How Heavy Metal Concentration in Bottom Ash Effects its Future Disposal & Utilisation

Abdul Samad Khan

S1936574

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Dr Robert Muir

School of Computing, Engineering and Built Environment, Glasgow Caledonian University, Glasgow, UK

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Abstract

Historically speaking, the concept of energy recovery from burning waste is new, as prior to this waste was initially mass burnt with no energy recovery. Unfortunately, this would lead to a lot of emissions and air pollution for no justifiable reason. When burning waste, it does not all convert to energy and some of the burnt waste produces ash residue such as bottom ash. Throughout the whole world, each country has their own respective position on the appropriate handling of bottom ash. This debate revolves around whether or not bottom ash is considered to be recycling or waste material which would indicate whether it would be better suited to be utilised for construction purposes or to be disposed into landfill. A big factor in this choice is the level of heavy metal contamination that is in the bottom ash sample. In this report, the effects of heavy metal concentration and leachate in bottom ash on utilisation and disposal is studied. The purpose is to showcase to what extent do laws in Britain regarding heavy metal concentration/leachate have on bottom ash utilisation/disposal. It is also to demonstrate the correct procedure to determine whether a sample of bottom ash has hazardous levels of heavy metal concentration/leachate. This was done by taking bottom ash samples from several different waste to energy plants throughout Scotland to analyse their data with use of appropriate documentation. These waste to energy plants varied in their operations from using incineration to gasification technology. There was a good variation between the results indicating which samples were suitable for utilisation/disposal and which were not. Recommendations were made to each plant on what was the most suitable steps they should take; for instance, for facilities that had samples too hazardous, the recommended steps were to investigate factors effecting heavy metal concentration and investigates leaching remediation. The three main factors that affect heavy metal concentration is waste input, combustion process and condition of facility. To prevent future samples being too hazardous these are the factors that facilities should investigate. The importance of these guidelines is imperative to keep the wider society safe from the potential harm that hazardous bottom ash can cause. The real struggle going forward would be the balancing act of providing suitable bottom ash that can be utilised, that is not heavily contaminated with a hazardous level of heavy metal.

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Glossary

Combustion: The act of oxidation accompanied by heat or light (Definition of combustion, 2016)

Municipal Solid Waste: Household waste and waste similar in nature and composition to household waste (European Commission, 2017)

Permeability: the property of a magnetizable substance that determines the degree in which it modifies the magnetic flux in the region occupied by it in a magnetic field (Permeable, n.d.)

Aggregate: Material that is used to mix with cement, sand, water and other materials to make concrete (Aggregate, 2018)

Modulus of Elasticity: the ratio of the stress in a body to the corresponding strain (modulus of elasticity, n.d.)

Flexural Strength: The amount of stress and force an unreinforced concrete slab, beam or other structure can withstand such that it resists any bending failures. (What is a Flexural Strength?, 2018)

Physiochemical: Relating to the physical and chemical conditions (Physicochemical, n.d.).

Plasma: "an electrically conducting medium in which there are roughly equal numbers of positively and negatively charged particles, produced when the atoms in a gas become ionized. It is sometimes referred to as the fourth state of matter, distinct from the solid, liquid, and gaseous states" (Plasma, 2019)

Electromagnetic Radiation: "Electromagnetic radiation is energy that is transmitted at the speed of light through oscillating electric and magnetic fields." (Mirhadi MD, 2010)

Abbreviations

WTE= Waste to Energy
SEPA= Scottish Environment Protection Agency
IBA= Incinerator Bottom Ash
IBAA= Incinerator Bottom Ash Aggregate
EU= European Union
ESA= Environmental Service Association
EWC= European Waste Catalogue
MSW= Municipal Solid Waste
MSWI = Municipal Solid Waste Incineration
NORD= National Organization for Rare Disorders
WAC= Waste Acceptance Criteria
TCLP= Toxicity Characteristic Leaching Procedure
EP= Extraction Procedure
ASTM= American Society for Testing & Material
MCA= Modified Complex Agent
EDTA= Ethylenediaminetetraacetic Acid
ICP-OES= Inductively Coupled Plasma Optical Emission Spectroscopy
MRF= Material Recovery Facility
SRF= Solid Recovery Fuel
RDF= Refused Derived Fuel
BTEX= Benzene, Toluene, Ethylene and Xylene
APC= Air Pollution Control

1.0 Introduction

1.1 Background

As the production of greenhouse emissions such as carbon dioxide and methane increase so does the global temperature. Indicating that global warming is a serious threat and that there is a need to look into greener alternatives in the way we live our lives, especially regarding construction practices. This is evident in the fact the construction sector is reported to be responsible for 39% of all global carbon emission (IEA, 2019.). The uses regarding bottom ash can be divided into either utilisation for construction purposes or be disposed into landfill. There are laws that already exist in order to ensure that the bottom ash being used for these purposes have a safe level of heavy metal concentration. The specific relationship between heavy metal contamination in bottom ash and the laws that are set up to ensure safe utilisation and landfill disposal will be the key point of investigation in this report. Figure 1.1 displays an example of bottom ash photographed

Figure 1.1: Bottom ash (Mauriya, 2019)

Bottom ash is a form of ash residue that is produced from a waste to energy (WTE) plant. As displayed in figure 1.2, there are many different types of ash residue that forms in different areas of operation. In particular incineration bottom ash (IBA) is passed through the grate and just below the combustion unit.

WTE plants typically incinerate/mass burn waste in order to distribute energy for an allocated area. Through the means of incineration and mass burning, some of the waste is not converted into energy and instead forms ash residue as displayed in figure 1.2. They are different forms of WTE technology that are available; incineration, gasification and pyrolysis. All of these types of WTE plants differ regarding their combustion process: incineration relies on fully oxidised combustion whereas gasification and pyrolysis rely on either half or non-oxidised combustion. The other major difference regarding these forms of technology is the bottom ash production, as incineration is reported to produce the most amount of bottom ash and typically the least clean out of all of these forms of technology (Syngas Applications, 2019.).

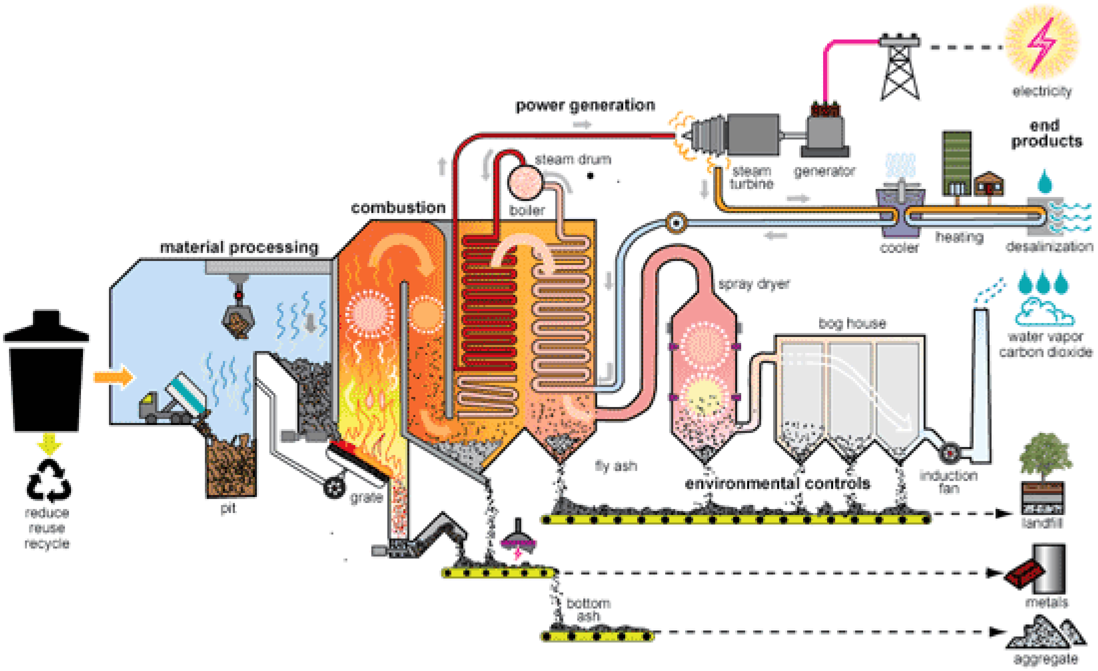


Figure 1.2: Waste to energy diagram (Waste-to-energy (MSW) in depth, 2020)

The need for WTE facilities originated from many issues that have existed for a long time. Historically speaking, prior to WTE recovery, waste was typically just mass burnt with no energy recovery. This would entail that any form of waste would have gone through this process, leading to many different types of greenhouse gas (GHG) emissions being released into the atmosphere. It would also entail that the waste that goes through this process and does not burn would form ash that would be transported to landfill. This process was the norm in Europe throughout the late 1800s, till EU legislation was made to outlaw this form of waste treatment. Initially, two pieces of EU legislation were made to tackle this form of waste treatment, which were the Hazardous Waste Directive 94/67/EC and Council Directive 89/369/EEC. Subsequent modifications were made however, which lead to the Waste Incineration Directive on the 24th December 2000. This further prompted the use of WTE recovery and outlawed the use of burning waste with no recovery (Ec.europa, 2019). The increased application of WTE recovery can also be further attributed to the EU legislation that were passed in regards to landfill. For instance, The Landfill Directive (1999/31/EC) sets out a standard and precedent of waste that can enter landfills (Landfill waste, 2019), which would prompt more waste being diverted from landfill and being sent to WTE plants. It would also set a standard that would need to be followed in order to prevent disposing bottom ash that contains hazardous levels of heavy metal leachate.

WTE plants typically need municipal solid waste as an input for the energy production of homes. It is reported that in Britain the total waste production in households is estimated to be 26,411,000 tonnes with a recycling rate of at least 45 % (UK Statistic on Waste, 2020). However, in the context of this report, it is reported that in Scotland the recorded generated amount of waste in households is 2,292,000 tonnes with a recycling rate of 42.8 % (UK Statistic on Waste, 2020). There are many different options for wastes which are all highlighted in the EU waste hierarchy, which is demonstrated in figure 1.3. The process of WTE conversion would fall under the category of recovery meaning it serves a very important purpose in diverting waste from landfill. The point is solidified by the fact that in 2018, the amount of waste sent to landfill in Scotland saw a reduction of 2.2% and decreased by 84,876 tonnes (SEPA, 2019). It is safe to assume that the increased amount of waste sent to recovery would have definitely played a pivotal role in the reduction of the amount of waste sent to landfill. Moreover, in this waste hierarchy, the utilisation of bottom ash is a main priority as it comes under the recycling layer. Making sure that the handling of bottom ash is safe from an environmental and an engineering perspective is imperative to ensure that it can be safely utilised. If this option is not available then disposal into landfill must take place, as per the hierarchy demonstrated in figure 1.3. However, before disposing into landfill, the bottom ash will also need to be examined to make sure its leachate content is not exceeding any hazardous thresholds.

Figure 1.3: Waste Hierarchy (Directive 2008/98/EC on waste (Waste Framework Directive), 2019)

The types of hazards that the utilisation of bottom ash would entail is irritation, corrosion, ecotoxicity and carcinogenicity. For bottom ash to be utilised it must *not* exceed the legal threshold for the aforementioned categories of hazards. The steps that are taken to test if it exceeds this legal threshold is laid out in the literature review later in this report. Regarding landfill disposal it is imperative to make sure the heavy metal leachate is not exceeding hazardous thresholds. It is also important to acknowledge that the definition of leaching is when a chemical or mineral drain away from soil or ash through the action of a percolating liquid.

1.2 Structure of Thesis

Following this section will be a discussion covering the available literature on this topic. The purpose is to go over what has already been covered and express how this current thesis can build upon the overall body of literature. Following that will be the methodology used for this report. This will cover the facilities that have sent their data to be analysed for the purposes of this thesis and the methods/equipment they used to measure their data. Following this will be both the results and discussion. The purposes of the discussion will be to comprehend the complex nature of the results in an easy to understand manner for the reader as well to make clear recommendations to each WTE plant regarding their bottom ash handling practices. The conclusion at the end will summarise everything to the reader as well as explain how the findings of this report answers the initial question that was posed.

1.3 Aims & Objectives

Moreover, the aim of this paper is to tackle the question of “To what extent does heavy metal concentration affect bottom ash utilisation/disposal and what can be done to lower these hazards?”. Furthermore, the recommendations given in this report, aims to demonstrate the different options available to lower the hazardous affects that can occur from utilising/disposing bottom ash with high heavy metal concentration. Altogether, the following will hopefully provide further functional information to utilise/dispose bottom ash efficiently and thus lower carbon emissions that would occur from conventual concrete production and lower harmful landfill leachate.

2.0 Literature Review

2.1 Introduction

This report is to compliment the bottom ash analysis data that is included in the later sections, however, before understanding the data of the bottom ash and the proceeding analysis, it is imperative to have an understanding of the body of literature that is available on this topic. The purpose of this section is, thus, to convey the essential information that is associated with this topic to the uninformed reader. This will relate to such topics as: different international views on bottom ash, heavy metal toxicity, official guidelines, leaching, WTE equipment/technology, metal recovery, utilisation purposes, pretreament methods/inputs, ash residue and finally new research within this topic. The reader will then hopefully be well read and prepared to comprehend the extensive data and analysis in the proceeding sections of this report.

