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ENVIRONMENTAL ASSESSMENT OF MUNICIPAL SOLID WASTE INCINERATOR BOTTOM ASH IN ROAD CONSTRUCTIONS

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Susanna Olsson

Stockholm, September 2005

ABSTRACT

There are several incentives for using bottom ash from municipal solid waste incineration (MSWI bottom ash) as a construction material, such as for road construction. These incentives include decreased disposal of material on landfills and a reduced amount of raw material extracted for road building purposes. However, one of the main obstacles to utilising the material is uncertainties regarding its environmental properties. The overall objective of this thesis is to describe the potential environmental impacts of utilising MSWI bottom ash in constructions and to improve the tools for environmental assessments.

An environmental systems analysis (ESA) approach based on a life cycle perspective was outlined and used in a case study, with the aim of describing the differences in resource use and emissions that can be expected if crushed rock in the sub-base of a road in the Stockholm region in Sweden were to be substituted by MSWI bottom ash. The whole life cycle of the road was taken into account and the alternative disposal of the bottom ash was included. It was found that the studied alternatives would cause different types of potential environmental impact; whereas the conventional alternative with only crushed rock in the road's sub-base would lead to larger use of energy and natural resources, the alternative with MSWI bottom ash in the sub-base would lead to larger contaminant leaching. It was concluded that a life cycle approach is needed in order to include both resource use and emissions in the comparison between the two alternative scenarios. The leaching of metals turned out to be the most important environmental aspect for the comparison and in particular the difference in copper (Cu) leaching was shown to be large.

However, a large amount of Cu may not pose an environmental threat if the Cu is strongly bound to dissolved organic carbon (DOC). In order to improve the basis for toxicity estimates and environmental risk assessments, and thereby provide better input values for ESAs, the speciation of Cu to DOC in MSWI bottom ash leachate was studied. It was found that Cu to a large extent was bound to DOC, which is consistent with previous research. The results also suggest that the hydrophilic fraction of the MSWI bottom ash DOC is important for Cu complexation and that the pH-dependence for Cu complexation to MSWI bottom ash DOC is smaller than for natural DOC. This implies that models calibrated for natural DOC may give inconsistent simulations of Cu-DOC complexation in MSWI bottom ash leachate.

Keywords: bottom ash; environmental impact; LCA; waste management; leaching; copper; dissolved organic carbon

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II. Olsson, S., van Schaik, J., Gustafsson, J.P., Berggren Kleja, D. & van Hees, P. Speciation of Copper in MSWI bottom ash and soil leachates -the role of hydrophobic and hydrophilic compounds. *Manuscript*.

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INTRODUCTION

Today about 70 million tonnes of waste are produced annually in Sweden. Disposal of waste is resource-consuming. In addition, the space at existing landfills is limited and it is hard to find new suitable areas for waste disposal. To stimulate the reuse of wastes, society has therefore issued a variety of directives (fees on deposited waste, ban on the disposal of certain types of waste, etc.). This means that there are strong incentives to find ways to utilise the wastes. Waste from households, municipal solid waste, is increasingly being combusted for heat extraction. Previous research has shown that in Sweden it is generally environmentally advantageous to combust this kind of waste instead of disposing of it at landfills (Björklund 2000, Sundqvist et al. 2002). However, incineration of waste results in the formation of other waste products, such as different ash types. Management of this material in a sustainable way is now an important issue.

The possibility of utilising municipal solid waste incineration (MSWI) bottom ash for construction purposes, such as for road construction, is a topic that has been thoroughly discussed during the last ten years. The utilisation of waste material for construction purposes is motivated by reduced management costs, insufficient local raw material supply, inadequate local disposal capacity and a desire to preserve natural resources (Hartlén 1996). There is great demand for road building material in Sweden. In the Stockholm region alone, the use of rock and gravel for this purpose was around 4.75 million tonnes during year 2002. The annual production of MSWI bottom ash and industrial waste incineration bottom ash in the Stockholm region in 2002 was almost 50 000 tonnes dry substance, constituting the major ash type produced in the region (Appendix 1), (Fig. 1). In the same year, the total production of MSWI bottom ash in Sweden was up to 400 000 tonnes (Bjurström 2002).

So far, bottom ash has not been used for road construction to any great extent in Sweden, even though previous studies have shown that it is technically suitable for this purpose (Hartlén et al. 1999, Vägverket 1999, Arm 2003). One of the main obstacles to the use of recycled materials in constructions in Sweden is that the laws and regulations are ambiguous (Kärrman et al. 2004). Because the environmental risks from using MSWI bottom ash in constructions are not yet fully understood, the precautionary principle that is practised in Sweden often makes the authorities restrictive to the utilisation of the material. There is also a lack of national established norms regarding the materials that can be used in a particular construction, which often causes decisions to be unpredictable (Wilhelmsson et al. 2003). This situation may be a result of the uncertainties that still remain regarding the potential environmental impact from the utilisation. A further obstacle is the lack of methods for showing the benefits of recycling (Kärrman et al. 2004).

MSWI bottom ash is a highly heterogeneous material, predominantly composed of oxides

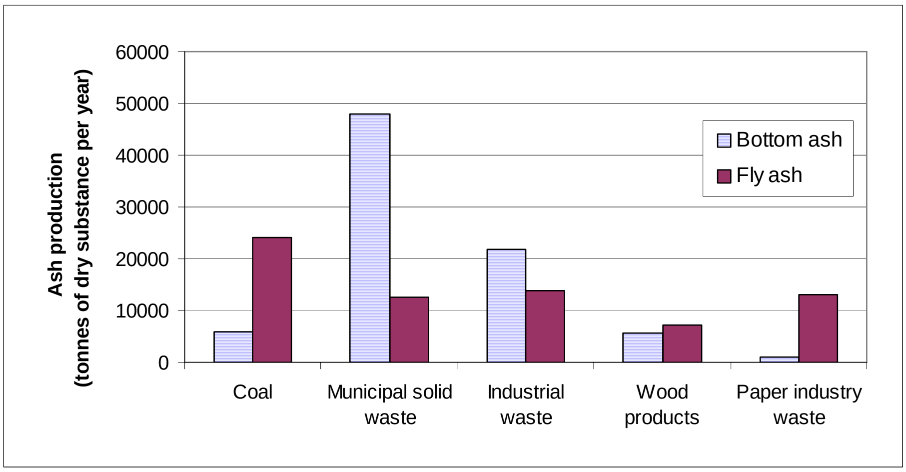

Figure 1. Production of the most common ash types (>10 000 tonnes/year) from different fuels in Stockholm county, 2002.

and aluminosilicate minerals of Fe, Na, K and Ca (Abbas et al. 2001, RVF 2002). The material also contains a relatively large amount of heavy metals that may be released during utilisation (Chandler et al. 1997). To assess environmental risks, leaching tests are often used to calculate the release of contaminants and extensive research has been carried out on this topic. However, there are still some uncertainties remaining that limit the possibilities for risk assessments. There is, for example, an ongoing discussion on whether the total concentration of a substance in the leachate, or only its toxic forms, should be considered. This is an important issue concerning copper (Cu), the toxicity of which to aquatic organisms is reduced by complex formation with dissolved organic carbon (DOC) (Zitko et al. 1973, Sunda & Guillard 1976, Borgmann 1983, Pagenkopf 1983). It has been found that more than 95% of the dissolved Cu in MSWI bottom ash leachate is bound to DOC (Meima et al. 1999). In order to decrease the uncertainties regarding the potential environmental impact from MSWI bottom ash utilisation, the effects of DOC on the leaching and toxicity of metal contaminants need to be further investigated.

However, improved assessments of the risks and effects from leaching are not sufficient, since these assessments fail to consider other types of environmental impact, such as resource use and pressures relevant on a regional or global scale (Roth & Eklund 2003, Roth 2005). While much emphasis has been placed on risks for contaminant leaching, less attention has been paid to these types of impacts, which should be equally important according to the Swedish Code of Statues (1998) for strategic decisions on MSWI bottom ash management. The utilisation of MSWI bottom ash in constructions would, for example, enable both decreased disposal of bottom ash and reduced amounts of natural aggregates extracted for road building purposes. If those aspects are neglected there is a risk that non-optimal solutions are chosen. To enable the inclusion of impacts other than leaching, such as resource use and emissions to air, the assessment would have to expand and a life cycle perspective may be useful.

