deg after each reading and then the average of these readings was used as a final result of each point. Since the NDG most likely does not provide correct water content (%) results with

Table 2
Test methods used for the quality control during and half a year after the construction.

		Property	Test method	Standard (if applicable)
During construction	1	Grain size distribution[a]	Sieving	SFS-EN 933-1 (SFS, 2012)
	2	Moisture content (w-%)	Drying in ventilated oven	SFS-EN 1097-5 (SFS, 2008)
	3	Maximum dry density (ρ_{dmax}), optimum water content (OWC)	Modified Proctor compaction test	SFS-EN 13286-2 (SFS, 2013)
	4	Density	Nuclear density gauge	
	5	Bearing capacity (E1, E2)[b]	Static plate load test	–
After construction	1	Grain size distribution[a]	Sieving	SFS-EN 933-1 (SFS, 2012)
	2	Moisture content (w-%)	Drying in a ventilated oven	SFS-EN 1097-5 (SFS, 2008)
	3	Bearing capacity (E1, E2)	Static plate load test	–

[a] Used for evaluating the preliminary E-modulus values for MSWI BA materials (see Section 2.3.1).
[b] Used also for back-calculating E-Modulus values according to the Odemark elastic layer theory (see Section 2.3.2).

Table 3
Number of measurement points for the static plate load test (SPLT) and the density measurements (DM) in each structural layer of the interim storage field during construction.

Structural layer	Material	Number of measurement points (n)	
		SPLT	DM
Base	Rock agg #0–32 mm	19	–
Base	BA mixture I	21	5
Sub-base	BA mixture II	18	15
Filtration	BA #0–2 mm	20	16

n = 3.

this particular material (Reid et al., 2001), the water contents (dry weight-%) were determined in the laboratory from the material samples taken from each measurement point. These water content results were then used to correct the dry density values given by the equipment in order to calculate correct DoC values with Eq. (2). The obtained NDG results were then compared with the general Finnish target values of corresponding natural aggregates in each structural layer (RTS, 2010).

The bearing capacities (E1 and E2, MPa) were determined with a static plate load test (SPLT) from several locations on top of each structural layer in the interim storage field. The number of measurement points on top of each layer are given in Table 3. A dial gauge was used to measure the amount of settlement (mm) under a metallic loading plate with a diameter of 300 mm, while increasing the load gradually with a hydraulic jack up to 89.3 kN (1260 kPa). An excavator was used as a counterweight for the static loading. The SPLT was done twice at each measurement point in order to calculate the bearing capacities (E1 and E2, MPa) with Eq. (3). In addition, the ratio E2/E1 was calculated to assess the amount of compaction caused by the first loading cycle of the SPLT. The obtained results were then compared to the bearing capacity requirements set for each layer during the field design phase (see Section 2.2.2).

$$E_i = \frac{1.5 * p * a}{S_i} \qquad (3)$$

where,

E_i = the bearing capacity determined in the ith loading cycle (E1 or E2, MPa);
p = the maximum applied pressure (kPa);
a = the radius of the loading plate (m);
S_i = the total settlement of loading plate in the ith loading cycle (mm).

2.2.5. Quality control after the construction
In order to investigate the development of bearing capacity of the interim storage field structure over time, a few additional SPLTs

and density measurements (%) were made half a year after the construction. These SPLTs were performed only on top of the BA base layer ($n = 4$) and the base layer made of crushed rock aggregate ($n = 10$). These layers were chosen as they are the most critical when considering the overall bearing capacity of the interim storage field structure. The bearing capacities E1 and E2 were again calculated using Eq. (3).

In addition, material samples were taken from five measurement points of each BA structural layer to analyse the materials moisture content (w-%) half a year after the construction in the laboratory. The aim was to see whether the materials moisture content had changed over time and whether it corresponded to the development of bearing capacity in a similar way as has been found in the laboratory study with the same material regarding its stiffness and strength properties (Sormunen and Kolisoja, 2016). Furthermore, combined samples of each BA layer material were collected from three measurement points and used for analysing the grain size distributions of the BA structural layer materials using the wet sieving method (SFS, 2012). This was done in order to clarify whether the compaction had caused BA particle crushing in the field as much as it had caused particle crushing during the previously conducted laboratory compaction tests (Sormunen et al., 2016).