2.2 International view on IBA

Throughout the world there has been a significant debate on IBA; in particular, whether it is considered a recyclate or a waste. This distinction is imperative due to the implications it can have on laws regarding recycling and waste, itself. This view varies all around the world, which leads to IBA being treated and utilised very differently from country to country. For instance, SEPA have issued their own position statement in regards to this debate. Their stance is that incinerator bottom ash aggregate (IBAA) should be considered as a waste, however, under a series of conditions, the utilisation of it would not require a waste management license or an exemption in construction (SEPA Position Statement: Use Of Incinerator Bottom Ash Aggregate, 2018). The series of conditions are as such:

2.2.1 SEPA's Position Statement

- “The IBAA may only be used in the following applications; sub-base or general fill in roads or construction platforms where the IBAA is covered with a low permeability surface or buildings.”
- “The IBAA must only be manufactured from non-hazardous IBA. Classification is determined using a combination of “Guidance on the classification and assessment of waste – WM3”1 and the “ESA Sampling and Testing Protocol to assess the status of incinerator bottom ash”
- “The IBAA must be manufactured in accordance with the relevant aggregates standards and specifications.”

- “The total area of IBAA placement in any single project must be less than 5000m2 with an average thickness of less than 1m.”
- “The IBAA must not be placed directly into groundwater or within 1m of the water table”
- “The IBAA must not be stored or used within 50 metres of surface water”
- “The IBAA must not be stored at the place of final use for longer than 6 months.”
- “Suppliers and users of IBAA must keep records of the following information and make them available for inspection by SEPA on request; Name and location of the project to which IBAA has been supplied, Date of supply, Quantity of IBAA supplied “
- “Suppliers must provide to each user a statement that the material meets the relevant standard for an end use specified in this position statement and has been supplied only for that use”
- “Where IBAA is identified as part of excavations, it is be stored and managed separately from other excavation wastes. Any further use must either be in accordance with this position statement or in accordance with waste management licencing legislation.”

(SEPA Position Statement: Use of Incinerator Bottom Ash Aggregate, 2018)

It should also be noted that SEPA has acknowledged that there are some further amendments and work required for these conditions, such as exploring the possibility of improving upon the washing process, to observe whether that improves upon the environmental performance of granular unbounded IBAA or blending unbounded IBAA with primary aggregate or the use of IBAA in bound applications. In spite of this, the initial conditions stated in SEPA’s Position Statement has been put into place due to the fact that IBAA is reported to underperform when compared to other forms of aggregate, so, therefore, its weak performance will limit its use when compared to other forms of aggregate (Abdullah et al., 2019).

2.2.2 England’s View

However, it should be noted that, as of December 2017, ferrous metal that is extracted from IBA – IBA metal - is now considered to be recycling material in England (UK GOV: Statistics on waste managed by local authorities in England in 2018/19, 2019). This change towards the classification of IBA metal has been applied to the “waste from household” perspective. Due to the inconsistent tracking of recycling materials, this change was only able to be tracked back to April of 2015. Furthermore, this change has led to the recycling rate increasing by 0.7% in the year 2016 (equivalent to 143,000 tonnes) and 0.4% in the year 2015 (equivalent to 97,000 tonnes) (UK GOV: Statistics on waste managed by local authorities in England in 2018/19, 2019). Moreover, it is worth noting that the 2015 figure is an underestimate because months January to March were not recorded and therefore were not included in the overall count for that year. Despite that, the fact that recovered heavy metal is considered to be a recyclate is especially significant, as it is reported that there is a growing market for these recovered metals (Kahle et al., 2015).

2.2.3 Germany's View

Germany has also been extensively covered in this study, as their position on the matter is of significant concern in the context of this debate. The aforementioned countries have either taken a stand that IBA can be considered as waste or a recycling material or somewhere in between with a nuanced position on this topic. However, Germany have fully accepted IBA as a recycling material. Due to this stance, it has very much been reflected on its laws in regards to this topic. The "Kreislaufwirtschafts und Abfallgesetz" - which translates to "recycling economy waste act" - law came into fruition in 1996, with the purpose to enhance the recycling rate of IBA and to preserve natural resources.

Another law in Germany that goes by the name of "Bundes-Immissionschutz-Gesetz" - which translates to "Federal Emission Control Act" - which came into force in 1990, was set up to protect the environment. This was done by stating that if IBA is utilised then it must be compliant by regional standards and its environmental affects must be disclosed. This is referring to the heavy metal content in bottom ash that are hazardous to the surrounding environment. Due to this reason, the regional laws and standards restrict IBA in construction to only well-defined road construction purposes. The criteria to implement IBA in construction is as follows:

- "Composition; the content of mineral matter, inert fractions (glass and ceramics), metals and organic matter of the bottom ash has to be within a specified range".
- "Stability of volume; the volume of the bottom ash has to be nearly constant to ensure, that technical buildings do not suffer any damage after the completion of the building."
- Resistance against frost; the bottom ash has to maintain its physical abilities at temperatures well below 0°C."
- "Resistance against sudden impacts; the bottom ash has to withstand high load impacts and shall not suffer in structure."

- “Resistance against sudden impacts; the bottom ash has to withstand high load impacts and shall not suffer in structure”
- “Distribution of grain size; the size of the mineral grain has to be within a certain range to ensure, that the physical properties of the material are stable”
- “Shape of the grain; the surface structure of the grain is important for the physical properties of the mineral material”.
- “Defined density to which the bottom ash can be compressed during construction (Proctor density)”
- “Characteristics of the material to interact with water; the bottom ash has to be stable against water penetration. The leaching of harmful substances has to be reduced to a minimum”.

(Crillesen, Skaarup and Bojsen, 2006)

2.2.4 Holland’s View

According to Crillesen, Skaarup and Bojsen (2006) the Netherlands is also a country that heavily regulates the use of IBA. For instance, a lot of regulations have been put in place to make sure that bottom and fly ash are handled differently and to make sure that there is close to a 100 percent utilisation rate on ash that forms. The hazard levels of IBA is determined on an individual basis through the European Waste Catalogue (EWC). The EWC determines if IBA is too hazardous through the number of organics found in the IBA that is being implemented. There are also numerous amounts of legislation regarding IBA being utilised, with the purpose to protect the environment from the hazardous content of it (such as heavy metal). The waste sector in the Netherlands has also developed a standard and criteria of quality checking IBA that is being utilised, which is displayed in table 2.1:

<table>
<tr><th>Component</th><th>Category 1 mg/kg</th><th>Category 2 mg/kg</th><th>Special Category MSWI bottom ashes</th></tr>
<tr><td>As</td><td>0.83</td><td colspan="2">7.0</td></tr>
<tr><td>Ba</td><td>6</td><td colspan="2">155</td></tr>
<tr><td>Cd</td><td>0.022</td><td colspan="2">0.061</td></tr>
<tr><td>Co</td><td>0.23</td><td colspan="2">2.3</td></tr>
<tr><td>Cr</td><td>0.35</td><td colspan="2">12</td></tr>
<tr><td>Cu</td><td>0.32</td><td>3.3</td><td>23</td></tr>
<tr><td>Hg</td><td>0.017</td><td colspan="2">0.075</td></tr>
<tr><td>Mo</td><td>0.51</td><td>2.5</td><td>23</td></tr>
<tr><td>Ni</td><td>0.7</td><td colspan="2">3.5</td></tr>
<tr><td>Pb</td><td>0.97</td><td colspan="2">8.2</td></tr>
<tr><td>Sb</td><td>0.09</td><td>1.2</td><td>2</td></tr>
<tr><td>Se</td><td>0.09</td><td colspan="2">0.27</td></tr>
<tr><td>Sn</td><td>0.08</td><td colspan="2">2.3</td></tr>
<tr><td>V</td><td>3.15</td><td colspan="2">95</td></tr>
<tr><td>Zn</td><td>2.3</td><td colspan="2">14</td></tr>
<tr><td>Br</td><td>3.4</td><td colspan="2">44</td></tr>
<tr><td>Cl</td><td>560</td><td colspan="2">8800</td></tr>
<tr><td>F</td><td>11</td><td colspan="2">228</td></tr>
<tr><td>SO_4</td><td>3300</td><td colspan="2">65000</td></tr>
</table>

Table 2.1: Netherlands bottom ash utilization standard (Crillesen, Skaarup and Bojsen, 2006)

2.2.5 Japan's View

Finally, the last country of note is Japan, due to their highly unique views on IBA overall. As a rule of thumb, IBA is considered to be waste and typically is not allowed to be reused as secondary material for the construction of roads (Tanigaki, 2015). Furthermore, there is a number of procedures that would need to take place to stabilize the bottom ash before it is sent to landfill. The following procedures are:

- Melting
- Sintering
- Cement
- Chemical (Chelate)
- Stabilization with acid or other solvent

(Tanigaki, 2015)

The aforementioned procedures are only used to stabilize bottom ash that do not satisfy the leaching values stated in table 2.2:

Japan’s Landfill Heavy Metal Leachate Standard	
Component	**mg/L**
Cadium	0.3
Lead	0.3
Cr(VI)	1.5
Arsenic	0.3
Total-Hg	0.0005
Alkyl-Hg	Not Detected
Selenium	0.3

Table 2.2: Japan’s heavy metal leachate standard for bottom ash sent to landfill (Tanigaki, 2015)

Typically, Japanese WTE plants are subsidized by the central government if they meet certain conditions in order to facilitate the environmental goals that have been set in place by the acting government. This initially started in 1996 when the requirements for WTE plants to receive subsidies was to have melting equipment installed to reduce and recycle more bottom ash. In 1998 a guidance document regarding recycling molten slag for MSW was released, which essentially built upon the principles of the 1996 requirements for a subsidy. By 2005, changes were made for the requirements for subsidies to be granted, which stated that melting equipment were no longer required. Finally, in 2014 the conditions for a subsidy were now decided on an individual basis which is based on each of the WTE plants’ capacity. All these changes accumulatively have led to 80% of all bottom ash being sent to landfill annually despite efforts being made to minimize this amount (Tanigaki, 2015).

Overall, this topic of the classification of IBA has been highly debated, with different countries coming to their own conclusions on the matter. It should be noted that the EU itself classifies waste to be “any substance or object which the holder discards or intends or is required to discard” (Waste Framework Directive, 2008). Based on this description, an argument for both IBA being either waste material or recycling material can be made, which is why this issue is typically left to countries to decide for themselves and is not decided at an EU level. The typical trends that we see is that WTE plants are incentivised economically to utilise bottom ash due to the acting government making an environmental effort to preserve natural resources, as they might be limited, as seen in countries such as Germany and Denmark. Another trend that is observable is that countries such as Japan that take a hard-line stance against classing IBA as a recycling material, in concept, will typically see a higher amount of IBA being sent to landfill. This may seem like it would be problematic, however, if the correct precautions are made to prevent high levels of heavy metals being leached into the environment before the IBA is sent to landfill then this reduces the environmental risk.

2.3 Heavy Metal Toxicity

2.3.1 Lead, Mercury, Cadmium and Chromium

Each heavy metal affects the environment and, thus human health, in their own individual way. Therefore, before analysing the IBA used for this project, it is important to cover the available literature on this topic. The EU have compiled a document that covers the harmful effects, the sources and the pathway for many relevant heavy metals such as lead, mercury, cadmium and chromium (European Commission, 2002). The harmful effects of some of these heavy metals, particularly lead, is quite concerning to the developing nerve systems in children. It is reported that in many epidemiological studies, that even a low level of exposure to a foetus and a child can lead to many different reprotoxic effects. These effects can inhibit the learning capacity and can cause damage to the child's neuropsychological development (European Commission, 2002). It is also reported that some of the harmful effects of mercury can cause inhalation issues and kidney related problems. In fact, it is also reported that occupational exposure to mercury has been linked to the development of proteinuria in workers (European Commission, 2002). Cadmium is also linked to critical kidney, lung and stomach cancer (European Commission, 2002). Chromium is also linked to irritations of cancers, thus causing them to being lethal (European Commission, 2002). Not only do these heavy metals affect humans, they also affect other aspects of the environment such as birds and mammals, microorganisms and other terrestrial organisms. Limiting the pathway source of heavy metal leaching from bottom ash disposal is crucial to limiting all these health and environmental concerns.

2.3.2 Arsenic & Barium

Other documentations such as Heavy Metal Poisoning - NORD (National Organization for Rare Disorders), 2006, have also compiled the effects on human health associated with some heavy metals. For instance, it is reported that a low-level exposure to arsenic can lead to a lot of nausea and vomiting, decreased production of red and white blood cells and can lead to abnormal rhythm of heartbeat. A long exposure of high-level arsenic can also lead to death, which is why it is important to restrict the amount that is leached from IBA. Another heavy metal that is reported on is barium, which is also commonly found in IBA samples. Regarding its short-term exposure, the affects that can be had on human health are vomiting, diarrhoea and difficulties in breathing. The risks associated with the long-term exposure are high blood pressure, paralysis and possible death.

2.3.3 Selenium

Selenium is also a heavy metal that is commonly found in IBA. In principle, a trace level is not toxic, and, in fact, it is necessary to serve a cellular function in the human body. For example, selenium is an essential nutrient for humans as it is required to play a significant role in the thyroid gland. Any level above the acceptable threshold can lead to severe issues in human health, however. For instance, short term exposure to high concentration can lead to nausea, vomiting and diarrhoea. Long term exposure to high concentration can produce selenosis, which it is worth noting that the signs of selenosis are major hair loss, nail brittleness and neurological abnormalities (Heavy Metal Poisoning - NORD (National Organization for Rare Disorders), 2006).