Objectives

The overall objective of this thesis was to describe the potential environmental impacts of utilising MSWI bottom ash in road constructions and to improve the tools for environmental assessments. Specific aims were to:

- Investigate ways to perform environmental assessments of the use of MSWI bottom ash in constructions and identify topics on which more knowledge is needed.
- Develop an approach, based on a life cycle perspective, for environmental assessment of the use of MSWI bottom ash in road constructions.
- Describe the differences in resource use and emissions to air and water that can be expected from utilising MSWI bottom ash in a road construction compared to a conventional material.
- Investigate the metal binding properties of the dissolved organic carbon in MSWI bottom ash leachate.
- Improve the basis for leaching and toxicity estimations of selected metals.

A literature review was performed in order to organise previous research on the environmental impacts from using MSWI bottom ash in constructions, to gain an increased understanding of how such environmental assessments may be performed and to identify data gaps. The potential environmental impact from using MSWI bottom ash instead of crushed rock in a road construction was then studied (Paper I). An approach based on a life cycle perspective was developed for this purpose in order to include a broader perspective than that commonly used on the utilisation of MSWI bottom ash. Not only contaminant leaching, but also resource use and emissions to air were included. Based on the results from that study and from the literature review, leaching of Cu and dissolved organic carbon (DOC) from MSWI bottom ash was chosen as the focus for a second study (Paper II).

METHODS

Literature review: Environmental assessment on different system levels

To utilise bottom ash from municipal solid waste incineration in constructions, it has to be proven that the material is technically and environmentally suitable for this purpose. How to define and evaluate the environmental impact is therefore an important issue. Environmental assessment of using MSWI bottom ash in road constructions can be carreid out in several ways. Different types of environmental impact may be considered, and those may be estimated by separate methods. There have been several previous studies in this area of research. They have addressed a wide range of aspects and provide extensive information on the environmental impact associated with the utilisation of the material.

By defining different levels of systems perspective on which environmental assessment of by-products in road constructions can be made, Roth and Eklund (2003) provide a useful basis for organising and interpreting the outcome of those previous studies. They describe four different levels on which environmental assessment of reuse of by-products in road constructions can be made and some of the tools that can be used (Fig. 2).

These levels are:

1. Material
2. Road environment
3. Narrow life cycle level
4. Industrial system level

The material level addresses the properties and content of the material and can be studied by leaching tests. Studies on the road environment level deal with the material in its spatial context and for this purpose substance flow analysis can be used. The narrow life cycle level (hereafter referred to as the LCA-level) and the industrial system level require that the system boundaries be expanded to include more parts in the construction's life cycle than only the operations stage. While the narrow life cycle level includes environmental pressures from the life cycle of the materials, the industrial system level adds a cross-sectoral dimension and addresses the generation and substitution of material in the whole industrial system. Furthermore, the authors argue that the different systems perspectives are appropriate for addressing different questions and they suggest that environmental assessment of by-products in road constructions should be complemented by using wider system boundaries than only the currently used leaching tests.

In this literature review, these system levels were used as a basis for the organisation of previous scientific work. All scientific papers concerning the environmental aspects of using MSWI bottom ash in constructions were sought in different databases, resulting in a great number of published works. As a complement, some reports that were not scientifically published concerning Swedish conditions were also included. The focus was only on the environmental aspects of using the material in constructions, since the technical aspects of different applications have been discussed elsewhere (Izquierdo et al. 2002, Arm 2003). The aim was to analyse the previous studies on the environmental im-

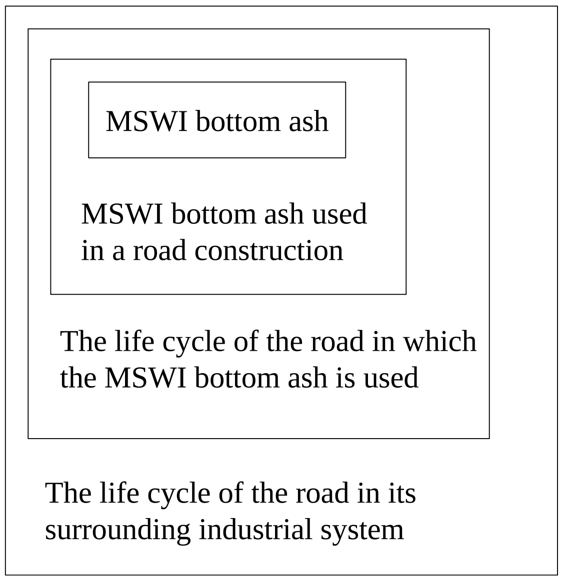

Figure 2. Different system levels on which environmental assessment of the reuse of by-products such as MSWI bottom ash in constructions can be made (adapted from Roth 2005).

pacts from the use of MSWI bottom ash in constructions in terms of the systems perspective used in the study, the type of environmental impact considered and the information gained. This also included a discussion of whether the studies reviewed provide sufficient information for environmental assessment of using MSWI bottom ash in constructions to be made for decision purposes.

Environmental systems analysis

In order to study the potential environmental impacts of using MSWI bottom ash instead of crushed rock in a road construction, an environmental systems analysis (ESA) based on a life cycle perspective was performed (Paper I). The aim was to quantitatively include not only the emissions to water but also emissions to air and the potential positive effects, such as saved resources. It was assumed that the resource use and the emissions would occur at different stages of the road's life cycle (Mäkelä & Höynälä 2000). Hence, a life cycle perspective would be needed to include them in a comparison.

Life cycle analysis (LCA) is a common tool for evaluating the environmental burdens from the total life cycle of a product, 'from cradle to grave', i.e. from the extraction of basic resources, through production and transportation, to use and disposal of the product (ISO 1997). LCA is often used to compare products with equivalent functions or to determine the parts of the life cycle that are most critical to the system's overall environmental impact.

Based on the concepts and methodology used in LCA, an ESA approach was developed to study the differences between two alternative scenarios where crushed rock (Alternative 1) or MSWI bottom ash (Alternative 2) was used as sub-base material in a road. The approach included the definition of system boundaries and production of a conceptual model of the system, an inventory of flows (energy, material and emissions, hereafter referred to as aspects) to, from and within the system and, finally, processing of this information and an assessment of the system's environmental impact.

The definition of system boundaries is in many ways a crucial part of an LCA, since it may affect the results to a large extent (Tillman et al. 1993). In this study, all life cycle stages significant for the chosen aspects of those system components that would be different in the different alternatives were included. Aspects were chosen based on available data and on their potential to affect any of the impact categories described by SETAC-Europe (1999). The life cycles of products used in the system were limited to include the production of fuel and electricity from raw material (Fig. 3). The system boundaries were also expanded to include the effects of less landfilling, implying that the disposal of MSWI bottom ash was consid-

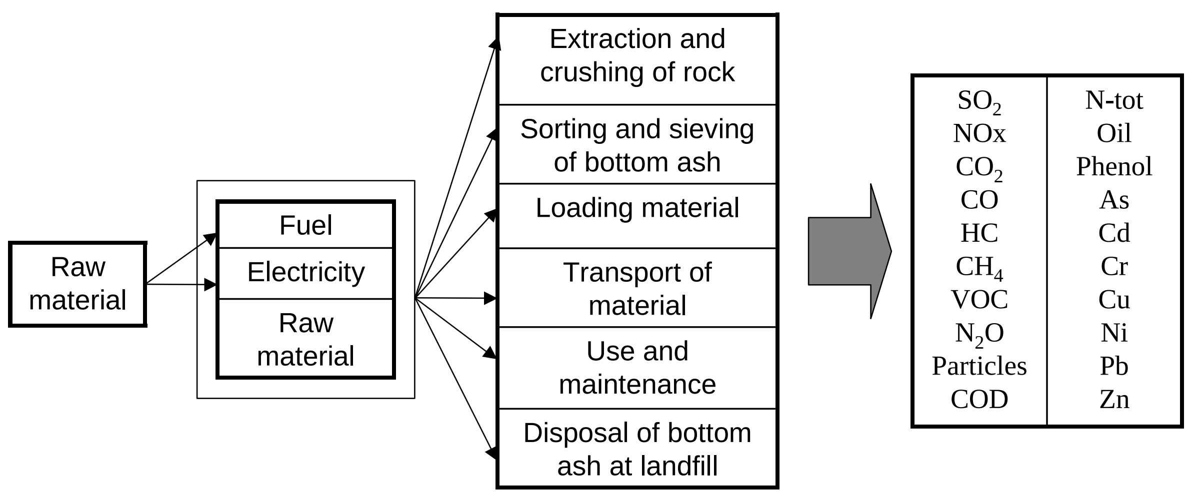

Figure 3. Resources and emissions investigated for the life cycle stages of the road studied (Paper I).