2.3. E-modulus values of recovered MSWI BA materials

2.3.1. Preliminary E-modulus values based on the BA materials grain size distribution
According to general civil engineering practices in Finland, the stiffness modulus values (i.e. E-Modulus) of natural and crushed rock aggregates intended to be used in the different structural layers of roads and field structures are evaluated based on the materials grain size distributions (Tiehallinto, 2005). The same approach was taken for the MSWI BA materials used in this study. The preliminary E-Modulus values corresponding to the respective natural aggregates (Tiehallinto, 2005) were determined for each BA structural layer material based on their analysed grain size distributions. These E-Modulus values were chosen based on the weakest E-Modulus class in which the grain size distribution falls as guided by Tiehallinto (2005). The aim was to compare how these preliminary evaluated E-Modulus values of BA materials corresponded to the actual E-Modulus values derived from the bearing capacity measurements in the field (see Section 2.3.2).

2.3.2. E-modulus values of BA materials based on back-calculation
The Odemark elastic layer theory (Ullidtz, 1998) and Eq. (1) can also be used to back-calculate the E-modulus values (MPa) of structural layer materials if the bearing capacity (E2) on top of each structural layer has been measured with the SPLT. This approach was taken in this study to calculate the E-modulus values of BA materials from the field data and to compare these E-modulus val-

ues with those estimated based on the materials grain size distributions and thus their correspondence to natural aggregates as well (see Section 2.3.1). The back-calculated E-modulus values were also compared with the stiffness values obtained for the same material in the laboratory (e.g. Sormunen et al., 2016; Sormunen and Kolisoja, 2016) and the stiffness values obtained for conventionally recovered MSWI BA by Arm (2004).

In the first step of the back-calculation process, the E-modulus value of BA filtration layer material was iterated until the measured bearing capacities on top of the filtration layer and those given by Eq. (1) corresponded with each other. Thereafter, the same iteration procedure was repeated layer by layer for all the structural layers of the interim storage field structure. This calculation was made for all those measurement points in which the SPLT was conducted on top of each structural layer in the field (Table 3). When using this type of back-calculation approach it is important to bear in mind that the use of Odemark elastic layer theory always comprises many assumptions, such as the bearing capacity of the subsoil (see Section 2.2.2). Therefore, it can only be used as a coarse evaluation of E-Modulus values for the BA materials used in this study.

3. Results and discussion

3.1. Properties of MSWI BA materials

Table 4 presents the maximum dry densities ($kN\,m^{-3}$) and the optimum water contents (%) for the BA materials used in the filtration, sub-base and base layers of the interim storage field.

The maximum dry densities (Table 4) were lower than they typically are for Finnish natural aggregates (gravel: $21\,kN\,m^{-3}$ and sand: $20\,kN\,m^{-3}$) (RTS, 2010), whereas the optimum water contents (Table 4) were higher for the BA materials than they typically are for sand (10%) and gravel (7%) (RTS, 2010). The obtained maximum dry density values were of the same order of magnitude as those obtained in the previously conducted laboratory experiments for these materials (Table 4). Conversely, the optimum water contents (%) were higher especially for the sub-base and base layer materials than what was obtained in the laboratory in a previous study of Sormunen et al. (2016) (Table 4). The cause for this difference was not clear (perhaps a test error) but it was suspected that the OWC values given in Sormunen et al. (2016) do not represent the actual OWCs of these materials and should therefore be neglected.

3.2. Quality control

3.2.1. Density measurements

Fig. 2 summarizes the results of the density measurements during the construction for each BA structural layer.