2.3.4 Copper & Zinc

Copper is another heavy metal that is commonly found in IBA and can potentially lead to various adverse human health conditions. Like many other heavy metals, nausea, vomiting and diarrhoea are all potential symptoms if exposed to a high concentration of it. However, intentional long-term exposure can also lead to liver and kidney damage and, in some cases, even death (Public Health Statement: Copper, 2004). Furthermore, copper at a reasonable level is harmless, like other metals such as zinc. In fact, copper is a metal that is an essential nutrient for humans. One of the main causes of deficiency in copper is an overexposure to zinc as it has been reported that this typically interferes with copper intake (Plum, Rink and Haase, 2010). Plum, Rink and Haase (2010) also detail the symptoms of excessive zinc and zinc deficiency. Excessive zinc is reported to cause focal neuronal deficits and zinc deficiency is known to cause a decrease in nerve conduction.

2.3.5 Bioaccumulation

Another concept that is covered in Ciupa, Nadgórska-Socha, Barczyk and Ciepał (2017) is bio-accumulation. This is a reference to a number of elements leaching into the environment and accumulating over a specific area, which is very significant because in IBA there are multiple heavy metals present. The concept of bio-accumulation is typically seen more in soil than in plants because soil particles don’t wash as easily. Despite this, root plants that grow near soil are still at risk of metal contamination from bio-accumulation that forms in soils. Signs of a highly contaminated plant would be changes in colouring and growth pattern. These conditions can allow for bio-accumulation to eventually take place in plants. Deficiencies in plant nutrition can also allow for metals to accumulate in plants.

2.3.4 Geochemical Software

Geochemical software can be very helpful in illustrating a pathway for heavy metal contaminants found in IBA. Papers such as Dijkstra, Sloot and Comans (2002) and Zhang, He, Shao and Li (2008) showcase the effectiveness of the use of geochemical software that predicts the leaching behaviour of heavy metals in bottom ash and, thus, it predicts path of transport. It is concluded that in both papers the most predominant factor effecting leaching is pH level. For the most part, geochemical software can be very accurate, although it is reported to overestimate the leaching in several circumstances (Dijkstra, Sloot and Comans, 2002). This overestimation can be explained by the several uncertainties in the modelling parameters as well as the insufficient description of the leaching process and pH level.

Feng et al. (2007) studied the genotoxicity effects of heavy metals leaching from bottom ash and entering the environment. The genotoxicity effects of the leachates were studied with the use of a micronucleus (MN) assay with vicia faba root tip cells. It was reported that as the heavy metal concentration increased so did the toxic effects in the Vicia faba root tip cells, implying that heavy metals are the main factor in genotoxicity effects regarding leaching. This method of testing can be very useful in determining how the bottom ash can be utilised, treated or disposed.

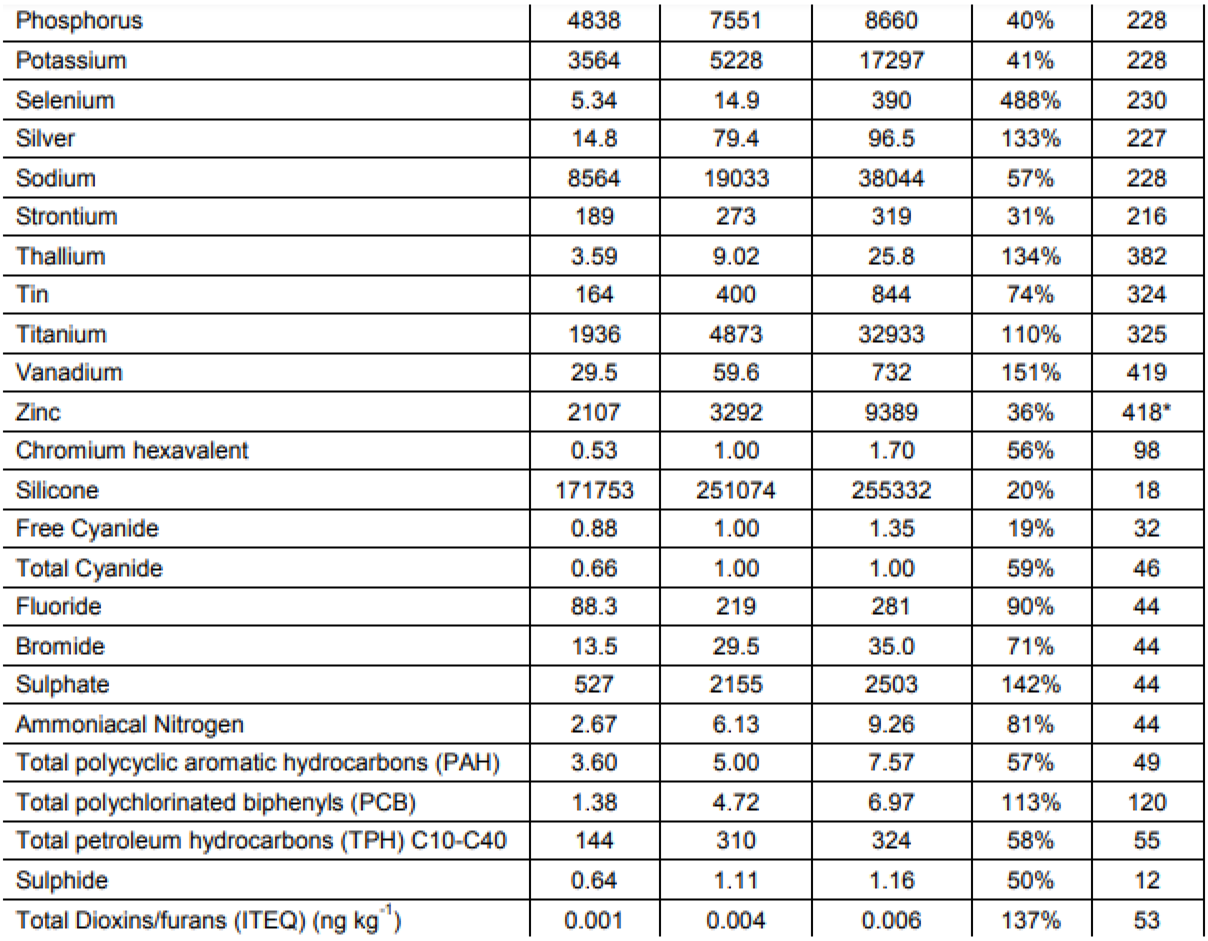
2.4 Official Guidelines

This section will cover the relevant documentation that will be used when examining the IBA data for this paper. Earlier in this section, SEPA's position statement on IBA was covered in detail. Within their position statement two other pieces of documentation were referenced, which were WM3: Waste Classification and ESA IBA guidance documents. "Waste Classification: Guidance on the classification and assessment of waste" (2018) classifies and quantifies the varying levels of different heavy metals hazard levels. This document is essential for studying the bottom ashes hazard levels from both a leaching and utilisation perspective. This document specifies the four main hazards relating to IBA utilisation; irritation, corrosion, carcinogenic and ecotoxicity. The document also lays out the threshold for heavy metal leachate regarding the different types of landfill; inert, non-reactive hazard and hazard waste. These thresholds for each individual heavy metal make up the waste acceptance criteria (WAC), which is an essential piece of guidance to consider before disposing into landfill.

Another guidance that is recommended by SEPA's position statement is the IBA guidance's documentation compiled by ESA (Environmental Service Association). The first document of note is "A Sampling and Testing Protocol To Assess The Status Of Incinerator Bottom Ash" (2018), which describes the correct procedure that should be practised when testing IBA samples, especially testing to see if they are suitable to be implemented for utilisation purposes. For instance, it is recommended by ESA that samples should approximately be between 40kg-50kg, which is a representative sample of lorry loads. The frequency of testing that is recommended is twice per month, which annually adds up to 24 test samples. To get to this testing sample, which is representative of the lorry load, 200kg of IBA composite is brought and mixed with a representative sub sample, which would generate 40-50 kg needed for the sample testing.

Lewin, Turrell, Benson and Petrolati (2012) lay out the correct procedure that should be taken to determine if the testing sample is hazardous or not. As previously mentioned, 24 samples are required to be tested to measure the content of it. Lewin et al. (2012), state that for a set of IBA samples to be considered non-hazardous, at least 90% of the samples must be within the hazardous threshold. If more than 10% of the samples exceed any of the hazardous threshold stated for each heavy metal, then the IBA tested will be considered too hazardous. To contextualise the number of samples within this scenario that equates to 10%, this comes to 2.4 samples. This means if more than 2.4 samples measured show hazardous results this would indicate that the IBA tested for this year is too hazardous. The hazard threshold for these heavy metals is determined with use of the aforementioned "Waste Classification: Guidance on the classification and assessment of waste" (2018). This method is officially recommended by SEPA, which, as a result, will be the method used for determining the hazard level in the IBA in this report. It is also worth noting that in Lewin et al. (2012), a survey was conducted of every single WTE plant situated in the UK, where they all disclosed the heavy metal content of their IBA. Table 2.3 and 2.4 displays the findings of this survey of 419 different WTE plants. This table can also serve another purpose by being compared to individual sample findings. A lot can be said for comparing the individual findings to this table, especially when one considers that Turrell, Petrolati and Lewin (2013) correlate which of the WTE plants in table 2.3 and 2.4 exceed hazard thresholds. The final piece of documentation that should be examined for IBAA is any form of standards or regulation regarding concrete aggregate. For instance, in the UK, the BS EN 1744 states specification to follow regarding chemical analysis of aggregate for concrete purposes.

Determinand	Average	95th percentile[1]	Maximum[2]	RSD%[3]	Count[4]
Concentration in mg kg^{-1} as received unless stated					
pH (-)	11.7	12.6	12.9	8%	418*
Alkali Reserve (mg NaOH $100g^{-1}$)	0.78	3.84	5.40	149%	399
Moisture Content @ 30°C (%)	16.3	25.6	34.0	39%	383
Residual moisture @ 105°C (%)	1.85	4.90	10.2	97%	186
Total carbon (%)	2.03	3.58	5.35	49%	134
Total organic carbon (%)	1.13	2.23	4.80	53%	248
Nitrogen as N	1618	2525	40783	270%	105
Aluminium	21625	39364	74775	45%	325
Antimony	67.5	135	289	55%	419
Arsenic	8.44	28.2	160	154%	410
Barium	324	594	2270	61%	325
Beryllium	1.36	2.35	5.00	48%	224
Boron	74.2	125	977	115%	323
Cadmium	11.2	30.1	72.4	91%	419
Calcium	91677	151075	164064	36%	222
Chromium	246	990	1358	124%	419
Cobalt	26.9	51.8	362	82%	419
Copper	1900	3679	17871	65%	419
Iron	25722	47953	80420	48%	228
Lead	820	1608	2296	53%	419
Lithium	17.0	47.6	51.6	61%	228
Magnesium	6980	10251	12300	31%	325
Manganese	823	1217	4597	45%	419
Mercury	2.21	11.4	65.0	223%	384
Molybdenum	8.74	21.8	104	116%	316
Nickel	135	420	1050	95%	417



Phosphorus	4838	7551	8660	40%	228
Potassium	3564	5228	17297	41%	228
Selenium	5.34	14.9	390	488%	230
Silver	14.8	79.4	96.5	133%	227
Sodium	8564	19033	38044	57%	228
Strontium	189	273	319	31%	216
Thallium	3.59	9.02	25.8	134%	382
Tin	164	400	844	74%	324
Titanium	1936	4873	32933	110%	325
Vanadium	29.5	59.6	732	151%	419
Zinc	2107	3292	9389	36%	418*
Chromium hexavalent	0.53	1.00	1.70	56%	98
Silicone	171753	251074	255332	20%	18
Free Cyanide	0.88	1.00	1.35	19%	32
Total Cyanide	0.66	1.00	1.00	59%	46
Fluoride	88.3	219	281	90%	44
Bromide	13.5	29.5	35.0	71%	44
Sulphate	527	2155	2503	142%	44
Ammoniacal Nitrogen	2.67	6.13	9.26	81%	44
Total polycyclic aromatic hydrocarbons (PAH)	3.60	5.00	7.57	57%	49
Total polychlorinated biphenyls (PCB)	1.38	4.72	6.97	113%	120
Total petroleum hydrocarbons (TPH) C10-C40	144	310	324	58%	55
Sulphide	0.64	1.11	1.16	50%	12
Total Dioxins/furans (ITEQ) (ng kg^{-1})	0.001	0.004	0.006	137%	53

Table 2.3 & 2.4: Survey of WTE plants bottom ash data (Lewin, Turrell, Benson and Petrolati, 2012)

2.5 Leaching

2.5.1 Mechanic of Leaching

One of the biggest concerns regarding implementation/disposal of residue ash, such as IBA into construction or landfill, is the potential for dangerous contaminants such as heavy metals leaching into the environment. Therefore, before making the decision of implementation of the residue, there are many different factors to consider. It is important to first recognise that there are many different mechanical properties that affect the performance of leaching that should be considered. Luo, Cheng, He and Yang (2019) conducted extensive research on the topic of leaching behaviour of heavy metals from MSWI ash. All the factors that affect leaching were studied and concluded to be:

- Ash behaviour
- Liquid to solid ratio (The leaching of heavy metal is typically done through solubility, therefore, ash with a liquid to solid ratio will accelerate the release of heavy metal)
- The impact of pH level
- Weathering and aging

- Use of chemical reagent
- Use of bacteria and fungi

It was also reported that the difference between solubility and sorption control is very significant to leaching. Solubility refers to general solubility control of dissolution of metal oxides, whereas sorption refers to when absorption and adsorption combined together as a single process. It was also reported in Racho and Jindal (2004), that the leachability of metals increased as the particle size decreased. This is due to the small particle size increasing the available surface area to being exposed to the leaching fluid, therefore increasing the liquid to solid ratio.