ered in case the ash was not used in road construction. Thus, the functional unit, to which all aspects were related, consisted of both the road and the management of a certain amount of MSWI bottom ash. The demolition stage of the life cycle was excluded from the analysis due to lack of data and the assumption that there would be no significant demolition differences between the alternatives. To obtain the relative magnitude of each aspect studied, the result was normalised by relating each substance or energy flow to the same kind of flow on a national basis. The outlined approach was used in a case study, where information from the test road Törringevägen (Hartlén et al. 1999, Arm 2003) in southern Sweden was applied on a theoretical road, with given dimensions, in the Stockholm region. The technical performance of the materials was assumed to be the same. Case-specific parameters and assumptions can be found in Paper I and in Appendix 2.

Copper speciation in MSWI bottom ash leachate and in soil solution

In order to understand the speciation of Cu in MSWI bottom ash leachate and the contribution from DOC to Cu leaching, the DOC in a MSWI bottom ash leachate was characterised and the Cu-binding properties of its hydrophilic and hydrophobic components were studied (Paper II). As a reference, the Cu-binding properties of the hydrophilic and hydrophobic components in a soil leachate were also studied. MSWI bottom ash leachate (BA1) was produced by leaching of stored (>6 months) and sorted bottom ash (<10 mm) with deionised H_2O for 24 hours in an end-over-end rotator (L/S 5). Soil solutions (S1 and S2) were collected from lysimeters in an untreated Oa horizon from a Haplic Podzol. After filtration through a 0.2 µm membrane, pH, cations, anions, DOC and low molecular weight organic acids (LMWOA) were measured in the MSWI bottom ash leachate and in the soil solution.

The MSWI bottom ash leachate was fractionated according to Leenheer (1981) in order to determine its content of different DOC fractions. By passing the leachate through a column containing Amberlite® XAD-8 and exposing it to cation and anion exchange, the hydrophobic acids and neutrals and the hydrophilic acids, bases and neutrals were estimated (Fig. 4). The hydrophobic acids, which are retained in the XAD-8 column and then recovered by using 0.01 M NaOH are often referred to as 'fulvic acids' (FA) in literature (Ritchie & Purdue 2003). A simplified fractionation procedure, where the hydrophilic components were isolated from the hydrophobic components by the Amberlite® XAD-8 containing column, was used to produce subsamples for the titration experiments.

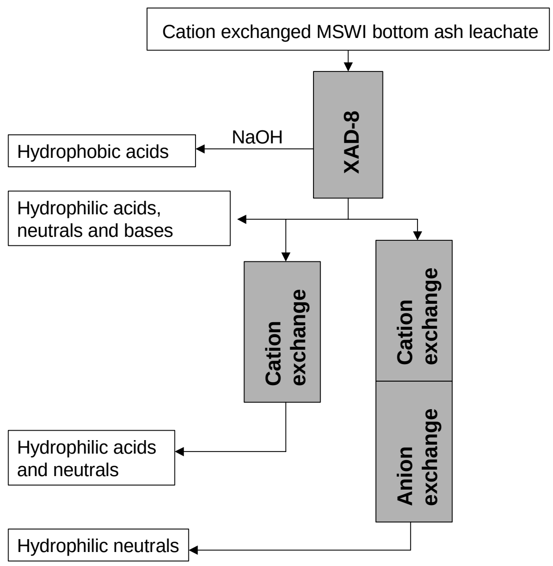

Figure 4. Fractionation of DOC in MSWI bottom ash leachate based on Leenheer (1981).

Titrations were made on subsamples of the MSWI bottom ash leachate and the soil solution in order to measure the Cu^{2+} activity at different pH values. The Cu^{2+} activity was measured potentiometrically using a Cu-ion selective electrode. Prior to titration, the subsamples were exposed to different treatments (Table 1) in order to adjust pH or the Cu to DOC ratio. The copper titrations were performed with NaOH on 40 ml sample solution that was constantly stirred and purged with N_2 (g) (Fig. 5). After each addition of base, the pH and the Cu^{2+} concentration in solution were measured. The amount

Table 1. Subsamples for titration. Additions were made in order to adjust pH or the Cu to DOC ratio.

Sample	Column treatment	Additions
BA1-a	Untreated	HCl
BA1-b	Cation column	NaOH, $Cu(NO_3)_2$
BA1-c	Cation coumn, XAD-8 colmn	NaOH, $Cu(NO_3)_2$
S1-a	Untreated	HNO_3, $Cu(NO_3)_2$
S2-c	XAD-8 coumn	HNO_3, $Cu(NO_3)_2$

of complex-bound Cu(II) was estimated as the difference between total amount and the calculated concentration of Cu^{2+} ions (as obtained from the measured Cu^{2+} activity).

The results from the titrations were compared with speciation calculations made using Visual MINTEQ (http://www.lwr.kth.se/English/OurSoftware/vminteq/index.htm), which uses submodels for organic matter such as NICA-Donnan (Kinniburgh et al. 1999, Milne et al. 2003) and Stockholm Humic (SHM) models (Gustafsson 2001). When applying the models, all inorganic and LMWOA complexes as well as fulvic acid were considered. It was initially assumed that 65% of the DOC was active, consisting of fulvic acid, while the remaining 35% was inert with respect to proton and metal binding, as found for natural DOC by Bryan et al. (2002).

LITERATURE REVIEW: ENVIRONMENTAL ASSESSMENT OF MSWI BOTTOM ASH IN ROAD CONSTRUCTIONS

Environmental assessment on the material level

Studies on the material level were by far the most common among the studies found. Typically, on this level a specific application is not considered and therefore this category includes studies of the properties of MSWI bottom ash that are related to its environmental performance, regardless of the intended use (though different types of mixed materials with other major components than bottom ash have not been considered). Leaching was found to be the main focus when studying the environmental impact from MSWI bottom ash utilisation on the material level. Commonly, the authors refer to the national policies as an argument for studying leaching properties of the ash, or to leaching as an important factor in the assessment of the potential hazards associated with the use of the material in constructions.

The studies found on the material level may be divided into four subgroups based on their main focus: Material characterisation; methods for material characterisation; chemical mechanisms of trace metal leaching; and innovations to make the material more suitable for a certain purpose. Besides these,

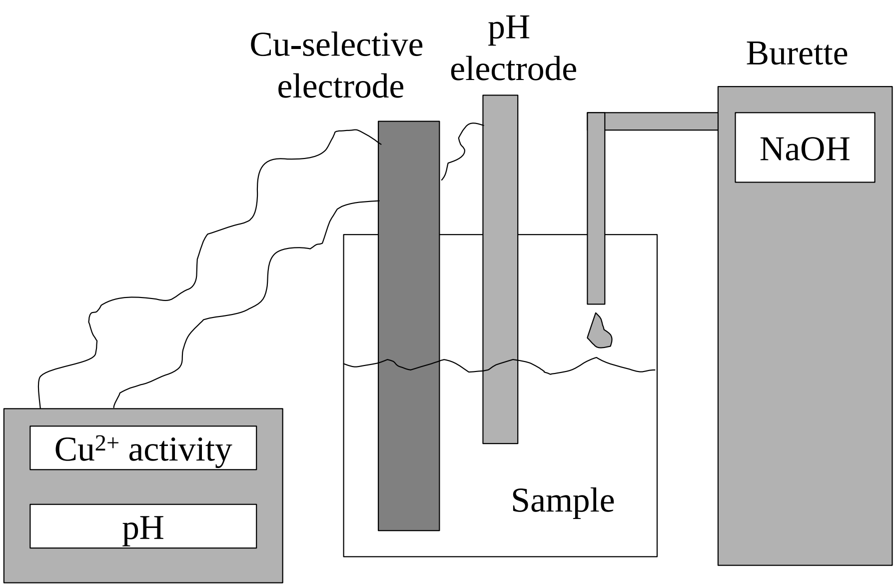

Figure 5. Titration experiment setup for the measurement of Cu-DOC complexes at different pH values.

there are also numerous papers investigating chemical reactions that are of a general character and thus not directly linked to MSWI bottom ash even though they might be useful when discussing leaching mechanisms of the ash. Some of the major findings on MSWI bottom ash that are relevant for environmental assessment of the material are described below.