The density measurement results were quite scattered (Fig. 2). This implies that the density results obtained with the NDG should be assessed with caution when considering whether the BA materials fulfil the general density requirements given for each structural layer (RTS, 2010). However, it can be observed from the E2/
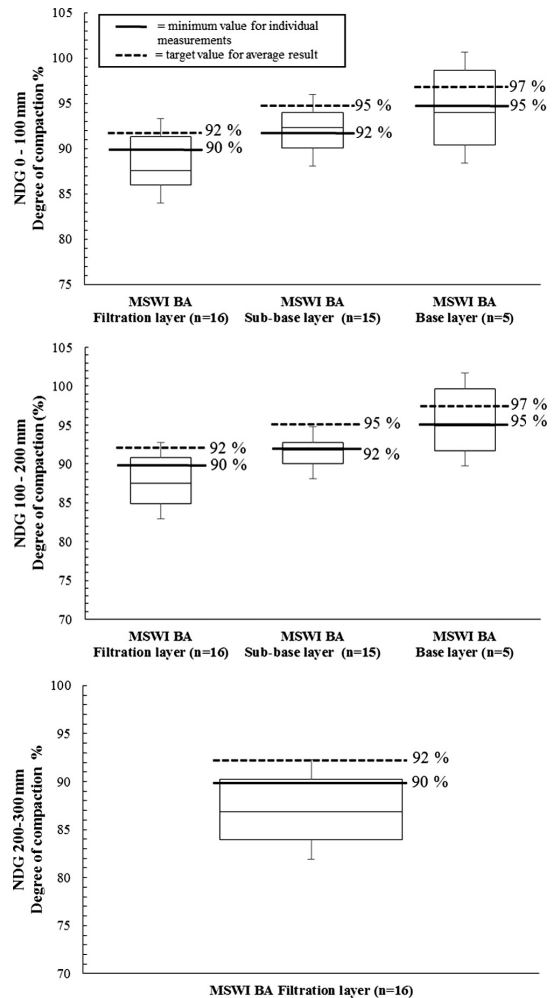

Fig. 2. The degrees of compaction (%) determined based on the nuclear density gauge (NDG) measurements from different depths during the construction on top of each municipal solid waste incineration bottom ash (MSWI BA) structural layer of the interim storage field.

E1 ratio (see Fig. 4 in Section 3.2.2) that the MSWI BA structural layers of the interim storage field were properly compacted, even though the target values set for the DoC were not fully achieved based on the density measurements performed in-situ (Fig. 2). It is also important to bear in mind that these target values are set for natural aggregates, and they are based on materials maximum dry densities determined using the Proctor compaction method. The MSWI BA particles are prone to crushing especially in Proctor

Table 4
The results of the modified Proctor compaction tests for the BA materials used in the base, sub-base and filtration layers of the interim storage field.

Structural layer	Maximum dry density ($kN\,m^{-3}$)			Optimum water content (%)		
	Average	Range	Previously analysed[a]	Average	Range	Previously analysed[a]
Base	18.0	17.8–18.2	16.8	15.7	15.0–16.5	10.0
Sub-base	17.2	17.0–17.4	16.0	17.5	16.5–18.5	9.80
Filtration	14.7	14.4–15.2	12.5	27.7	26.5–28.5	27.0

[a] Sormunen et al. (2016).

compaction tests where heavy compaction effort is used (Izquierdo et al., 2011; Sormunen et al., 2016). This means that the target values of DoCs set for natural and crushed rock aggregates may not be suitable for this waste derived material, since it behaves differently in the Proctor compaction test than natural aggregates. At the moment, no other target values exist for DoC in Finland. Therefore further studies should be conducted in order to determine more suitable target values of DoC for the recovered MSWI BA in case in-situ density measurement techniques are used.