2.5.2 Stabilisation/Testing of Leaching

Even after considering these factors, it is still very difficult to prevent the leaching of harmful contaminants into the environment from ash residue. Therefore, there is a desperate need for available post treatment to bottom ash before it is disposed into landfill. Furthermore, Luo, Cheng, He and Yang (2019) covered different methods to treat and remediate leaching of harmful heavy metals into the environment:

- Separation techniques
- Washing
- Electrochemical process
- Solidification & stabilization
- Vitrification
- Thermal treatment
- Accelerated carbonation
- Hydrothermal solidification
- Chemical stabilization
- Thermal treatment
- Melting/fusion

When studying bottom ash, it is also important to select the best suited leaching test to examine the sample for the number of dangerous contaminants that are present in the whole bottom ash batch. It is reported that a toxicity characteristic leaching procedure (TCLP) and extraction procedure (EP) typically can provide a more precise analysis when compared to the American Society for Testing and Materials (ASTM) method (Chang, Chiang, Lu and Ko, 2001). This is due to the relative standard deviation being more accurate in a TCLP and EP test, making it a more reliable method of examination of heavy metal content leaching from ash, whereas the ATSM method was concluded to be possibly more accurate as a lysimetry test (Chang, Chiang, Lu and Ko, 2001). It is also worth noting that what is the most cost-effective method available for an institution is also another factor to consider when choosing an analytical method. For instance, Forrester (2008) compares a number of methods of extraction and extensively studies which method performs the best whilst being cost effective. It was concluded that using a modified complex agent (MCA) was the most cost-effective method that could extract lead from incinerator ash. The temperature as an environmental factor was studied and was concluded to be a major factor, as at a higher temperature, more extraction/leaching takes place.

As Forrester (2008) indicates, different types of leaching/extraction methods are better suited than one another depending on the heavy metal present in the bottom ash. Moreover, Dung, Vassilieva, Swennen and Cappuyns (2018) demonstrate this synopsis very clearly. For instance, it was noted that generally using acetic acid performs very well in extracting all metals, with the exception of arsenic and molybdenum. Both of these metals experienced more extraction with the ammonium-EDTA extraction method. Therefore, this is another consideration that should be taken into account when deciding on a leaching/extraction method suited for a test sample.

2.6 Waste to Energy Equipment/Technology

2.6.1 Fluidised Bed Technology Explained

It is important to acknowledge that a fluidised bed is typically used to treat sewage waste and the principle of the process is that waste is fed into the input as a solid state and is converted into a fluid state, which then passes through the bed (Mitchell, and Pearce, 1975). Therefore, the bottom ash would typically form in the bottom of the fluidised bed where it would be discharged on to a conveyor. Figure 2.1 displays the typical operations of a fluidised bed.

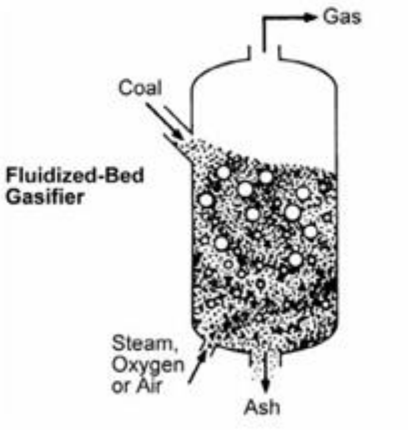


Figure 2.1: The operations of a typical fluidised bed (Phillips, 2006)

2.6.2 Gasification vs Incineration

One of the main differences between a typical incineration and a gasification plant is the presence of oxygen in the combustion process. For instance, in an incineration plant the combustion process is fully oxidised whereas in a gasification plant it is only partially oxidised (Syngas Applications, 2019). Therefore, with gasification less ash residue is produced and a cleaner end product is produced such as syngas (Syngas Applications, 2019). Figure 2.2 displays the difference between the operations of both an incineration and a gasification plant. It is clearly demonstrated that the end product of a gasification plant is more viable to many more different markets when compared to an incineration plant.

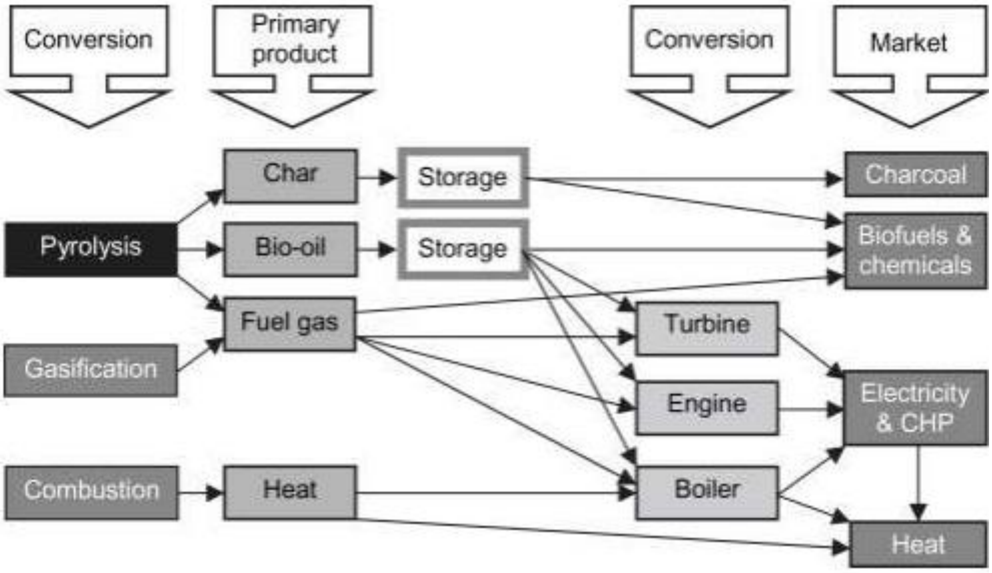


Figure 2.2: Operations of both a Gasification & Incineration facility (GCU Learn, 2020)

2.7 Metal Recovery

Heavy metal recovery is an essential treatment in order to lower the hazardous risk of IBA being utilised for different purposes. These methods gained popularity during the 1990s and expanded to a wide range of different methods of varying efficiency (Syc et al., 2020). These methods may involve different equipment such as an eddy current separator and magnetic separator. WTE plants do have the option to have this equipment installed at their own facility in order to treat discharged IBA, although this comes with the downside of higher expenses. This is especially concerning when one considers the already high expenses that come with the operations of an WTE plant. Additionally, there is an option to invest this money back: as mentioned in the latter section of this thesis (2.8), a market for these recovered metals exist. Each of these heavy metals vary regarding their value, therefore, if a facility is going to invest their money in equipment to recover heavy metal, it is worth calculating if this money invested can be returned through selling on the heavy metals.

There are several different types of IBA discharge from the combustion process. This is imperative due to the fact that the type of discharge that takes place effects the form of recovery method that an IBA sample will receive. Furthermore, the type of recovery that an IBA sample receives will then affect its application in its utilisation purposes such as road filing or concrete production. The discharge systems in WTE plants are divided into wet and dry systems. A wet system is the more advanced system and allows for quenching (rapid cooling in order to extract material) of the hot IBA through contact of water (Syc et al., 2020). Dry discharge on the other hand is a more outdated system that is not typically seen in more modern WTE plants. This system comes with its fair share of disadvantages such as IBA that comes through this discharging system will not be applicable in utilisation purposes such as road filing and concrete production (Syc et al., 2020). There are several pre-metal recovery treatment options available to facilities that operate with dry discharging systems in order to allow for the IBA sample to be applicable in construction purposes.

These pre-metal recovery treatment options are available to both facilities that operate under wet and dry discharge as these treatment options increase the metal recovery that can occur. Examples of these pre-treatment methods would be ageing, crushing and sieving. Aging is a technique that is typically used to treat bulk IBA prior to metal recovery, landfill disposal and construction purposes. This is because ageing IBA before any of these acts has many benefits such as improving upon its leaching properties, decreasing its water content and stabilizing its meta-reactive IBA matrices (Syc et al., 2020). Sieving is a pre-treatment method that involves accurately fractioning IBA samples prior to metal recovery. This method, as a result, leads to more recovery with metals that are homogeneous with one another in small particles (Syc et al., 2020). Crushing is another crucial pre-treatment method as it improves metal recovery by liberating metal particles that are trapped inside of mineral conglomerates (Syc et al., 2020).

They are many types of metal recovery technology methods available, all varying in expenses, however, in this section the focus will be on only two types of technology; magnetic separator and eddy current separator, as they are the most common types of metal recovery technology to be found in a WTE plant. Magnetic separators are the most standard and simplest method of metal recovery. This method typically takes place after IBA discharge and any pre-treatment method through the means of an overbelt or drum magnets. Due to the simplicity of this method, it is only limited to large pieces of ferrous metal scraps (Syc et al., 2020). Eddy current separators are a lot more advanced and efficient when compared to magnetic separators. Due to its further advanced operations, it also requires proper calibration based on the size of material that is being recovered (Syc et al., 2020). Different types of eddy current separators with different levels of rotational speeds are available. This will allow for various levels of performance: as the rotational speed increases, so does the efficiency of the separator to recover smaller size particles (Syc et al., 2020). Since eddy current separators are a lot more advanced compared to the standard magnetic separator, it is also capable of recovering smaller particles and non-ferrous metals (Syc et al., 2020).

2.8 Utilisation Purposes

There are many uses that can be found with IBA, such as construction aggregate, road filling and asphalt. It is imperative to not only understand the geochemical effect that can be had on the environment as a result of utilising IBA in this manner, but to also understand how well it performs as an alternative compared to the status quo. This is well demonstrated in an assessment of global data that analysed the performance of IBA in road construction specifically (Lynn, Ghataora and Dhir, 2017). In this assessment it is reported that IBA in low content can typically serve the given requirements needed for road construction. Although, it is important to note that when the IBAA content increases, the overall compressive strength decreases. Therefore, it is imperative to find the right level of IBAA needed without comprising the overall strength and design of the road construction. Lynn et al. (2017) were able to conclude that higher bitumen content would be required with IBAA to meet Marshall Mix design limits. This idea is also concluded in Abdullah et al. (2019), as this was also an extensive assessment of engineering applications of IBA. Despite IBA being a weaker alternative, it is reported to still be in serviceable condition after one season in road construction (Abdullah et al., 2019). It also demonstrated, when used in concrete aggregate, during longer curing times that the compressive strength can increase by 10% (Abdullah et al., 2019). The consensus regarding concrete aggregate is to stick to a 2:1 ratio of normal concrete material and bottom ash aggregate (Abdullah et al., 2019).

The aforementioned synopsis is challenged in Kim and Lee (2011) as it displays an extensive study comparing fine bottom ash and coarse bottom ash aggregate performance. The study was demonstrating a way that bottom ash can be implemented in concrete aggregate without dropping in performance like the overall body of literature work would suggest. It was reported that increasing the cement paste used would make sure that the compressive strength would be unaffected with both the coarse and fine bottom ash, regardless of the content size. Unfortunately, other mechanical properties, such as the modulus of elasticity and flexural strength, both decrease in respect to replacement ratio of fine and coarse bottom ash. This was demonstrated in this example from the fact that the modulus of elasticity dropped down from 49% when compared to the control sample.

Another use for bottom ash is converting it to a synthesis of a zeolitic type adsorbent to act as a heavy metal which is well researched in Chiang et al. (2012). Its performance was reported to be very successful as a heavy metal adsorbent especially when compared to a natural zeolite. Figure 2.3 displays the performance of both methods regarding different metals. This method can prove to be very useful in providing further life and utilization for bottom ash and preventing the harmful effects of heavy metal leaching that may occur if this process was not considered.

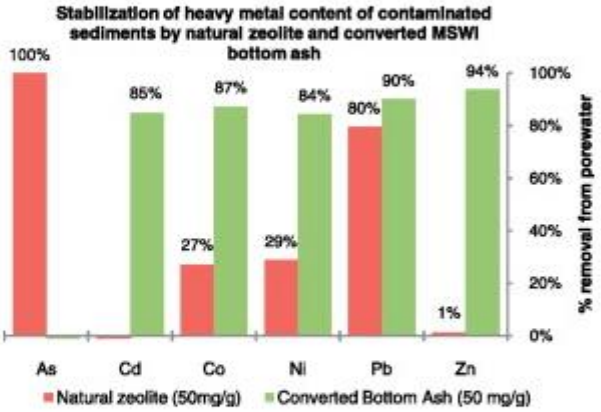


Figure 2.3: Natural Zeolite vs Synthesis Zeolite as a Heavy Metal Adsorbent (Chiang et al., 2012)

However, if the IBA is examined and is found to be too hazardous for utilisation purposes, then another option is recovering the metals in future samples and selling it on. This option could potentially be more finically viable when compared to disposing IBA into landfill as there are many different valuable metals that can be recovered such as gold (Au), silver (Ag), copper (Cu) and lead (Pb) (Kahle et al., 2015). Table 2.5 displays the common market value that is found for all these metals if extracted and sold. This option would be very appealing especially if there is a hazardous concentration of heavy metals in the IBA, as this option could prevent the IBA being sent to landfill.

Metal	Amount [kg/tonnes]	Estimated scrap prices [€/kg]
Fe	31.4	0.12
Al	16.1	0.8
Cu	2.2	4
Zn	0.9	0.73
Pb	0.3	1.07
Ag	0.004	270
Au	0.0004	27600

Table 2.5: Market value for recovered metals (Kahle et al., 2015).