Characterisation of MSWI bottom ash

The composition of MSWI bottom ash has been reported for many different incineration plants and countries (Hjelmar 1996, Wiles 1996, Chandler et al. 1997, Chimenos et al. 1999, Izquierdo et al. 2002, Forteza et al. 2004) showing that the bottom ash is a heterogeneous material with a great variation in content and leaching properties. This variation is due to different waste materials but also different types of incineration processes. Information on Swedish MSWI bottom ash can be found in some doctoral theses (Fällman 1997, Johansson 2003) and in other publications such as RVF (2002) and Bjurström et al. (2004). Generally the main emphasis regarding the bottom ash has been on trace metals rather than organic pollutants, even though the organic content in ash has been studied (Brunner et al. 1987, Dugenest et al. 1999, Johansson et al. 2000, Johansson 2003, Kim & Osako 2004). The reason may be that the amounts of organic pollutants are often small, so they are considered to be of minor importance (Wiles 1996, RVF 2002). The leaching potential for Cu, Pb, Cd, Zn and Mo has been most frequently investigated.

Bottom ash contains relatively high amounts of trace metals, especially Cu, compared to natural aggregates such as sand or crushed rock (Table 2). Such metals may pose an environmental threat if they are leached into the surroundings. The metal content in the bottom ash may be controlled by the incineration temperature, since a higher temperature results in increased transfer of many metals into the gaseous phase (Belevi & Langmeier 2000). For most of the trace metals, however, there is not necessarily a correlation between the total content and the leached amounts or between the composition of the incinerated waste and the leaching from the bottom ash (van der Sloot et al. 2001). There may also be numerous other factors, together with the total content of a certain metal, determining its leachability in a simultaneous and complex manner as has been reported for lead (Jeong et al. 2005). To make predictions of potential leaching from different management alternatives it is therefore essential to understand the controlling mechanisms for the leaching from the ash. This information can then be used for mathematical extrapolations in coupled mass

Table 2. Data on average and maximum leaching from Swedish MSWI bottom ash, average leaching from fresh crushed rock (Gabbro-diorite) and maximum leaching from crushed bedrock, moraine and gravel. All measurements are made at L/S 2, and the result is given in µg/l. Background concentration for lakes in southern Sweden is reported as a reference.

Metal	Average MSWI bottom ash leachate[1]	Maximum MSWI bottom ash leachate[1]	Average crushed rock leachate [2]	Maximum crushed bedrock, moraine and gravel leachate [2]	Lake background concentration[3]
Cd	1.1	8.0	0.1	0.50	0.016
Cr	9.0	45	0.5	3.4	0.2
Cu	1212	6000	5.5	9.1	0.5
Ni	18	40	2.7	40	0.4
Pb	4.5	30	0.3	1.0	0.24
Zn	34	195	3.3	16	2.0

[1] (RVF 2002)

[2] (Tossavainen & Håkansson 1999)

[3] (Naturvårdsverket 1999)

transport models for long-term leaching predictions.

Methods for characterisation

By using specifically designed or standardised leaching tests, extensive information can be obtained on ash properties and the mechanisms controlling leaching. There are a number of relevant test methods for determining leaching of inorganic components from MSWI bottom ash on a laboratory scale, either exploring the mechanisms of leaching or simulating what would happen in a field situation. However, it is essential to know how to interpret the results from such tests. There may be substantial differences between laboratory and field conditions (Belevi et al. 1992, Fällman & Hartlén 1994, Fällman & Aurell 1996, Fällman 1997, Fällman & Rosén 2001) and test conditions, such as acidity or redox potential or leaching affecting different trace metals differently (Bruder-Hubscher et al. 2002). Furthermore, according to Quilici (2004), there is not necessarily a correlation between the results from physico-chemical testing and the resulting ecotoxicity. In order to understand how the material will develop chemically over a long time in a field situation, the laboratory tests need to be combined with modelling tools and field verification tests (van der Sloot 1996, van der Sloot et al. 2001). Three different levels of waste characterisation have been suggested by CEN (European Committee for Standardisation):

1. Basic characterisation test (several parameters are determined, considering both short-term and long-term leaching properties of the material)
2. Compliance test (focusing on some identified key parameters)
3. On-site verification test

In Sweden, environmental assessments of construction materials are often based on total analyses (the material is dissolved in strong chemicals or melted), batch tests (extraction test), or column tests (dynamic test) (Carling & Hjalmarsson 1998, RVF 2002, Wadstein et al. 2002).

Extraction tests typically involve mixing a sample with a specific amount of leaching solution, which is not renewed during the test. The mixing is performed with the aim of reaching equilibrium conditions and is followed by filtration and analysis of the leachate. Examples of extraction tests are the NT ENVIR 003, SS-EN 12457 (1-4) and prEN 14429 (Table 3). The availability test NT ENVIR 003 determines the amounts of different substances that are available for leaching in a long time perspective (several thousands of years). The SS-EN 12457 (1-4) and the pH dependent test prEN 14429, on the other hand, aim to describe leaching during a shorter time perspective and therefore lower L/S ratio and coarser particles are used. In dynamic tests, some aspects of

Table 3. Examples of common leaching tests for granular material.

Test	Type	Procedure	Results
prEN 12457 (1-4)	Extraction test	Sample is mixed with H_2O and HNO_3 for 24 h, L/S 2-10. Particle size is <10 or <4 mm.	Estimates of leaching during a short time perspective.
prEN 14429	Extraction test	Replicate samples are mixed with H_2O and HNO_3 for 48 h at different pH values (4-12). The L/S ratio is 10 and the particle size is <1mm.	Information on the impact of pH on leaching.
NT ENVIR 003 (availability test)	Extraction test	Sample is mixed with H_2O and HNO_3 in two steps, at pH 7 (3h) and pH 4 (18h). The L/S ratio is high and particle size is <125 μm.	Estimates of leaching during a long time perspective (several thousands of years).
prEN 14405 (up-flow percolation test)	Dynamic test	Sequential flushing with H_2O in a column of the sample at increasing L/S ratios (0.1-10). Particle size is <10 or <4 mm.	Information on how leaching progresses at different L/S ratios in a situation that is more similar to field conditions than in an extraction test.

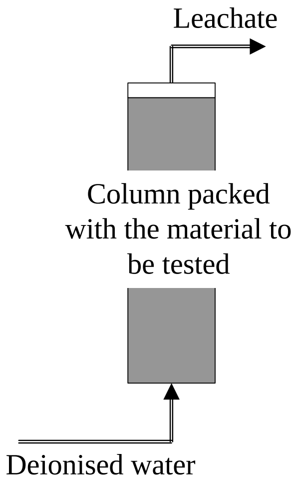

Figure 6. In dynamic tests, some aspects of leaching in which time is an important variable are typically addressed. One example of such a test is the upflow percolation test prEN 14405, which is under approval by CEN (European Committee for Standardisation) to become a European standard.

leaching in which time is an important variable are typically addressed. The test material and the leaching solution are mixed and the leaching solution is periodically or continuously renewed. An example of a dynamic test is the upflow percolation test prEN 14405, which is based on NEN 7345 and NT ENVIR 002 (Fig. 6).

Chemical mechanisms of trace metal leaching

The chemical mechanisms for the solubility of trace metals from MSWI residues have been the subject of discussion by several authors. Weathering processes have been found to have a significant effect on the leaching of trace metals. Meima & Comans (1997) distinguished between three different weathering stages, based on pH, in which different bottom ash types show largely similar leaching behaviour. In the most weathered MSWI bottom ash (1.5 years old), the pH was found to be 8-8.5. Later, the same authors concluded that leaching was lower in the more weathered (carbonated) bottom ash (Meima & Comans 1999). The decreased leaching was explained as an effect of pH and of the controlling processes being different than in the fresh ash. During weathering, the bottom ash is oxidised and the oxides are hydrolysed (Speiser et al. 2000), i.e. to Fe- and Al hydroxides. Carbonation then takes place, in which CO_2 is absorbed by the material, pH is decreased and calcite ($CaCO_3$) is formed until equilibrium with the atmospheric CO_2 is reached (Goumans et al. 1994, Chandler et al. 1997, Meima & Comans 1997) (eq. 1). At the same time, amorphous aluminosilicates have been found to precipitate (Goumans et al. 1994). Calcite works as an important long-term buffer in the bottom ash, keeping pH relatively high for several thousands of years (Fällman et al. 1999, Johnson & Furrer 2002).