When assessing the overall usability of NDG for measuring the field density of MSWI BA, it is important to bear in mind that the NDG equipment did not directly give correct water content (%) results with the recovered MSWI BA in the field. This has also been pointed out by Reid et al. (2001), who recommended that NDG should not be used for the determination of in-situ density of MSWI BA. In the current study, this problem was solved by analysing separately the water content (%) of BA materials in the laboratory (see Section 2.2.4). The difference in water content (%) given by the NDG equipment and the laboratory analysis for the BA material samples was on average 8% (Table 5). This verifies that it is necessary to analyse the water content (%) of MSWI BA from material samples of each measurement point in the laboratory in case the NDG is used to measure the in-situ density of MSWI BAs. This however causes additional costs and most likely time-delay, which in turn hinders the use of NDG in real-life construction projects.

3.2.2. Bearing capacity measurements

Figs. 3 and 4 summarize the measured bearing capacities E2 (MPa) and the ratios of E2/E1 for each structural layer during (white boxes) and half a year after the construction (grey boxes). The target values set for each layer in the design phase (see Section 2.2.2) and the national target value for unbound base layers of main roads (Tiehallinto, 2005) are given as well. The latter was shown in order to illustrate the level of general requirements for natural aggregates used for road construction in Finland. When interpreting Figs. 3 and 4, it should be taken into account that while the measured E2 in Fig. 3 should exceed the corresponding target value, the ratio E2/E1 in Fig. 4 should be below the given maximum value.

Based on the SPLT measurements conducted during the construction, the measured bearing capacities (E2) of the BA filtration layer were on the same level as the target bearing capacity (E2) defined during the field structural design (Fig. 3). However, this was not the case for the BA sub-base, the BA base nor the crushed rock aggregate base layers (Fig. 3). The ratios of E2/E1 were, however, below the given maximum values in all the layers (Fig. 4). This indicated that the additional compaction caused by the first loading cycle of SPLT measurements was not substantial and the materials can be considered properly compacted during construction. The reason, why the target values were not reached, is because they were initially set too high. This was demonstrated by Sormunen et al. (2016). They used confined laboratory scale test setup, which markedly overestimated the E-modulus values of

MSWI BA materials that were further used in the interim storage field design. This in turn resulted in such high target bearing capacities that could hardly be reached with these materials in the field, as was the case in this field performance study.

Despite of these low bearing capacity values during the construction, it was interesting to find out that the bearing capacities (E2) measured on the top of both base layers had increased half a year after the construction (Fig. 3). These E2 values already exceeded the general target value set for the unbound base layers in main roads in Finland (160 MPa) (Fig. 3). This observed development on bearing capacity over time was not in accordance, for example, with Arm (2003), who found only slow stiffness increase for a bottom ash layer in a 12-year-old structure but not in a one-year-old test section. The reason for this difference could be due to changes in the MSWI BA quality as the incineration technologies, the quality of incinerated waste and also the BA treatment processes have altered during the past ten years.

Recently, Sormunen and Kolisoja (2016) studied the stiffness properties of the same recovered MSWI BA materials in laboratory conditions using cyclic load and static triaxial tests. The authors demonstrated that the materials stiffness and strength properties increased over time due to material aging and changes in moisture content (Sormunen and Kolisoja, 2016). The most prominent increase in stiffness and strength properties was obtained for the test specimens whose moisture content decreased 5–7%. In this study, the moisture content decreased approximately 5% in the MSWI BA base layer half a year after the construction (Fig. 5), whereas the bearing capacity measured on top of that layer increased almost up to 30% during the same time period (Fig. 3).

This result supports the conclusions of Sormunen and Kolisoja (2016): when the recovered MSWI BA dries out, the material stiffness increases over time. It should, however, be borne in mind that this stiffness increase is not related to merely the changes in moisture content but also the material aging in constant moisture content (Sormunen and Kolisoja, 2016). As discussed by Reichelt (1996), during the MSWI BA aging different chemical reactions can affect the materials mechanical properties. In later studies, it would be interesting to study this phenomena further in order to understand the actual reactions that cause the increase in stiffness properties of recovered MSWI BA.