2.9 Pre-treatment Methods/Inputs

As previously mentioned, taking care in post-treatment is crucial to ensure the lack of heavy metals hazards posed onto the surrounding environment. Another aspect to consider is the pre-treatment of the waste, as it is arguable that pre-treatment plays an incredibly crucial role as well. For instance, literature such as Patra, Whaung and Kwan (2017) and Yao et al. (2010) study the behaviour of heavy metal concentration in certain provinces in Singapore and China, respectively. Both of these papers were able to conclude that there are three main factors that affect heavy metal concentration in bottom ash. The first is the occurrence and distribution of heavy metal in the input of MSW, indicating that extensive pre-sorting will benefit the quality of the bottom ash that forms. The other two factors are the physiochemical condition of the incinerator and the combustion kinetic parameters. It was reported in Patra et al. (2017) that under atomic spectroscopy examination such as SED-EDS analysis the predominant metals that were found were lead debris, calcium, iron and aluminium. However, it was also reported that under different environmental settings, such as testing under different pH levels, these heavy metals would vary regarding how concentrated they would be in the bottom ash. It was concluded that the IBA examined in these papers are suitable to be used in engineering applications, however, when compared to other material such as asphalt surface and recycled aggregate, it performs weaker. Therefore, if considering bottom ash for engineering purposes, it is crucial to consider extensive pre-sorting of the input MSW prior to the combustion process.

2.10 WTE Ash Residue

Despite WTE plants being an environmentally friendly alternative to waste disposal in landfill, it is impossible to recover the entirety of the waste input for energy purposes as it is inevitable for some waste residue to form. This is evident in the two main forms of ash that are produced: bottom and fly ash. These different types of ashes would typically form at different locations of the incinerator plant. Typically, bottom ash is the remains of the unburnt solid waste that is caught on the grate of the incinerator plant. Bottom ash would typically consist of unburned organic material, large pieces of metal, ceramics and inorganic fine particles (Waste Incineration & Public Health, 2000). On the other hand, fly ash is the solid and condensable vapour phase matter that leaves the furnace chamber and is suspended in combustion gases. Typically, fly ash is made up of volatile metals and metal compounds, inorganic chemicals and acid condensed onto particle surfaces (Waste Incineration & Public Health, 2000).

Due to the different locations of where both of these ashes form in a typical WTE plant, different amounts of these ashes would form. For instance, as displayed in table 2.6, the average mass of bottom ash found in a typical WTE plant is estimated to be around 250-420 kg, whereas fly ash is estimated to be 10-30 kg. Obviously, there are many different factors to consider so it is crucial to note that there is a room for error in these results. Regarding fly ash, however, a major factor to consider is the air unit that is installed. An excessive air unit tends to produce the most amount of fly ash, whereas a controlled unit tends to produce the least amount (Kalogirou, Themelis, Samaras and Karagiannidis, 2010).

Type of Residue	Typical amount of produced, kg/tonne of feed waste
Bottom ash	250-420
Grate sifting	5
Boiler ash	2-12
Economizer ash	Small
Fly ash	10-30

Table 2.6: Typical amounts of each type of residue forming (Kalogirou, Themelis, Samaras and Karagiannidis, 2010)

Dias-Ferreira, B. Ribeiro and M Ottosen (2003) extensively study fly ash in terms of heavy metal concentration. This was done by conducting a series of lab scale extraction experiments under different levels of pH. The most prevalent metals found were zinc and magnesium, although the extraction of all the heavy metals would perform differently depending on the pH conditions. The variance of how the fly ash performs under different levels of pH is demonstrated in figure 2.4. This figure demonstrates that with cadmium (Cd) and zinc (Zn), both began their leaching process at pH 10, till it was fully extracted at pH 4. Whilst copper (Cu) and lead (Pb) began extracting at pH <6 and was fully extracted at pH <2. It is also interesting to note that in the study by Pöykiö, Manskinen, Nurmesniem and Dahl (2011), samples from both bottom and fly ash from the same WTE plant were compared with each other and it was subsequently discovered that certain metals were higher in concentration in fly ash than in bottom ash. For instance, antimony and lead were found to be 1.1 and 3.5 times higher in fly ash than in bottom ash, respectively.

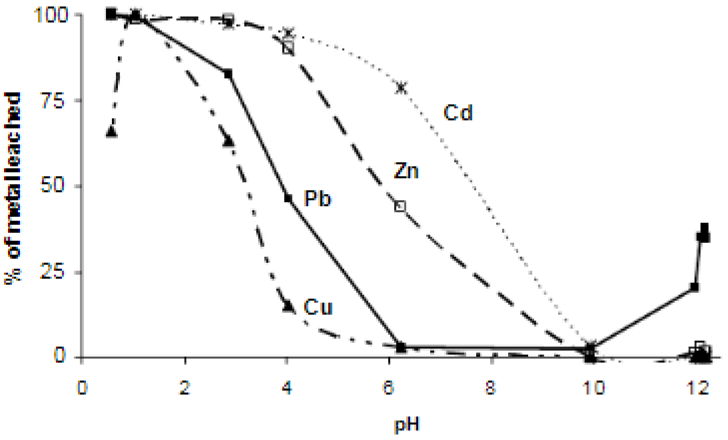


Figure 2.4: % of metal extracted vs pH (Dias-Ferreira, B. Ribeiro and M Ottosen, 2003)

The topic of leaching/concentration of heavy metal is already heavily covered in the overall body of literature of this topic, however, in the study by Todorovic and Ecke (2006), many methods are covered extensively, particularly carbonation. Many different types of municipal solid waste incinerator (MSWI) ash such as fly ash and various forms of bottom ash were examined. Components that were found to be generally the most critical in the study by Todorovic and Ecke (2006) was chlorine, chromium, copper, molybdenum, lead, antimony, selenium, sulphate and zinc. The performance of demobilising these components varies under different environmental setting e.g. pH level. Carbonation can greatly affect these environmental settings as it can decrease the pH level in some circumstances. It was reported that the release of chromium in bottom ash after carbonation was greatly decreased (by 93 %) along with copper and antimony (by 63% and 45%, respectively). It was concluded that carbonation had a greater effect in demobilising heavy metals in bottom ash than it did in the fly ash.

2.11 New Research in the Field

The implementation of thermal technology in India is evidently very popular as it is estimated that 2/3 of the electricity produced originates from waste to energy technology (Arun, Singh and Gupta, 2020). Therefore, a lot of ash residue that is produced, which is the rationale behind Arun, Singh and Gupta, 2020 research into the topic of bottom ash utilisation in the Indian construction industry. In this report four different bottom ash samples were studied with different ground time intervals; 0 hours, 1 hours, 2 hours and 4 hours. The purposes were to study the effects of grind has on the overall compressive strength of bottom ash. Over a 28-day period it was found that the longer the ground time interval is, the more compressive strength the sample will have. It was demonstrated that the 2- and 4-hour samples had more compressive strength than the fly ash sample that was tested (Arun, Singh and Gupta, 2020). Demonstrating this is a factor that manufactures should consider when utilising bottom ash in concrete.

Linh et al. (2020) cover the effects of varying levels of rainfall on the leaching behaviour of heavy metals in bottom ash that are landfilled. The tests conducted in this paper used 15 mm/h as normal rain fall and 25, 50 & 100 mm/h as heavy rainfall. It was concluded that heavy rainfall is able to decrease the level of leachate leaching from the bottom ash due to the effects it also has on the pH level and ions, which were also reported to increase. Despite the fact that this paper was carried out in Japan, these findings would be very useful in European countries where rain is more prevalent. Especially when one considers the heavy rain that occurs in Scotland, the findings of Linh et al. (2020) may potentially serve to be very useful, depending on the implementation of the bottom ash used in this paper.

Jeon, Son, Kim and Kim, 2020 conducted intensive research pertaining to the use of bottom ash and oyster shells being used as drainage material and mixed with soil material. This was done by conducting environmental life cycle analyses of bottom ash, oyster shells and sand. It was demonstrated that when taking into account the acquisition, processing, transportation, and construction stages, bottom ash and oyster shells results in a 19% -47 % and 17% - 34% carbon emission reduction respectively, when compared with natural sand (Jeon, Son, Kim and Kim, 2020). It was also found in South Korea that when bottom ash and oyster shells are implemented into drainage material, a 6–15% and 21–31% reduction of carbon emission is experienced respectively (Jeon, Son, Kim and Kim, 2020). Demonstrating more innovative ways to utilise bottom ash and divert it being disposed into landfill.

3.0 Methodology

To recap, the aim of this dissertation is to decisively illustrate the effects that different heavy metals have on the utilisation/disposal of IBA. The effects of heavy metal concentration can be seen in the type of landfill that the IBA is sent to and whether or not the IBA sample can be considered too hazardous for construction purposes. Therefore, to illustrate this effect, the annual leaching data and hazard reports for five different WTE plants' IBA samples are analysed in this paper. The categories of hazards that will be measured are irritant, corrosion, carcinogenic and ecotoxicity, as these are the most likely hazards to occur in IBA. The waste acceptance criteria (WAC) determines which type of landfill that the IBA sample is suitable to be disposed in: inert, non-reactive hazardous or hazardous landfill. The following are the WTE facilities, whose data was compiled for the purposes of this paper; Viridor Glasgow Recycling and Renewable Energy Centre (GRREC), FCC Millerhill, Viridor Dunbar Energy Recovery Facility (ERF), Lerwick Energy Recovery Plant & Levenseat Renewable Energy Ltd. Table 3.1 demonstrates how each WTE plant differs regarding the technology that they utilise and the equipment that was used on their testing samples.

Waste to Energy Facility	Combustion Technology	Testing Equipment Used
GRREC	• Three-line gasification technology • Capacity is reported to be 154,000 tonnes per year	• Acidic fluid such as aqua regia used to act as a leaching fluid • An ICP-OES is utilised to measure the heavy metal leachate content
FCC Millerhill	• Capacity reported to be 189,500 tonnes per year • Single line moving grate technology • Functions as an incinerator • The IBA that forms are typically sent to an offsite facility for heavy metal removal before the IBA is utilised or disposed of	• Acidic fluid such as aqua regia used to act as a leaching fluid • An ICP-OES is utilised to measure the heavy metal leachate content
Dunbar ERF	• The largest capacity used in this paper, with it being at 325,000 tonnes per year • Two-line moving grate technology	• Acidic fluid such as aqua regia used to act as a leaching fluid • An ICP-OES is utilised to measure the heavy metal leachate content

	• Functions as an incinerator • Magnetic separator on-site to remove ferrous heavy metal	
Lerwick Energy Recovery Plant	• Capacity is reported to be 189,500 tonnes per year • Single-line moving grate technology • Functions as an incinerator • Magnetic Separator on-site to remove ferrous heavy metal	• Acidic fluid such as aqua regia used to act as a leaching fluid • An ICP-OES is utilised to measure the heavy metal leachate content
Levenseat Renewable Energy LTD	• Capacity reported to be 220,000 tonnes per year • Functions as a Gasification plant • Utilised a single fluidised bed technology • Both bottom ash and tramp ash is formed at the bottom of the fluidised bed	• Acidic fluid such as aqua regia used to act as a leaching fluid • An ICP-OES is utilised to measure the heavy metal leachate content

Table 3.1: Profile of the WTE facilities used in this report

3.1 Methods of Extraction & Detection

3.1.1 Leaching Fluid “Aqua Regia”

Aqua regia is a form of leaching fluid that is typically used to dissolve various heavy metals from non-soluble materials (Dogan and Kemaloglu, 2016). Aqua regia fluid is a highly corrosive mixture between nitric acid and hydrochloric acid (Dogan and Kemaloglu, 2016). This method will help to determine the heavy metal content within the IBA testing sample for the Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) to detect it. This will be very helpful especially when testing for WAC as this will clearly illustrate how the leaching of heavy metal may occur in landfill. Therefore, this will indicate which type of landfill the IBA is suited for based on its leachate values. Regarding hazard testing, the use of aqua regia will also determine the concentration of relevant heavy metals such as lead, copper, zinc and nickel. Determining these concentrations will be imperative to determine the HP4, 8, 7 and 14 nature of the bottom ash samples

3.1.2 Inductively Coupled Plasma Optical Emission Spectroscopy

The analysis of the heavy metal content serves to measure the leachability and hazard levels of the testing samples into the surrounding environment. This was conducted by passing acid fluid into the ash to act as a leaching extraction fluid. To measure the leachate content an ICP-OES was used which is an analytical machine that is used to detect and measure chemical elements. The functionality of an ICP-OES is a type of emission spectroscopy that relies on the use of inductively coupled plasma to excite ions and atoms to produce an electromagnetic radiation (Radboud Univeristy, 2017). These instruments would be ideal in a laboratory examination of trace level samples. The whole process behind the operations of a typical ICP-OES is displayed in figure 3.1 as the diagram clearly illustrates the pathways of the leachate within the ICP-OES setup. The way that the plasma towards the end is used, is to excites the atoms, which due to the placement of the plasma being at the end of a quartz torch, it is being cooled by an induction coil which also has a high frequency current flowing through it (Radboud University, 2017). Therefore, this allows a magnetic field to be induced which accelerates electrons into a circular trajectory (Radboud University, 2017). Due to the thermal energy that is taken by the accelerated electrons this creates an excited state which makes it easier to detect elements in the reading (Radboud University, 2017).