Equation 1. $CaO + CO_2 \rightarrow CaCO_3$

$$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$$

The processes that dominate in controlling the leaching of trace metals from weathered bottom ash are not yet fully understood. Precipitation of calcite and other carbonates may be one of the controlling mechanisms for the leaching of Cd and Pb (Johnson et al. 1996) or Cd and Zn (Meima & Comans 1999). Neoformed minerals such as Fe/Al-(hydr)oxides have also been discussed for controlling leaching as potentially important sorbent minerals (Kersten et al. 1997, Meima & Comans 1998, Meima & Comans 1999, Dijkstra et al. 2002), but additional sorption sites, which need to be identified, may also be important (Meima et al. 2002). For Cu, some indications have been found that sorption to amorphous Al-minerals reduces the mobility (Meima & Comans 1999, Meima et al. 2002), but there have also been several indications of Cu-DOC complex formation (Kersten et al. 1997, Meima & Comans 1997) (Fig. 7). Meima et al. (1999) found that more than 95% of the dissolved Cu was bound to DOC in leachate from both fresh and weathered bottom ash. Even though some research has been carried out on the organic material in the MSWI bottom ash and its possibility to form complexes with Cu, there is a need for further studies of the nature of DOC and the role of organic complexation in the long term

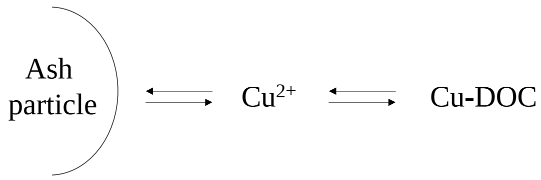

Figure 7. There are several indications that Cu in the leachate from MSWI bottom ash forms complexes with DOC. Hence, the concentration of Cu^{2+} in solution is dependent on equilibrium with DOC complexes and the solid phase.

(Fällman 1997, Grøn et al. 2003, Johansson 2003, van Zomeren & Comans 2004).

Improvement of environmental properties

There are different techniques described in the literature that may be used to improve the environmental performance of MSWI bottom ash. One possibility is to reduce the leachability of contaminants by chemical stabilisation or addition of sorbing components. Crannell et al. (2000) found that divalent metal cations in MSWI bottom ash were effectively stabilised by treatment with soluble PO_4^{3-}, whereas Comans et al. (2000) found addition of Fe(III) and Al(III) salts to be a promising technique to reduce the leaching of metals in the bottom ash. Washing (Stegemann et al. 1995) or carbonatisation (Van Gerven et al. 2005) of the bottom ash are other reported methods to reduce the leaching of some substances.

Thermal treatment of MSWI ash is another way to increase the feasibility of recycling incinerator ash as construction materials (Wang et al. 1998, Sakai & Hiraoka 2000, Nishida et al. 2001, Wang et al. 2003). Generally, a material with good technical properties and low metal leachability could be produced by this treatment. Co-heating or mixing of the bottom ash with other ash fractions may be a further alternative to get a product usable in construction (Abbas et al. 2001, Sorensen et al. 2001, Baun et al. 2004).

Environmental assessment concerning the material in its surroundings

While a large amount of scientific work has been devoted to characterising the chemical properties of MSWI bottom ash, there are fewer studies that focus on the material in its surroundings and that may thus be incorporated on the second system level. Most of these studies do not specifically consider a certain material but rather waste material expressed as residues, secondary materials, recycled materials and by-products. It is assumed that these categories may include MSWI bottom ash. On this system level, studies are therefore included that do not focus solely on MSWI bottom ash.

Environmental aspects considered

Few of the studies found on the second system level mention that there may be other types of environmental impact from the utilisation of the material in the construction apart from leaching during the use of the construction. Instead, leaching is brought forward as the main environmental impact, often without any further explanation. Hartlén (1996) addresses some other possible environmental aspects in addition to leaching, such as energy use and emissions during transportation. However, even though he considers it important to take all types of emissions into account, he focuses on the leaching from the material and states that leaching of hazardous substances to soil and water is the main environmental impact from re-use of secondary material without any further arguments.

Most of the studies on the second system level are method-focused, suggesting frameworks for assessing the leaching from different secondary materials in constructions during the use of the construction (Nunes et al. 1996, Kosson et al. 2002, Mroueh & Wahlström 2002, Apul et al. 2003, Svedberg 2003, Petkovic et al. 2004), or discussing the agreement between predicted and measured release in the field (Kosson et al. 1996, Schreurs et al. 2000). There are also some studies that focus on case study results in relation to a certain decision situation. It may be argued that these studies may also be categorised into the material level since they do not expressly consider the local environment in which the road is built but rather some kind of average environment for which limit values exist. However, since the leaching from the material as incorporated into the road body is considered, here they are included in the second system level. Comparisons between national regulations and leaching of MSWI bottom ash have been reported based on measurements in the field (Bruder-Hubscher et al. 2001) or the laboratory (Izquierdo et al. 2002, Forteza et al. 2004). Generally, these results indicate an acceptable level of contaminant release from the material. Only Bruder-Hubscher et al. (2001) includes a discussion of the contaminant release from conventional materials. In Sweden, leaching of heavy metals from bottom ash in road applications has been studied i.e. at Törringevägen in Malmö (Hartlén et al. 1999), Linköping (Flyhammar & Bendz 2003) and Dåva (Lind et al. 2005).

Framework for risk assessments and critical limit definition

To develop realistic estimates of constituent release from MSWI bottom ash in a certain application, a combination is required of laboratory tests which measure fundamental leaching parameters, mathematical modelling to carry out extrapolation of laboratory results to field scenarios and field certification of critical assumptions (Kosson et al. 1996). The leaching may then be compared to some kind of critical limit or acceptance level in order to assess the environmental impact caused by the material utilisation. The idea that the contaminants should leach into the surroundings at an environmentally acceptable rate has been expressed for disposal strategies by Hjelmar (1996) as the 'controlled contaminant release strategy' and this view seems to be the basis for the suggested frameworks. However, the problem is to know what degree of environmental risk should be accepted and at which point the critical limit is being exceeded for different types of environments.

The suggested frameworks may be used as valuable tools in defining such acceptance levels or critical limits for contaminant release in different surroundings. Frameworks for risk assessments and critical limit definition may be focused either on the source and the possible transportation of the pollutants, or on backtracking the pollution from an acceptable exposure level for human or ecological systems back to the source to determine the acceptable content within the source. In Sweden, the former perspective is advocated by Svedberg (2003) and the latter by ongoing work at the Swedish Geotechnical Institute (SGI).

Both Petkovic et al. (2004) and Kosson et al. (2002) base their frameworks on the measurement of intrinsic leaching properties of the material in conjunction with mathematical modelling to estimate release under field management scenarios. Kosson et al. (2002) in particular devote great effort to describing how to assess leaching and argue that intrinsic leaching parameters need to be assessed in order to provide a sound basis for estimation of release potential in a range of different potential waste management scenarios. Four steps are proposed to determine the potential for toxic constituent release from a waste by leaching under a selected management option. Firstly, scenarios and mechanisms are defined. This is followed by measurement of intrinsic leaching parameters for the material. Release models are then used to incorporate the measured leaching parameters to estimate release fluxes and long-term cumulative release. Finally, the release estimates are compared to acceptance criteria. In order to measure the intrinsic leaching parameters, Kosson et al. (2002) suggest a three-tiered testing programme:

1. Screening-based assessment (availability)
2. Equilibrium-based assessment (over a range of pH and L/S conditions)
3. Mass transfer-based assessment

The progression from tier 1 to tier 3 provides increasingly more realistic and tailored and less conservative estimates of release, but also requires more extensive testing. For the modelling of cumulative release, equations are demonstrated for both percolation and mass transfer-controlled scenarios.