3.3. E-modulus values of recovered MSWI BA materials

3.3.1. Preliminary E-modulus values based on the BA materials grain size distribution

Fig. 6 illustrates the grain size distributions of each BA material during and half a year after the construction. These grain size distributions were used to estimate the preliminary E-modulus values based on the materials grain size distributions as described in Section 2.3.1. According to the obtained grain size distributions, the corresponding E-Modulus design values for BA materials were 70 MPa for the filtration layer material, 100 MPa (or very close to 150 MPa) for the sub-base layer materials and 200 MPa for the base layer material.

Table 5
The water contents (%) for each BA material in the nuclear density gauge (NDG) measurements and the laboratory analysis from the material samples.

Structural layer	Water content (%)			
	NDG		Laboratory[a]	
	Average	Range	Average	Range
Base ($n = 5$)	6.6	5.8–7.5	14.7	6.9–16.4
Sub-base ($n = 15$)	9.9	6.7–19.8	17.5	14.4–19.6
Filtration ($n = 16$)	20.0	14.5–24.8	28.5	23.6–32.5

[a] These were more comparable to the laboratory OWC values determined in this study (see Table 4) than the ones obtained with the NDG.
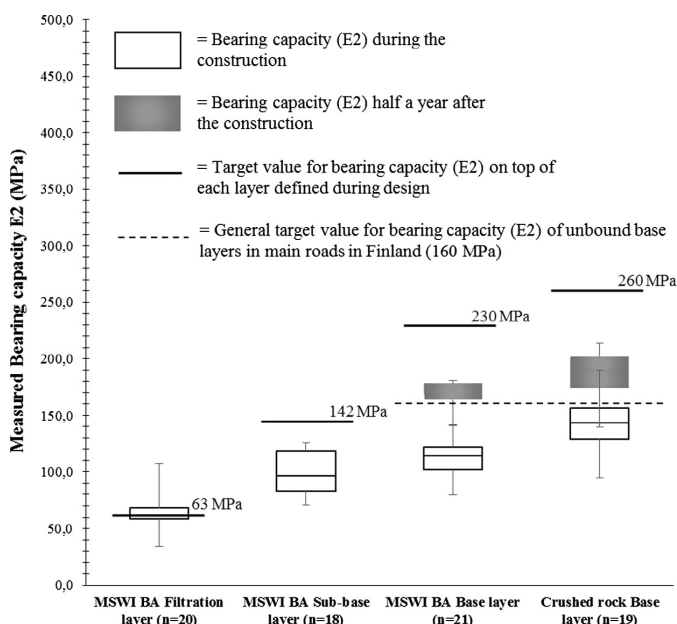
Fig. 3. The measured bearing capacities E2 (MPa) during the construction (white box) and a half a year later (grey box) compared with the target values set for each structural layer during the field design (Sormunen et al., 2016) and a target value given for unbound base layers in main roads in Finland (Tiehallinto, 2005).
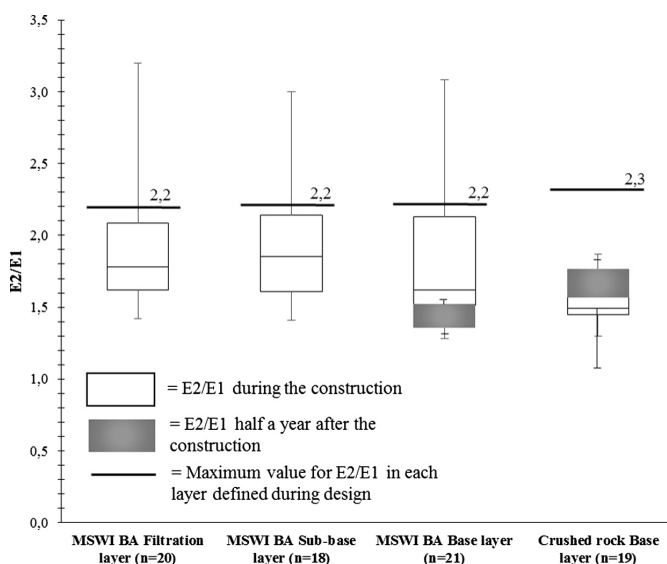

Fig. 4. The calculated E2/E1 ratios during the construction (white box) and a half a year later (grey box) compared with the maximum values defined for each structural layer during the field design (Sormunen et al., 2016).