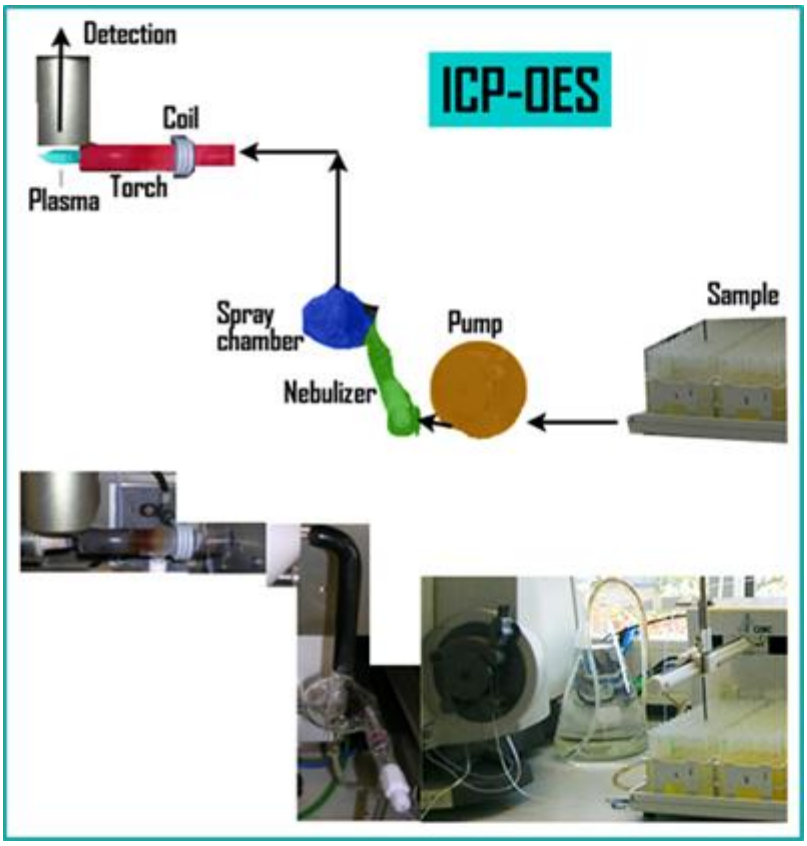


Figure 3.1: Illustration of ICP-OES operations (Radboud University, 2017).

3.2 Hazards and Leachate Being Measured

Choosing to analyse data from five different WTE plants will give a wide range of results demonstrating the different uses that can be had with IBA. The main point of this report is to show how heavy metal concentration can affect the use of IBA. Therefore, many different results from different WTE plants that have varying levels of heavy metal concentration will help to illustrate this point. The hazard/toxic nature regarding heavy metal concentration is being measured in five different metrics (HP4, HP8, HP7, HP14 and WAC) as they are the five main methods of determining the suitability in construction/disposal of an IBA sample in the UK. Determining the heavy metal concentration under these metrics is imperative to utilising IBA efficiently.

3.3 Room for Errors and Limitations

Given the fact that the data being analysed for this paper was produced by WTE plants and not examined personally in a laboratory, means that personal control for every single variable between samples could not be accounted for. Such variables include pH, moisture content and waste input. This limits this investigation's ability of exploring more experimental options. This direction was taken as a result of the recent global pandemic spread of COVID-19. As of writing this paper, universities throughout Britain have shut down due to social distancing policies that have been implemented by the government. Therefore, it has not been physically possible to personally examine IBA samples and thus require the data that was offered by WTE plants for the purpose of this paper. It is also worth noting that another limitation of this paper is that some of the facilities that have sent their data could not send both utilisation and disposal data. Some have just have sent one or the other (i.e. Lerwick only sending disposal data and Levenseat only sending utilisation data). Therefore, comments cannot be made on these facilities bottom ash regarding the data that is missing, for instance a statement cannot be made on Lerwick's bottom ash suitability in utilisation as data they did not send the relevant data for this.

The room for error is mostly reliant on the third-party methods of gathering their data. For instance, a popular method that was used for measuring heavy metal concentration was utilising an ICP-OES. An ICP-OES can measure trace levels of elements due to the high technical nature of its build, however, there is still room for error to occur. A source for error would most likely originate from the detection limit that the ICP-OES operates under (Sensitivity, Background, Noise, and Calibration in Atomic Spectroscopy: Effects on Accuracy and Detection Limits, 2018). The detection limit is in reference to how low a concentration that the ICP-OES can detect. This can vary depending on the type of atomic spectroscopy technology that is used as displayed in figure 3.2 (Sensitivity, Background, Noise, and Calibration in Atomic Spectroscopy: Effects on Accuracy and Detection Limits, 2018). Furthermore, there are also external variables that can affect the detection limit. These variables are signal strength, noise, background and stability (Sensitivity, Background, Noise, and Calibration in Atomic Spectroscopy: Effects on Accuracy and Detection Limits, 2018). Due to all of these factors affecting the detection limit, this means that the ICP-OES can deliver a result that is somewhat inaccurate.

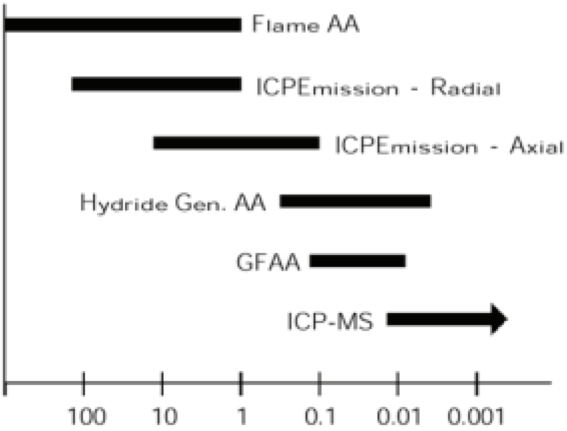


Figure 3.2: Detection range limits for different types of atomic spectroscopy technology (Sensitivity, Background, Noise, and Calibration in Atomic Spectroscopy: Effects on Accuracy and Detection Limits, 2018)

Another major source of error is a certain phenomenon that can occur which affects the precision and accuracy of the results which is called “spectral interference” (How to Reduce ICP-OES Remeasurement Caused by Sample Problems and Errors, 2019). This phenomenon occurs when elemental emission lines from different elements are very close to each other in a sample. This can happen due to the tens of thousands of elemental emission lines that are present in an UV-Vis wavelength range. Furthermore, it is worth noting that certain heavy metals are affected by false-positive reports. For instance, it is reported that there is almost a 100% false-positive reading for measured thallium in laboratories and with arsenic it is reported to be somewhere between 25-50% of the time (How to Reduce ICP-OES Remeasurement Caused by Sample Problems and Errors, 2019).

Another source of error that could be found is linked to the testing procedure for WAC. This is due to the fact that reports have indicated that toxicity characteristic leaching procedure (TCLP) are typically a conservative estimate of MSW leaching behaviour in landfill (Intrakamhaeng, Clavier, Roessler and Townsend, 2018). This is because this form of testing operates under smaller pH and higher organic content conditions when compared to MSW ash leaching in landfill. Since these are two major influences on the leaching mechanics and behaviour, therefore it is inevitably going to create a disparity between the lab results and the leaching that occurs in the landfill.

4.0 Hazard Description

4.1 HP4/8

HP 4 is in reference to the irritant nature of the IBA sample which causes reversible inflammation on a body part (Waste Classification: Guidance on the Classification and Assessment of Waste, 2018). This is observable in everyday household items such as cleaning products and shampoos that can cause mild irritation on skin (Lohr, 1979). It is also reported that when an irritant such as nickel chloride is combined with an allergen such as sodium lauryl sulphate, the synergistic skin effects that would be had with either of these hazards individually are amplified when combined together (Agner et al., 2002). The type of heavy metals that would cause irritancy and corrosive damage are alkali metals such as lithium, sodium, potassium rubidium, caesium and francium. All of these heavy metals belong to group 1 in the periodic table along with hydrogen. When mixed with other elements they typically lose their outermost electron and form a 1^+ charge. This leads to alkali metal being extremely reactive thus being required to be stored in oil despite being a very soft material.

HP 8 is in reference to the corrosive nature of the IBA sample which is a stronger form of an irritant that can destroy body tissues and cause irreversible damage to skin (Waste Classification: Guidance on the Classification and Assessment of Waste, 2018). The severe effects that are had on the human body are evident as it is reported that corrosive poisoning can lead to severe injuries to the upper gastrointestinal tract and can even lead to death (Chibishev, Pereska, Chibisheva and Simonovska, 2012). Corrosive substances can also lead to structural damage as well, which is something to consider if applying the IBA sample for concrete production. In IBA the most likely source of irritancy and corrosive qualities would be the pH and any concentration of alkali metals (Waste Classification: Guidance on the Classification and Assessment of Waste, 2018). Each facility has their own threshold limit of pH in their alkali metals due to the fact that there could be various levels of alkali metals present in each facilities sample and thus each of these alkali metal will vary in how reactive they are.

4.2 HP7

As previously mentioned, HP7 is in reference to how carcinogenic a substance can be. Carcinogenicity refers to the potential that a hazardous substance can cause cancer (Waste Classification: Guidance on the Classification and Assessment of Waste, 2018). In the context of carcinogenic elements/compounds that maybe present in IBA, the most likely is nickel hydroxide (Waste Classification: Guidance on the Classification and Assessment of Waste, 2018). There are two main ways that nickel compound exposure can cause lung cancer. The first being through heritable means caused by nickel compounds and the second being through the promotion of cells elicited by certain nickel compounds (Oller, Costa and Oberdörster, 1997). Therefore, it is imperative that when utilising IBA for construction purposes, the number of carcinogenic compounds is limited. It is worth noting that the general carcinogenic threshold is 1000 mg/kg (Waste Classification: Guidance on the Classification and Assessment of Waste, 2018). The mass of nickel hydroxide was calculated with the following formula:

(Mass of Nickel)/ (Mass of Nickel Hydroxide) = (Molecular Mass of Nickel)/ (Molecular Mass of Nickel Hydroxide)

Thus

Mass of Nickel Hydroxide= (Mass of Nickel x Molecular Mass of Nickel Hydroxide)/ (Molecular Mass of Nickel)

Nickel hydroxide $[(NiOH)_2]$ is an inorganic, green, crystalline compound which can become toxic upon heating (Oliva et al., 1982). There are two different known designs of the structure of nickel hydroxide. Both of these structures are denoted as α- and β-$Ni(OH)_2$ (Hall, Lockwood, Bock and MacDougall, 2015). The structure of the α-phase is formed by $Ni(OH)_2$ being intercalated with water (Oliva et al., 1982). The structure of the β-phase forms by adopting a hexagonal close packed structure of Ni^{2+} and OH^- ions (Oliva et al., 1982). This is demonstrated in figure 4.1.

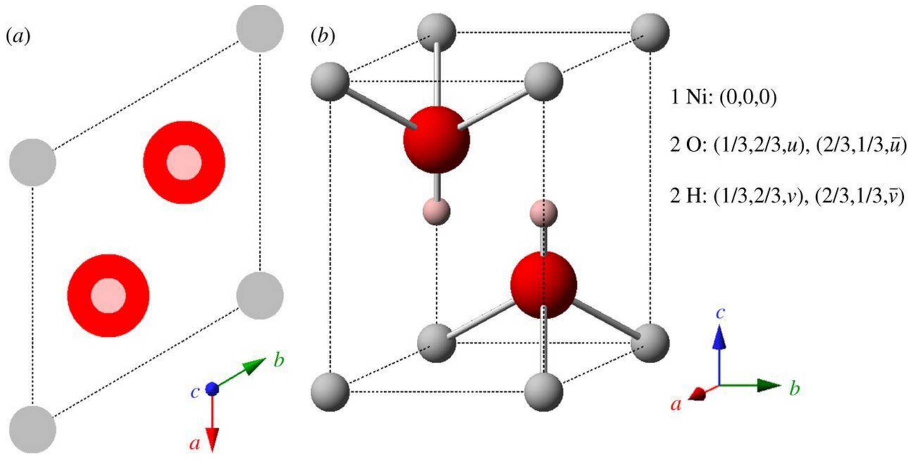


Figure 4.1: Nickel Hydroxide Model Structure (Hall, Lockwood, Bock and MacDougall, 2015)

4.3 HP 14

HP14 is the measure of ecotoxicity that can be caused from the IBA sample, as previously stated. Ecotoxicity is in reference to the biological stressors to the surrounding environment. It is also described by the three S’s; the study of the toxic effects of *substances* on nonhuman *species* in complex *systems* (Leeuwen, 1995). Heavy metals such as lead, copper, zinc and nickel and their ecotoxic effects of breaking down surrounding agriculture and aquatic life has been documented to be very detrimental to the local ecosystem (Nürnberg, Nguyen, Gödde and Urano de Carvalho, 1984).Copper hydroxide is typically a pale greenish blue solid powder which is structured with four Cu-O ions whilst their hydroxide ligands are either doubly or triply bridged (Oswald, Reller, Schmalle and Dubbler, 1990). Zinc hydroxide on the other hand is a white solid powder and is known to be structured with a hexa-aqua ion of zinc at a high concentration of water (Riddell, Lockwood and Irish, 1972). The threshold for each of the aforementioned compounds/elements is 1000mg/kg, however the threshold for the sum total is 2500 mg/kg (Waste Classification: Guidance on the Classification and Assessment of Waste, 2018). Copper and zinc hydroxide masses were calculated in a similar manner to that described earlier for nickel hydroxide.

4.4 Waste Acceptance Criteria (WAC)

This area of the results would be investigating restrictions of leachate heavy metal values in IBA that are disposed into landfill. In the UK, IBA can be classified as either inert, non-reactive hazardous or hazardous, depending on the heavy metal leachate values. This will determine which type of landfill that the IBA will be disposed into as each of the aforementioned classification of waste have their own designated landfill type. The liquid to solid ratio for the tested samples in this paper is 10:1 as this is the liquid to solid ratio that the WAC table has displayed the heavy metal leachates threshold values as. Table 4.1 displays the threshold leachate compiled by Waste Classification: Guidance on the Classification and Assessment of Waste (2018) for each different of landfill.