The testing programme and the release modelling described by Kosson et al. (2002) are used by Petkovic et al. (2004) as a basis for modelling leaching from recycled materials in road constructions. The latter authors present a combination of the European standard for characterisation of waste, ENV 12920, and the Norwegian guidelines for evaluating impacts on health and ecosystems. In the procedure, information on the amount of contaminants released is combined with a risk assessment, which includes source identification, transport pathway evaluation and exposure assessment of target organisms. In this way, threshold values for material input data can be determined for different scenarios and acceptance criteria for the acceptance or refusal of the recycled material for a given application can be formulated.

Apul et al. (2003) add a further dimension to such assessment by including guidance on how to incorporate different levels of uncertainty in contaminant release estimates.

Environmental assessment on an LCA level

The studies previously described have focused on the chemical properties of the material or the use of the material in a construction, thus neglecting environmental impacts that occur in other stages of the construction's life cycle than the use stage. There are, however, a few examples of studies that take a broader view and include some of the aspects connected with the whole life cycle of the construction.

Mroueh et al. (2001) describe results from a research project that includes the development of a life cycle impact assessment procedure for comparisons and evaluation of alternative road and earth constructions. The procedure outlined was used in case studies. It was found that the use of by-products as a substitute for natural aggregates could reduce the environmental impact for some of the impact categories. However, the project did not include MSWI bottom ash.

In Denmark, a model for life cycle analysis (LCA) of road construction and disposal of MSWI residues is under development (Birgisdottir et al. 2003). The model includes the total environmental impact from the constructions, and assessments of certain parameters such as water percolation through the material and the leaching of trace metals from the material are being extensively discussed within the project.

In Sweden, no scientifically reviewed publications from studies on the LCA level concerning MSWI bottom ash or other reused material in road constructions were found. However, a life cycle perspective on the utilisation of waste material in road constructions was found in a report by Carling & Hjalmarsson (1998).

Environmental assessment on an Industrial system level

There is a lack of studies on the widest system approach, the fourth system level, concerning reuse of waste material in constructions. Such research could include the issues of natural resource substitution by reuse of waste material and the pressures of the waste material production. In the case of MSWI bottom ash, the industrial system level may for example imply the consideration of environmental burdens from all the processes that are needed to form the ash, including the products that become waste and the combustion process. A large amount of information would need to be processed to make such an analysis.

According to Roth & Eklund (2003), one methodology that could possibly cope with these issues is strategic environmental assessment (SEA). An SEA can be seen as a comprehensive process of evaluation of the environmental impact from a policy, plan or programme. Another approach may be to evaluate the conservation of material quality on the basis of thermodynamics. Brown & Buranakarn (2003) use the concept of emergy to evaluate the environmental impact from using different construction materials. One of their conclusions is that investments in recycling materials yield very positive returns to society compared with landfill alternatives. Emergy is defined as the amount of energy of one form that is required, directly or indirectly, to provide a product or service. This might be a comprehensive way to include and aggregate the large amount of information that would result from including all the chain of processes making up a certain waste product.

Information demand and supply for decision situations

A large amount of information on the environmental aspects associated with the use of MSWI bottom ash or other waste materials in constructions has been gained through previous scientific work. Roth & Eklund (2003) conclude that the outcomes from an assessment at one level could differ from the others and that a question addressed at one level could not always be discussed on other levels. They also claim that pollution aspects are best studied on the first or second system level, while a higher system level is needed to include resource aspects. Furthermore, these authors argue that using wider system boundaries would improve the basis for decision-making.

From this literature review the same conclusions can be drawn regarding the differences in outcome on different system levels. While the material level contributed knowledge on the chemical properties of the material, the surrounding level was needed to answer questions on the risk of emissions during the use of the material in a construction. The LCA level was needed in order to obtain results on different types of environmental impacts, not only leaching, from using the material in a construction. This means that different system levels could be appropriate for different decision situations. A combination of results from different system levels, obtained with the tools specific for these levels, may probably be necessary in several cases. By quantifying resource use and emissions, the LCA level takes one step further towards the possibility of measuring a system's sustainability as described by (Robert et al. 2002). However, according to these authors, social aspects, such as the present and future needs of all the people on whom we have an impact, also need to be taken into account in a sustainability assessment.

Of all the scientific papers found that were concerned with the environmental aspects of using MSWI bottom ash in constructions, most were done on the material level (Table 4). Very few studies were made on the two highest levels. It was also found that studies made on a high system level were dependent on, and referred to, results from the levels below (Fig. 8). Without any studies on the material level, there would be no data input for risk assessment and the results from risk assessments are needed on the LCA level. There are few results reported from such risk assessments, which may cause a problem. There are also still relatively unexplored areas on the material level and on the construction's environment level that need to be further investigated in order to improve the leaching parameters in LCA level studies. For example, the mechanisms controlling trace metal leaching from weathered bottom ash in field applications, such as the role of organic complexation of Cu, remain uncertain. Furthermore, leaching needs to be assessed not only for the use stage of the construction's life cycle but also for the construction and the demolition stages.

Table 4. Results from literature review of scientific papers concerned with environmental aspects of using MSWI bottom ash in constructions.

Level	Information gained	Type of impact considered	Number of studies found
Material	Material chemical properties, results and method suggestions	Content and leaching, mainly of inorganic substances	40-50
Construction environment	Risk for emissions during the use of the material in a construction, results and method suggestions	Leaching during the use of the construction, mainly of inorganic substances	10-15
LCA	Different kinds of environmental impacts from using the material in a construction and where in the life cycle these occur	Resource use and emissions to air and water	1-2
Industrial system	-	-	0

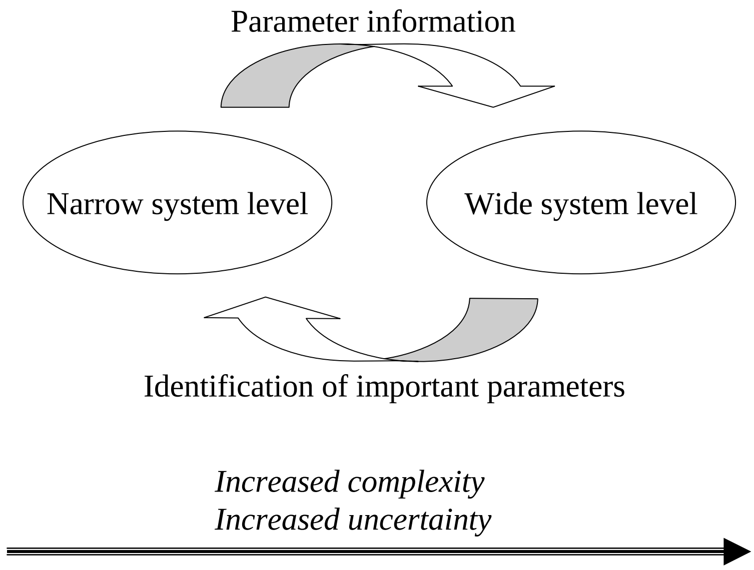

Figure 8. Information from a narrow system level, i.e. the material level, is needed in studies on wider system levels, i.e. in life cycle analyses. The information obtained on the wider system level can then be used to identify important parameters for further investigations.

However, a flow of information in the opposite direction would probably also be beneficial. Without studies made on a high system level, there would be no knowledge of the particular parameters that are of importance for studies on lower levels. In such cases, there is a risk that resources are spent only on investigating parameters that are easily determined, or have a high public interest (Wrisberg et al. 2002). Generally, a higher system level has been found to be associated with more complexity and uncertainty, and the results seem to be more difficult to communicate. However, such a broad view may produce more relevant results, depending on the question. A choice has therefore to be made between relevance and precision. More effort needs to be devoted to the LCA-level and the industrial system level in order to investigate the relative importance of different types of environmental impacts from MSWI bottom ash utilisation and where in the life cycle these would occur. For comparisons between different construction materials, information is needed on all types of potential environmental impact that may be expected for each alternative. Such information would decrease the risk of non-optimal decisions.