It should also be noted that the amount of BA particles smaller than 0.5 mm decreased up to 40% in the filtration layer material half a year after the construction (Fig. 6). This implies that the finer BA particles were partly agglomerated with each other in the six months' time. The cause for this agglomeration may be due to different chemical reactions (e.g. oxidation, carbonation) that take place especially on the surface of fine bottom ash particles. These chemical reactions are related to the MSWI BA aging (Rendek et al., 2006), that can continue for a long time after the material is produced. The same agglomeration was not, however, noticed for the sub-base and base layer materials, which may be due to the smaller specific surface area of these coarser BA materials.

During the construction	Δw%	Half a year after the construction
x̄ = 14.7 % (n=5)	**MSWI BA Base layer** -4.6 %	x̄ = 10.1 % (n=5)
x̄ = 17.5 % (n=15)	**MSWI BA Sub-base layer** -0.8 %	x̄ = 16.7 % (n=5)
x̄ = 28.5 % (n=16)	**MSWI BA Filtration layer** +3.7 %	x̄ = 32.2 % (n=5)

Fig. 5. Illustration of changes in moisture content (w-%) for MSWI BA structural layer materials in the interim storage field half a year after the construction.

3.3.2. E-modulus values of BA materials based on back-calculation

Fig. 7 illustrates the back-calculated E-Modulus values for each BA material using the Odemark theory and Eq. (1). These back-calculated E-modulus values are compared with the preliminary E-Modulus values of BA materials that were estimated based on their grain size distributions (see Section 3.3.1). The E-modulus values determined for each BA material in the previously con-

ducted SPLT in the laboratory were used as reference as well (Sormunen et al., 2016).

Generally speaking, the E-modulus values obtained in this field study corresponded to the findings of laboratory studies on MSWI BA stiffness and strength properties (e.g. Arm, 2004; Sormunen and Kolisoja, 2016). The back-calculated E-Modulus value of BA filtration layer material was on average 90 MPa (Fig. 7). It corresponded to the E-modulus values defined with the SPLT in the laboratory and was, in most cases, above the preliminary evaluated E-modulus value given in Section 3.3.1 (Fig. 7). To some extent, this applied to the BA sub-base layer material as well. The back-calculated E-modulus values were on average 140 MPa for the sub-base layer material and thus comparable to the preliminary E-modulus value defined based on materials grain size distribution (100–150 MPa) (Fig. 6). Conversely, the E-modulus values determined in the laboratory scale SPLT (270 MPa and 320 MPa) were not reached for the sub-base nor the base layer materials in the field (Fig. 7). This was due to the SPLT test arrangement in the laboratory, in which the distribution of stresses and strains could not take place as freely as in the unconfined conditions in the field
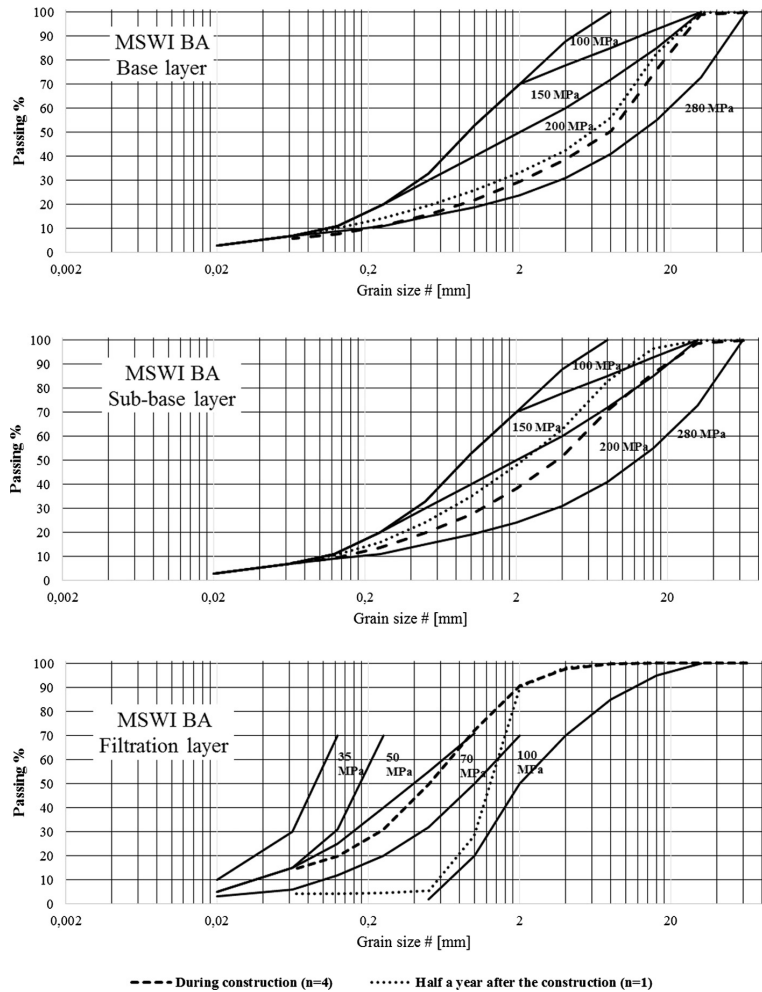