Heavy Metals	Inert Waste Landfill (mg/kg)	Stable Non-reactive Hazardous Waste in Non-Hazardous Landfill (mg/kg)	Hazardous Waste Landfill (mg/kg)
Arsenic	0.5	2	25
Barium	20	100	300
Cadmium	0.04	1	5
Chromium	0.5	10	70
Copper	2	50	100
Mercury	0.01	0.2	2
Molybdenum	0.5	10	30
Nickel	0.4	10	40
Lead	0.5	10	50
Antimony	0.06	0.7	5
Selenium	0.1	0.5	7
Zinc	4	50	200

Table 4.1: WAC leachate heavy metal values for landfill (Waste Classification: Guidance on the Classification and Assessment of Waste, 2018)

As previously mentioned, leaching is when a chemical/mineral drain away from a substance such as ash or soil by the action of a percolating liquid such as rainwater. There are many factors that can affect the degree of leaching that takes place. These factors are as previously mentioned in the literature review:

- Ash behaviour
- Liquid to solid ratio (The leaching of heavy metal is typically done through solubility, therefore, ash with a liquid to solid ratio will accelerate the release of heavy metal)
- The impact of pH level
- Weathering and aging
- Use of chemical reagent
- Use of bacteria and fungi

This is imperative to acknowledge, considering if the IBA is disposed in landfill, knowing what leachates can occur and their mechanics will protect the surrounding environment.

5.0 Result & Discussion

5.1 HP4/HP8 Result

It almost seems redundant to compare how each facilities' HP4/HP8 performance is with one another since each facility has their own subjective threshold for what constitutes as an irritant and corrosive material. This is due to the fact that there are many different alkali metals present in each facilities' sample and each of these alkali metals will vary with how reactive they are and thus pose different levels of threats. Therefore, each facility will require to use different thresholds to determine which samples can be classified as "irritant"/ "corrosive". Furthermore, discussing how each facilities' sample performs regarding their own threshold is a more effective way of examining the disparities of the results.

From observing the HP4/HP8 results, the only facility that has any legal threshold exceedances is Levenseat as displayed in table 5.1. Despite these exceedances, it is only two samples that exceed the irritant threshold meaning that Levenseat's sample can still be utilised because it is less than 2.2 samples (> 10% of the samples) exceeding the threshold. An explanation for Levenseat's exceedance would originate from its IBA sample having a high pH, indicating that there is a high level of alkali material in the IBA sample. Typically, heavy metal concentration in bottom ash is due to three different factors; waste input, physiochemical condition of incinerator and the combustion process. It is hard to speculate to what degree each factor played in this facility's results, although it is worth noting that alkali metals such as potassium, sodium and rubidium are reported to be found in the flames of WTE plants within the wavelength range of 500mm to 900mm (Yan et al., 2017). This indicates that if this facility wants to produce a less irritant form of IBA, then the equipment behind their combustion process should be investigated. Moreover, the samples of other facilities such as GRREC, Millerhill and Dunbars did not experience any exceedance as displayed in figure 5.1. Indicating that these facilities, from a HP4/HP8 perspective, seem to be applying a satisfactory practise regarding energy production and thus their bottom ash production.

Sample Count	1/12 alkali reserve	Irritant / Corrosive (pH+1/12th alkali reserve)	Exceeds HP4 limit?*Irritant >12.29	Exceeds HP8 limit? Corrosive >14.50
-	-	-	Yes/No	Yes/No
1	0.01	10.71	No	No
2	0.08	11.92	No	No
3	0.08	12.09	No	No
4	0.11	12.25	No	No
5	0.09	12.25	No	No
6	0.09	12.29	No	No
7	0.01	11.38	No	No
8	0.08	11.69	No	No
9	0.02	11.88	No	No
10	0.08	12.06	No	No
11	0.13	12.39	Yes	No
12	0.13	12.44	Yes	No
13	0.02	11.98	No	No
14	0.04	11.57	No	No
15	0.01	11.26	No	No
16	0.01	11.47	No	No
17	0.05	11.80	No	No
18	0.02	11.72	No	No
19	0.03	11.02	No	No
20	0.02	11.17	No	No
21	0.01	11.59	No	No
22	0.03	11.72	No	No

Table 5.1: Levenseat HP4 & HP8 data

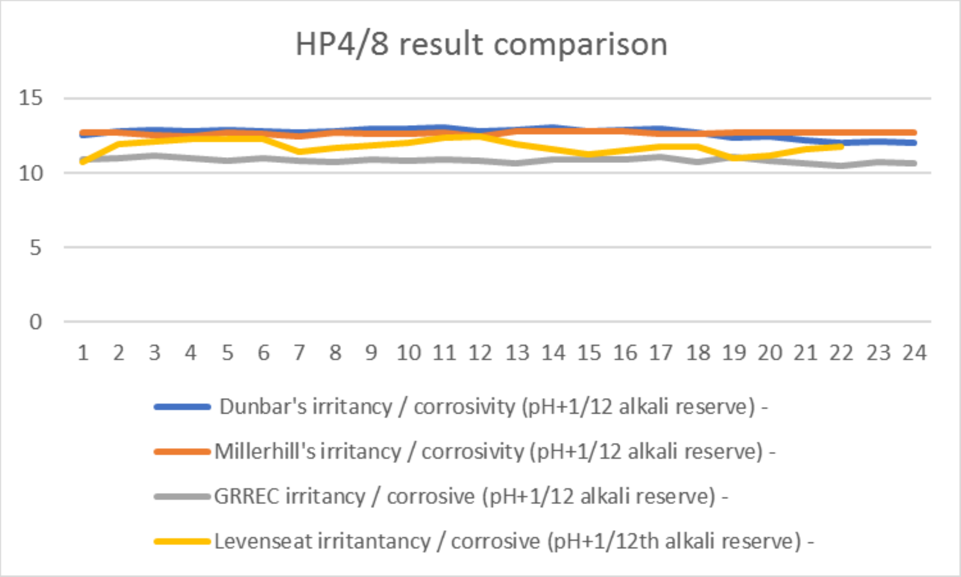


Figure 5.1: HP4/8 result comparisons

5.2 HP7 Result

From observing the nickel hydroxide concentration comparisons i.e. figure 5.2, it would indicate that all the facilities' IBA samples are clean, regarding carcinogenic risks. The only outlier was Levenseat's 19th sample which is 1260.84mg/kg as displayed in figure 5.2, exceeding the 1000mg/kg threshold. On average it seems as though Dunbar has the lowest amount of nickel hydroxide concentration as their average concentration is 82.03 mg/kg as displayed in figure 5.2, whilst Levenseat's average concentration is 405.1 mg/kg.

Even though none of the facilities' average trend exceeds the legal threshold of 1000 mg/kg there is still a clear disparity in the results. A major reasoning for this disparity between the results can be explained from the three major factors affecting heavy concentration in IBA; waste input, physiochemical condition of incinerator and combustion process. Overall, it is safe to say that all of the facilities' three major factors affecting heavy concentration in IBA, are up to par from a HP7 standpoint as there is less than a 10% exceedance for each of their samples. However, Levenseat may want to investigate these three main factors in order to produce cleaner IBA in the future, due to their higher average concentration and their 19th sample exceeding the legal threshold.

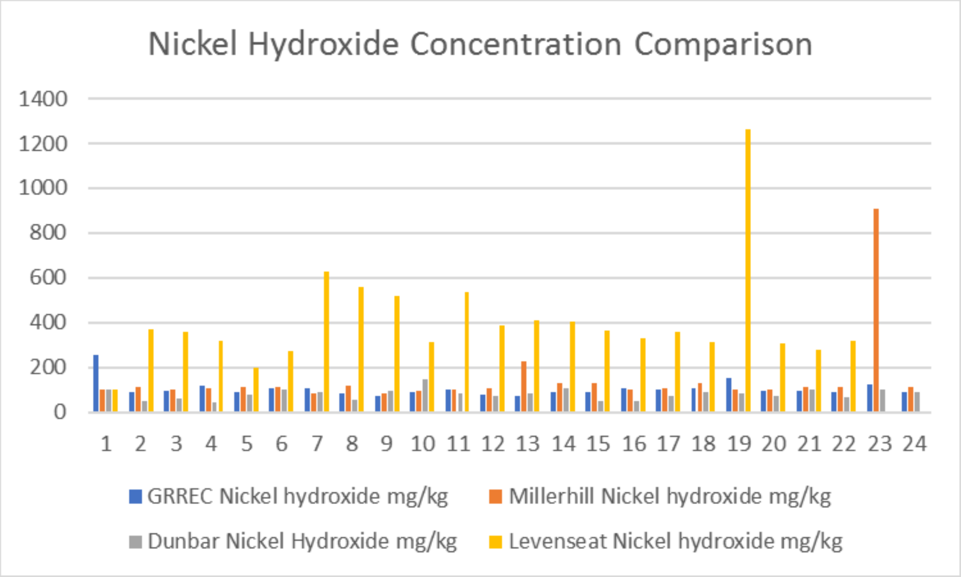
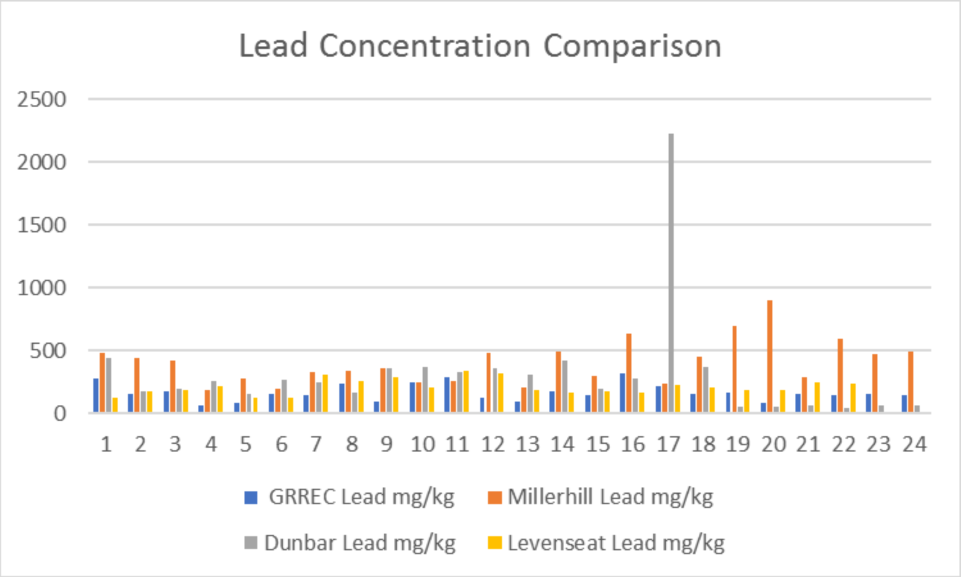
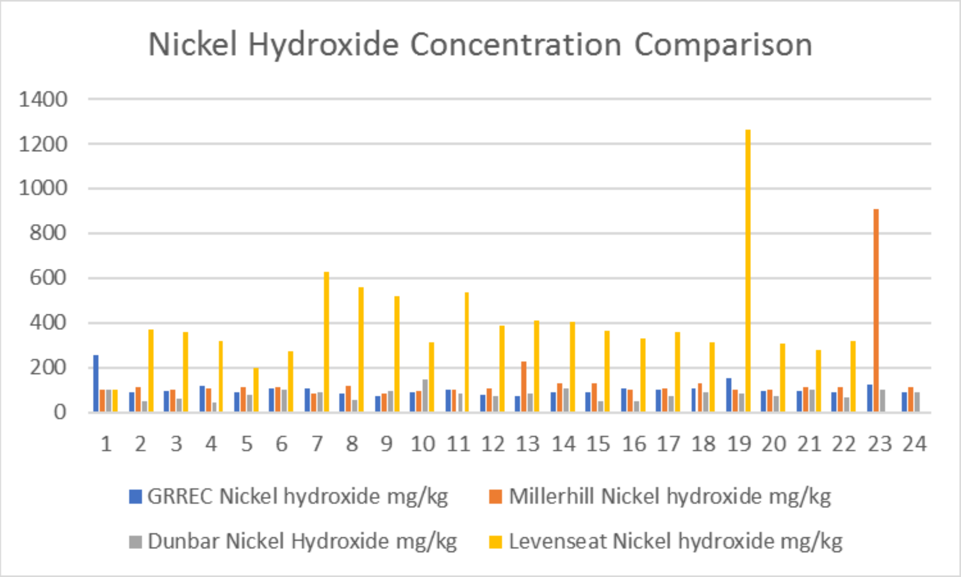


Figure 5.2: Nickel Hydroxide comparison (HP7 result)

5.3 HP14 Results

Overall, the facility that had the cleanest IBA is Millerhill as they had the least number of exceedances which is evident in figure 5.3, 5.4, 5.5 and 5.6. Figure 5.3 shows that lead overall did not have any exceedances over the 1000mg/kg threshold except for Dunbar's 17th sample, which had a lead concentration of 2225.15 mg/kg. Despite this being a large number, it also appears to be an exception from the overall trend to be below 1000 mg/kg and is not exceeding the 2500 mg/kg legal limit. The copper and zinc compound comparisons (figure 5.5 and 5.6) would indicate that all the facilities' samples appear to be clean except for Levenseat. Regarding Levenseat, all their copper and zinc compounds exceeded the 1000mg/kg threshold and additionally all the samples tested exceeded the 2500mg/kg making it far too hazardous to the surrounding ecosystem for it to be utilised for construction purposes. Regarding the zinc compound comparisons, only GRREC and Levenseat had zinc compounds in their samples. Figure 5.6 indicated that GRREC samples were cleaner compared to the Levenseat samples. They had a lot of samples exceeding the 1000mg/kg threshold but not the legal 2500 mg/kg, indicating that despite being fit for use, the sample can still be considered acutely hazardous.