Today, there is a gap between the societal environmental ambitions of reuse and how reuse in general is environmentally assessed. The view of leaching as the most important parameter commonly found without any explanation or criteria for this prioritisation may be the result of a lack of studies on high system levels. It may also be a result of the decision process, favouring such a choice in one way or another, or the policies and regulations for the utilisation of waste material. Several studies on the second system level aimed to cover the environmental impacts from utilisation of waste material in constructions, but in the end they only covered the leaching parameter during the use of the construction. A frequent explanation was that leaching was considered to be the most important factor limiting the potential use of the material due to national regulations and policies. However, the fact that this parameter seems to be the most important environmental parameter in regulations does not necessarily make it the most important one from an environmental point of view. The decision process for the use of waste material in constructions would need to be further investigated in order to create a more relevant basis for the choice of system boundaries and thus improve the information basis for the decisions.

A life cycle perspective on the use of MSWI bottom ash in road constructions

The approach outlined described the resource use and the emissions to air and water for the two alternatives that were compared in the case study (Paper I). The aspects associated with the alternatives included the use of natural resources (crushed rock) and energy (mainly fossil fuels), emissions to air from the fossil fuel combustion and emissions to water from the road material.

It was found that the alternatives would cause different kinds of potential environmental impact; whereas the conventional alternative with only crushed rock in the road sub-base would lead to larger use of energy and natural resources, the alternative with MSWI bottom ash in the sub-base would lead to greater contaminant leaching. Since these flows of resources and emissions would occur in different stages of the road's life cycle, it is essential to include those stages if comparisons are to be made between the alternatives concerning both resource use and emissions. The exclusion of the construction stage would lead to exclusion of the aspect of natural material and energy use, while exclusion of the use and maintenance stage would lead to contaminant leaching not being considered.

The extent of the contaminant leaching of Cd, Cr and Cu was important for the comparison, according to the normalisation results. However, leaching estimates are uncertain and they depend on hydrology, leaching mechanisms and the time frame used for leaching scenarios. Different leaching assumptions may change the results. Another parameter with the potential to change the results was the assumed transport distance for the material from the extraction to the road. A sensitivity analysis showed that the alternative where crushed rock was used in the sub-base would use more energy than the alternative with MSWI bottom ash in the sub-base only as long as the transportation distance for MSWI bottom ash was less than 140 km (all other parameters remaining the same).

The magnitude of each flow (energy, material or emission) in the case study depended on the specific assumptions made and should therefore be interpreted carefully. However, the time frame used for leaching estimates and the assumed transport distance were the only parameters with the potential to change the major results. Changes in other parameters would not be able to affect the relative importance of the flows and their location in the life cycle stages for the alternatives in the case study.

Speciation of Copper

The fractionation of MSWI bottom ash leachate showed that it contained a large proportion of hydrophilic components, 75%, of which the major proportion were hydrophilic acids (Fig. 9). Simplified fractionations of the soil leachates showed that these contained a much smaller proportion of hydrophilic components, only around 30-40%, and a full fractionation of a soil leachate from the same location as S1 and S2, performed by Fröberg et al. (2003), showed that the hydrophilic acids comprised around 30% of the DOC. These results are in agreement with previous research. Generally the DOC in natural waters has been shown to consist of around 20% hydrophilic acids (Leenheer & Huffman 1976, Malcolm & MacCarthy 1992, Martin-Mousset et al. 1997) while for MSWI bottom ash, the hydrophilic components have been shown to make up more than 80% of the total DOC (van Zomeren & Comans 2004).

The Cu-ISE gave consistent results between different measurements in all subsamples of the MSWI bottom ash leachate and the soil leachate. For the MSWI bottom ash leachate, however, the high amount of chloride was found to affect the result at pH values below 5. This interference has been found and explained in previous studies (Westall et al. 1979, Rivera-Duarte & Zirino 2004). For all subsamples of the MSWI bottom ash leachate and the soil leachate the titration results showed a decreasing Cu^{2+} activity with an increasing pH (Paper II). These results could not be explained by complexation with inorganic ligands or with low-molecular weight organic acids (LMWOA) alone and all solutions were undersaturated with respect to $Cu(OH)_2$. The decrease in Cu^{2+} activity was therefore interpreted as an increase in Cu-DOC complex formation.

One important finding was that removal of the fulvic acids (which are generally considered to constitute the metal binding fraction of DOC) had little effect on the Cu binding. This was found both for the MSWI bottom ash leachate and for the soil leachate. Hence, the hydrophilic component of DOC in these leachates appears to possess metal binding properties fairly similar to fulvic acids. This effect is important to consider when predicting Cu speciation in the MSWI bottom ash leachate, in which the hydrophilic acids constitute the major part of the DOC.

When the SHM and NICA-Donnan models were applied to the results, it was found that neither of the models could capture the pH dependence of the Cu^{2+} activity in the MSWI bottom ash leachate correctly. The agreement between predicted and obtained values was improved by assuming a lower amount of active DOC, but the pH dependence for Cu complexation obtained was still lower than expected from the modelling results. This suggests that the Cu complexation properties of the ash leachate DOC may not be strictly comparable to that of natural DOC. For the soil leachate, on the other hand, the model predictions of Cu speciation were in good agreement with the titration results. The best agreement was obtained when the SHM model was applied and when 65-100% of the DOC was assumed to be acting as active fulvic acids.

DISCUSSION

System levels used in this thesis

Environmental assessments of the use of MSWI bottom ash in constructions can be made on several different system levels, as shown in the literature review. While studies using narrow system boundaries lead to detailed information about well-defined issues, wide system boundaries provide information about larger systems. In this thesis, two perspectives were used. First, the LCA level was used to describe the resource use and emis-

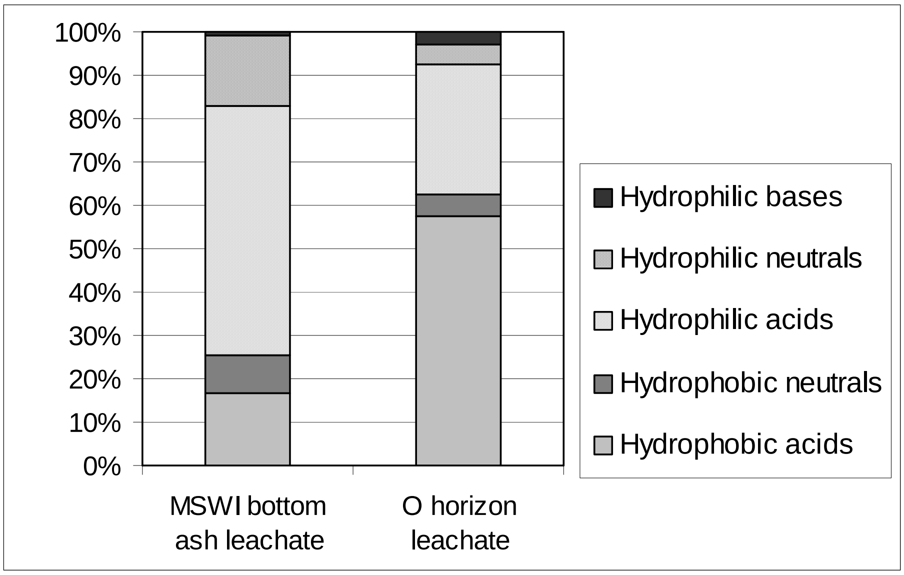

Figure 9. DOC fractions in leachate (L/S 5, native pH) from >6months old MSWI bottom ash sample and data from Fröberg et al. (2003) on DOC fractions in soil leachate from an O-horizon in a Haplic Podzol.

sions from two alternative scenarios and to identify the most important aspects and parameters. The reason for choosing such a broad perspective was to include aspects that have so far been neglected and thereby improve the basis for decisions concerning the management of MSWI bottom ash. It was assumed that a life cycle perspective was needed in order to include resource use as well as emissions to air and water, something which was confirmed by the fact that these flows were found to occur at different life cycle stages.

Leaching turned out to be the dominant aspects for the environmental performance of the system and, in particular, Cu leaching was shown to be large. This metal has been commonly included in previous studies, possibly since it was considered as important by those authors too. A large amount of Cu in the leachate, however, may not pose an environmental threat if the Cu is strongly bound to DOC. In order to decrease the uncertainties regarding the potential environmental impact from MSWI bottom ash utilisation, the effects of DOC from MSWI bottom ash on the leaching and toxicity of Cu from the ash were chosen as the focus for the second study. This study was made with narrow system boundaries, not including the construction and its surroundings but only the material itself.