Fig. 6. The grain size distributions of each BA structural layer material (base: top; sub-base: middle; filtration: bottom) analysed during and half a year after the construction and the respective E-Modulus design values of natural gravels and crushed rock aggregates (Tiehallinto, 2005).
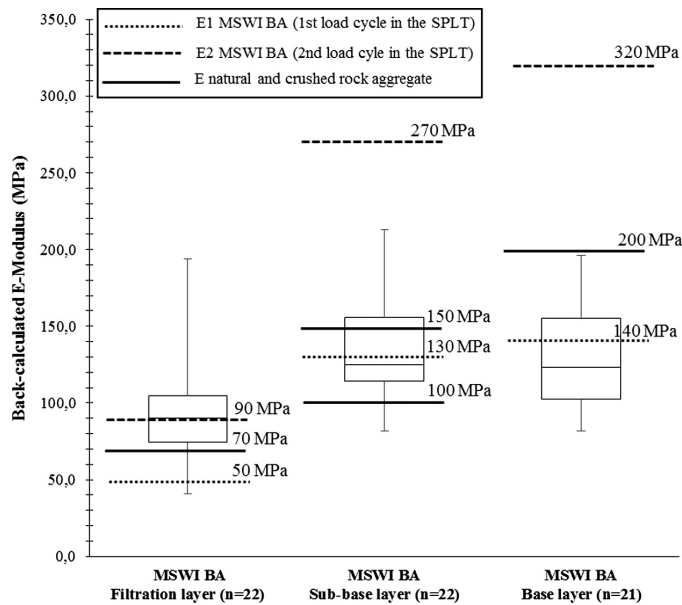
Fig. 7. The back-calculated Odemark E-Modulus values (MPa) for each BA structural layer of the interim storage field compared with the E-Modulus of BA materials determined using laboratory scale SPLT (Sormunen et al., 2016) and the preliminary evaluated E-Modulus values based on materials grain size distributions (see Fig. 6).

(Sormunen et al., 2016). The SPLTs conducted in the laboratory overestimated the determined E-Modulus values and cannot be used in future construction projects as the actual E-modulus values for these MSWI BA materials. Further studies should therefore be conducted in order to determine proper E-modulus values for the BA materials used in this study. This would further allow to design structures that have more realistic target bearing capacities (E2) for the structural layers built using these MSWI BA materials.

Finally, the back-calculated E-modulus value for the BA base layer material was on average 130 MPa (Fig. 7). This did not correspond to the preliminary estimated E-modulus value (200 MPa) based on materials grain size distribution (Fig. 6). The most likely reason for this is that MSWI BA particles are more prone to crushing and thus the material has lower stiffness values under higher stresses than natural and crushed rock aggregates. This result suggests that the recovered MSWI BA materials can be safely used especially in lower structural layers but not in the base layers where higher stress levels apply. The obtained results were in accordance with Arm (2003), who concluded that MSWI BA can be used in the sub-base layers, but not in the base layers especially below thin surfacing layer. In this study, an additional base layer of crushed rock aggregate was found necessary already in the design phase in order to fulfil the bearing capacity requirements set for the interim storage field. This additional base layer will also protect the BA particles from excessive crushing. The same effect might be obtained with a thicker asphalt concrete layer, which however, should be tested in further studies. In such studies, the cost effect should also be considered, since the interest of using this alternative raw material may decrease if it is does not enable cost-savings in real-life construction projects.

4. Conclusions

This paper presented a case study in which recovered MSWI BA was used in the structural layers (filtration, sub-base and base layers) of an interim storage field built within a waste treatment cen-

tre. The main aim of this study was to evaluate whether the mechanical performance of structures built with this recovered BA corresponds to the performance of natural aggregates. In addition, the aim was to compare the obtained results with the findings of two recent studies in which the same material was investigated in a laboratory scale (Sormunen et al., 2016; Sormunen and Kolisoja, 2016). Based on the obtained results and the mechanical behaviour of recovered BA materials, the following conclusions can be drawn from this field performance study:

- The MSWI BA recovered with the ADR is suitable material to be used in the lower structural layers (filtration and sub-base) of roads and field structures – Conversely, with current knowledge the material cannot be recommended to be used in the base layers as such, even though its stiffness properties increased over time due to material aging and changes in moisture content. The main reason for this is that BA particles are prone for crushing and therefore inadequate to resist the higher stresses occurring in the upper parts of road and field structures. This phenomena could be prevented by using an additional base layer of natural aggregate or a thicker asphalt concrete layer on top of BA base layer. The cost effect of these thicker layers should, however, be considered carefully, as the interest of using this alternative raw material may decrease, if it is does not enable cost-savings in real-life construction projects.

- The obtained results also indicated that the stiffness's of BA structures increase over time. This was in accordance with previous laboratory studies conducted with the same material. The increase in material stiffness is partly related to the changes in moisture content and is prominent especially when the material dries out. On the other hand, it is important to bear in mind that MSWI BA aging can also affect the materials mechanical properties. With the obtained field results, it was not possible to verify whether the increase in material stiffness's was only related to the decrease in moisture content but also material aging. Therefore, further studies on this matter would be interesting to conduct.

- The use of conventional quality control techniques, such as nuclear density gauge, was not that straightforward for this waste derived construction material. Therefore, it is of utmost importance to use appropriate quality control measures in order to ascertain that the BA structures are built fulfilling the given mechanical target values, and the durability of such structures is guaranteed in the long term. The results of this study also showed that the general target values used for natural aggregates (e.g. degree of compaction) may not be suitable for this waste derived aggregate. Thus, further studies should be conducted in order to set proper target values for this particular material. Such studies should also take into account the prominent increase in stiffness properties over time due to material aging and changes in materials moisture content.
- Finally, the leaching of potentially hazardous substances from the ADR-recovered MSWI BA is also a case of concern even though it was not discussed in this study. Hence, monitoring wells were placed underneath the BA structural layers and the leachate quality has been investigated as well. These results will be reported elsewhere.

Acknowledgements

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MSWI BA TREATED WITH ADVANCED DRY RECOVERY: COMPARING MATERIALS LEACHING PROPERTIES IN THREE DIFFERENT STUDY SCALES

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Submitted manuscript