Applicability and interpretation of results on the LCA level

Utilisation of bottom ash in road construction solves both the problem of waste management and the problem of natural resource extraction. There are two main sectors involved, the construction companies that need material and the energy producers that produce the ash. However, a third important actor is the national authorities whose goal is to ensure long-term sustainability. If both recycling of resources and emission aspects are to be considered, the scope goes beyond the individual companies and the changes require the engagement of governmental stakeholders. In that context the results from studies on the LCA-level could be used to incorporate different aspects in a comparison of alternatives and thus decrease the risk for suboptimisations. The LCA-based ESA approach outlined in this thesis may be used as an example and may also be further developed to solve other types of questions regarding the environmental performance of waste material in constructions.

The results from the approach outlined revealed that there are advantages and disadvantages with both the scenarios studied. A decision maker will need to weigh the potential local toxicity impact on human health and ecology against the resource use and the more global impact potentially arising from energy use. Since no alternative was free from potential negative environmental impacts, there is no easy decision for which alternative to choose. Different weighting methods have been developed within the LCA framework to help in such trade-off situations (Nordiska ministerrådet 1995, ISO 1997) (Table 5). In these methods, a one-dimensional value for the resource use and emissions is set, so that the system's total environmental impact can be calculated. The flows of resources and emissions may for example be weighted based on economics (as in the EPS method), on politically or scientifically determined targets (as in the ECO-scarcity method), or by experts or expert groups. The latter method has been used in an LCA of road constructions by Mroueh et al. (2000). Erlandsson (2002) suggests a method in which environmental impact categories are compared to an acceptable environmental load per person. This acceptable environmental load is calculated from the Swedish environmental objectives (Gov. Bill 1998, Gov. Bill 2001) and the evaluation may therefore be seen as based on 'distance to target', similar to the ECO-scarcity method.

Instead of using weighting methods, the relative importance of the different flows of resources and emissions can also be demonstrated by relating them to a common basis (normalisation). The flows may for example be divided with data on national anthropogenic resource use and emissions (Kärrman & Jönsson 2001), or related to what occurs 'naturally', i.e. the release of metals by weathering (Bergbäck et al. 1994). In this thesis, weighting was not used. It was considered to aggregate information to an unnecessary high degree and to decrease the transparency of the study. Instead, the results on the different flows were normalised by division with the national flow of each kind per person in Sweden.

Possibilities for improvement of environmental assessments

The outlined ESA approach proved to be useful in integrating resource use and emissions in the comparison of two alternative scenarios, but some limitations were identified. It could not, for example, answer the question whether MSW should be incinerated at all. To answer this, the system boundaries would have to expand to include further dimensions of the society, such as alternative energy production and the effects of waste recycling. An LCA approach has previously been applied to other parts of the waste management system in Sweden and the simulation model ORWARE (Organic Waste Research) has been constructed in order to study the management of organic waste in urban areas (Sonesson et al. 1997, Björklund et al. 1999, Finnveden et al. 2005). Integrating those results with the results on the use of MSWI bottom ash would lead the research on the beneficial use of MSWI bottom ash towards the industrial system level. Before doing this, the LCA perspective used in this thesis would need to be slightly different; the focus would have to be changed from the road construction to the management of a certain amount of waste. The results could contribute to the environmental assessment of the waste management system and reuse of by-products in a wide sense.

Furthermore, the outlined approach could not consider the site- and time-specific effects of contaminant release. This has also been evident in previous LCA-studies of landfills, in which leaching is an important aspect (Finnveden et al. 1995). Concerning this problem, a study using more narrow system boundaries would be appropriate as a complement to the LCA results. Several studies have been made on methods or frameworks for studying the leaching from a road to its surroundings and to define proper acceptance levels for different substances. Commonly, these include the use of geochemical modelling, field verification and toxicity estimations. There are, however, few scientifically reported results. There were also uncertainties found concerning some of the

Table 5. Examples of methods for determining the relative importance of different flows or impact categories.

Method	**Procedure**	**Basis for evaluation**
Panel or expert groups	Different flows or the environmental impact categories are weighted by a panel on an individual or a group level.	Depend on the members
EPS	Flows are weighted based on their impact on five objects through the willingness to pay for not degrading these objects.	Willingness to pay
ECO-scarcity	Flows are weighted based on the difference between the actual amount and a critical limit.	Distance to target
Method developed by Erlandsson (2002)	Environmental impact categories are normalised based on 'distance to target' for reaching the Swedish environmental objectives.	The Swedish environmental objectives

leaching parameters. One example is the Cu speciation in MSWI bottom ash leachate, on which information is needed in order to predict Cu release and to estimate its toxicity in the leachate.

The information gained in this thesis of Cu-speciation in MSWI bottom ash leachate (Paper II) may be seen as one step towards better leaching and toxicity estimates. The results confirmed previous knowledge that Cu in MSWI bottom ash leachate is to a large extent bound to DOC, which implies that only a minor part of the Cu in the leachate is bioavailable. This is an important issue not only in risk assessments, but also when aggregating and interpreting the results of studies on an LCA level. In the United States, the quality criteria recommendations for Cu in water, formulated by the Environmental Protection Agency (EPA), are being updated to include the fact that not all of the Cu in the water contributes directly to toxicity (United States Environmental Protection Agency 2003). The biotic ligand model (BLM), which is a recently developed metal bioavailability model (Di Toro et al. 2001), is used for developing these new criteria. In Sweden, however, water quality criteria for Cu pollution are still usually based on the total Cu concentration (i.e. Naturvårdsverket 1999).

It was also found that not only the fulvic acids, as previously believed, take part in the complex formation, but also that the hydrophilic fraction seems to be important. Furthermore, the results suggest that the Cu complexation properties of the ash leachate DOC may not be strictly comparable to those of natural DOC. This needs to be considered when using geochemical modelling to predict Cu-DOC complex formation. However, in order to optimise parameters for geochemical speciation modelling of MSWI bottom ash DOC, more detailed information is needed on the composition of the DOC and its ability to complex Cu under different conditions.

Besides the complementary use of other methods to consider time- and site-specific effects, it should be possible to increase the certainty of the leaching estimations used as input values in an LCA approach. This should include the use of risk assessment, since the environmental impact from the metal leaching is probably dependent on concentrations on certain occasions, rather than average concentration during a long time period. For example, the risk for cracks in the road's surface and the risk for flooding or reduced drainage conditions of the sub-base needs to be considered.

CONCLUSIONS

- An environmental systems analysis with a life cycle perspective gives information about waste management that cannot be gained through assessments of leaching only.
- A life cycle perspective is needed to include both resource use and emissions to air and water when comparing different road construction materials.
- In the case studied, the use of crushed rock in a road sub-base would lead to larger use of energy and natural resources, whereas the use of MSWI bottom ash would lead to larger contaminant leaching.
- For the utilisation of MSWI bottom ash in road constructions, the leaching predictions of contaminants, together with the transport distance, are the most important parameters for the overall environmental impact.
- Toxicity estimates of MSWI bottom ash leachate and the definition of acceptance levels for contaminant release should consider the fact that Cu is to a large extent bound to DOC, which reduces its toxicity.
- The pH-dependence for Cu complexation to MSWI bottom ash DOC is smaller than for natural DOC, implying that models calibrated for natural DOC may give inconsistent simulations of Cu-DOC complexation in MSWI bottom ash leachate.
- The hydrophilic fraction of the MSWI bottom ash DOC is important for Cu complexation.

FURTHER RESEARCH

In order to further decrease the uncertainties on the potential environmental impact from MSWI bottom ash utilisation, there are still several issues for future research in environmental assessments on the different system levels. For example, the processes that dominate in controlling leaching of trace metals from weathered bottom ash are not yet fully understood, and parameters for geochemical speciation modelling need to be optimised and validated. Methods for contaminant release predictions in the field and the definition of acceptance criteria need to be adjusted for different Swedish conditions and verified in field experiments. Furthermore, the LCA-approach should be developed to include more types of materials or applications and the system boundaries used may be expanded. However, even if improved, no single assessment method can probably obtain all types of information needed. The big challenge for the future will therefore be to integrate the information gained on different system levels in order to create a relevant and reliable basis for decisions on how we should manage MSWI bottom ash.

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