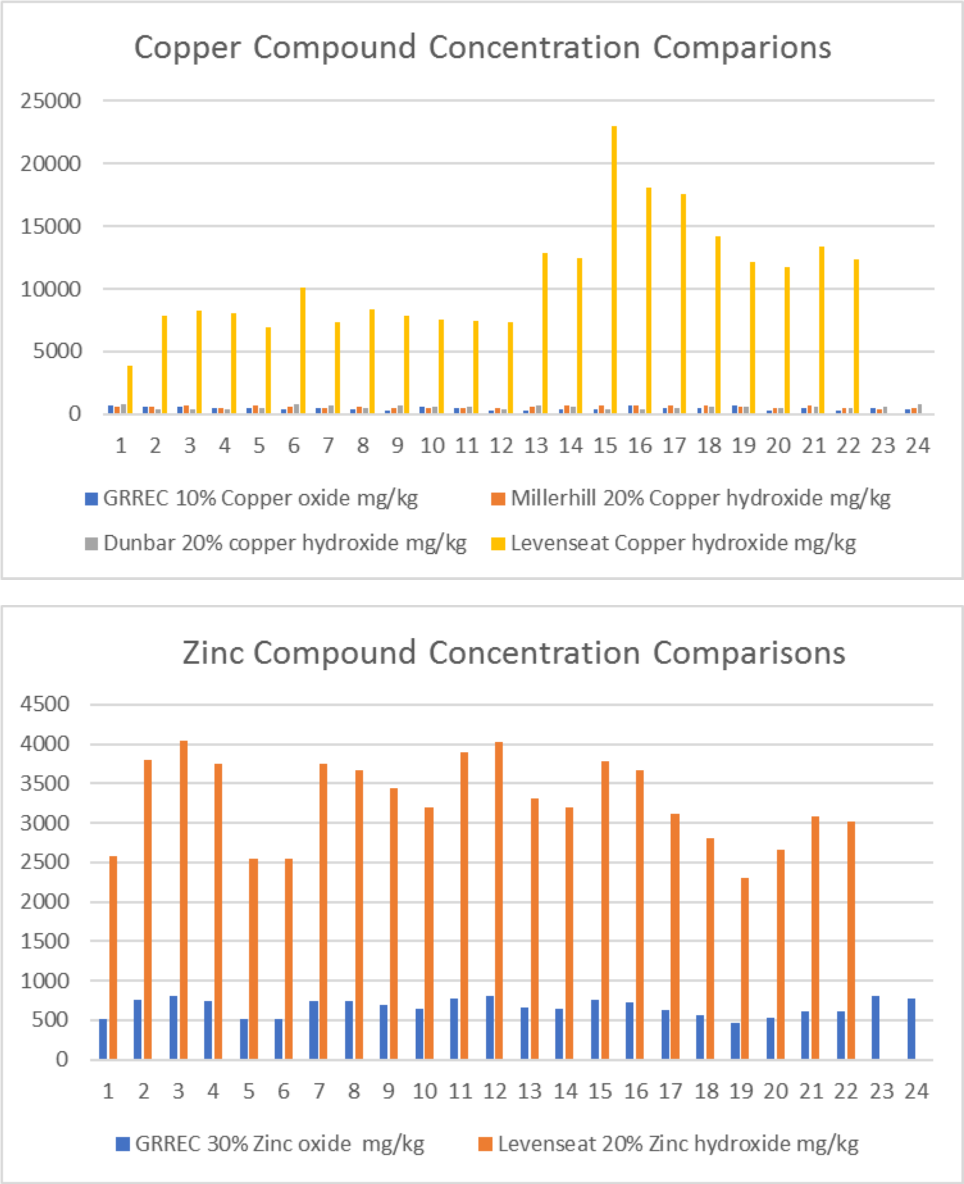


Figure 5.3, 5.4, 5.5 & 5.6: Lead, Nickel Hydroxide, Copper Compound & Zinc Compound concentration comparisons (HP14 result)

Again, the aforementioned three main factors that affect heavy metal concentration in IBA would be an explanation for the disparities and differences in these results. As previously discussed, Millerhill’s samples were the cleanest and had the least number of exceedances when compared to the other facilities. This would indicate that either Millerhill had a cleaner input (in respect to HP14 metals), the physiochemical condition of this plant would favour a less ecotoxic product or the combustion process of the plant lead to a cleaner product. Again, it does not need to be any one of these scenarios individually and could be a combination of any of these three factors together. It is also interesting to note that the only facilities that had zinc compounds in their HP14 samples were facilities that operated with gasification technology. Although not a certainty, as the sample size in this report is not enough to draw such a conclusion, but it may suggest that gasification plants may produce IBA with zinc compounds. If this is true this would mean that operating a gasification plant may lead to more ecotoxic IBA samples as there will be the addition of a zinc compound

5.4 WAC Results

When looking at figure 5.7 and table 5.2 we see the disparity in the results between the three facilities. For instance, it is shown that GRREC has the cleanest IBA product with only one leachate exceeding the inert waste landfill threshold. Millerhill also has a few leachates exceeding threshold limits; three exceeding inert and one exceeding stable non-reactive hazardous waste. However, Lerwick has three exceedances with one exceeding the hazardous landfill threshold. It is important to note that the heavy metal leachates that were commonly exceeding thresholds were zinc and antimony throughout all the facilities samples.

Heavy Metals	GRREC	Millerhill	Lerwick	Inert Waste Landfill (mg/kg)	Stable Non-Reactive Hazardous Waste in Non-Hazardous Landfill (mg/kg)	Hazardous Waste Landfill
Arsenic	<0.05	<0.05	0.01	0.5	2	25
Barium	0.3	**48.4***	1.9	20	100	300
Cadmium	<0.01	<0.01	<0.00001	0.04	1	5
Chromium	<0.2	<0.02	0.17	0.5	10	70
Copper	<0.05	0.87	**7.26***	2	50	100
Mercury	<0.01	<0.01	0.006	0.01	0.2	2
Molybhedium	0.49	0.38	0.74	0.5	10	30
Nickel	<0.1	<0.1	0.06	0.4	10	40
Lead	<0.05	**10.9****	**92.7*****	0.5	10	50
Antimony	**0.45***	**0.24***	<0.01	0.06	0.7	5
Selenium	<0.03	<0.03	0.05	0.1	0.5	7
Zinc	<0.5	6	**10.87***	4	50	200

** indicates when a test sample exceeds the heavy metal leachate threshold for its disposal inert in a waste landfill*

*** indicates when a test sample exceeds the heavy metal threshold for its disposal stable in a non-reactive hazardous waste in non – hazardous landfill*

**** indicates when a test sample exceeds the heavy metal leachate threshold for its disposal in a hazardous waste landfill*

Table 5.2: WAC result comparison

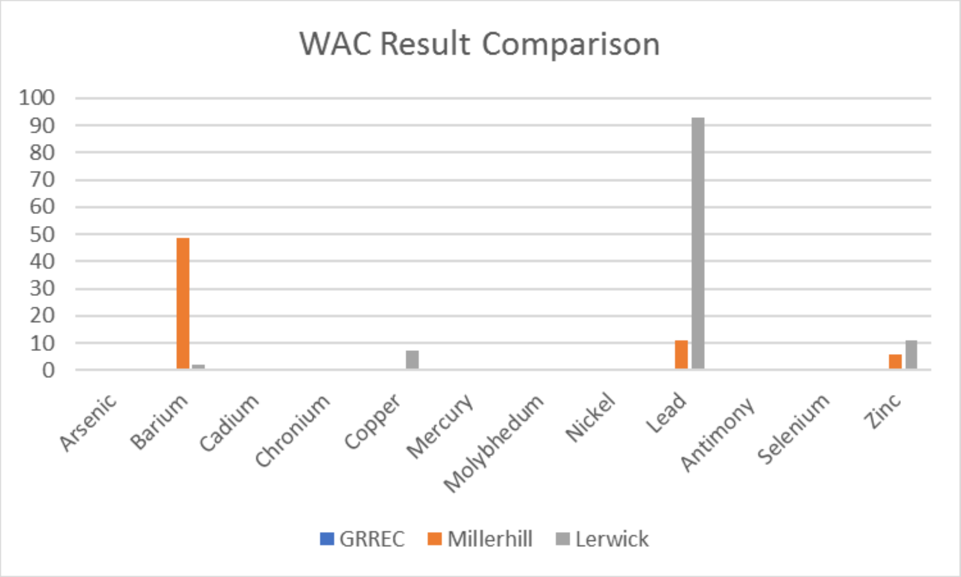


Figure 5.7: WAC result comparison

Other than the three main factors affecting heavy metal concentration in bottom ash, an explanation for the results would be the factors affecting leaching behaviour as previously discussed. The disparity can be explained from the fact that these factors may favour GRREC samples and affect the leaching behaviour of Lerwick's samples more negatively. If this is the case than obviously these are factors that Lerwicks facility should look into for future samples. It is also worth noting that GRREC also incorporates gasification technology, which typically produces a cleaner end product when compared to incineration technology. Due to the incomplete combustion nature of gasification, this also leads to less ash residue being produced.

The heavy metal leachates that exceeded their threshold are barium, copper, lead, antimony and zinc. Despite all these heavy metals being very toxic to the surrounding environment, the only heavy metal of concern is lead in this situation. This is due to the fact that the other heavy metals are still within a reasonable limit despite the fact that they are exceeding some of the landfill thresholds. However, the lead concentration in Lerwick's sample is exceeding the hazardous landfill threshold making this sample too hazardous to dispose to any landfill.

Understanding the pathway of landfill leachate is imperative to understanding its risk to the surrounding environment. Figures 5.8 and 5.9 demonstrate the pathway for the heavy metal leachates in landfill. These figures clearly demonstrate a risk of the leachate traveling into the river where it would affect the aquatic life. The leachate travelling into the river would also severely affect the water supply at a hazardous level. In both situations' humans would be the receptor due to the consumption of water and aquatic sea life. Since the leachate is also traveling through both the water table and soil, the surrounding plants will also be affected.

Humans and animal life will be the receptors to this form of contamination since both will consume these plants. Figure 5.9 shows the overall pathway for landfill leachate and demonstrates how in each scenario humans are the receptor. As previously mentioned, even a low concentration of lead can damage the developing nerve system in children and thus inhibit a child's learning capacity and lead to damage in neuropsychological development (European Commission, 2002).

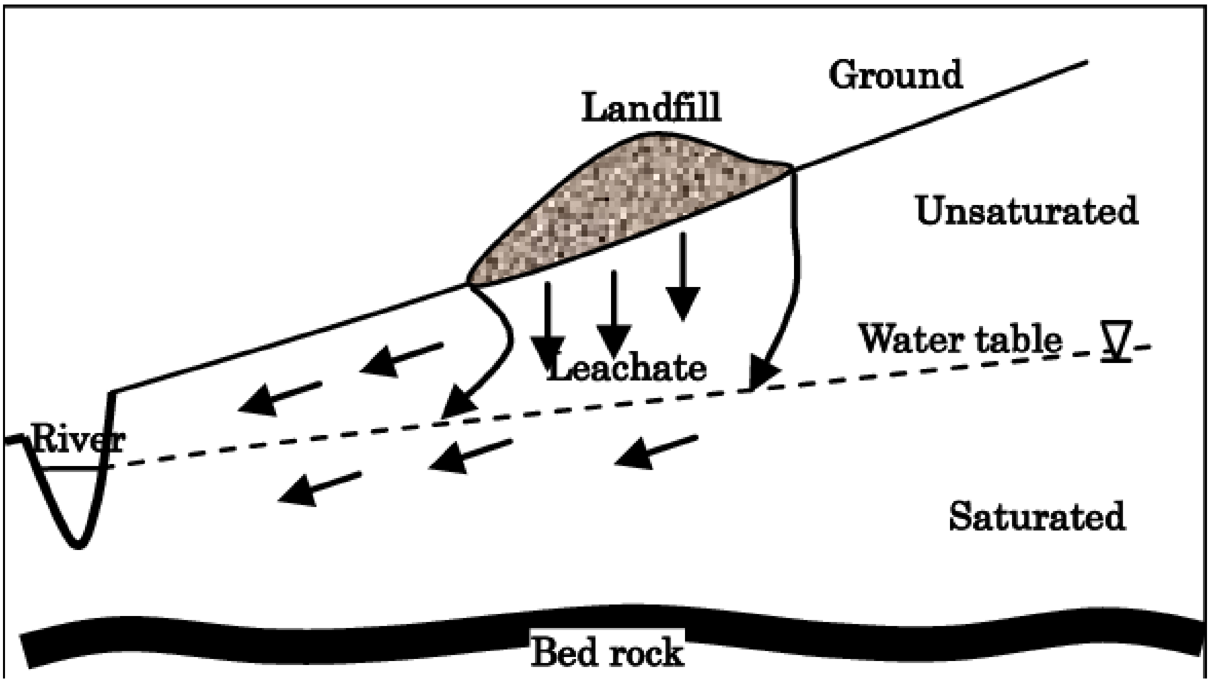


Figure 5.8: Leachate pathway

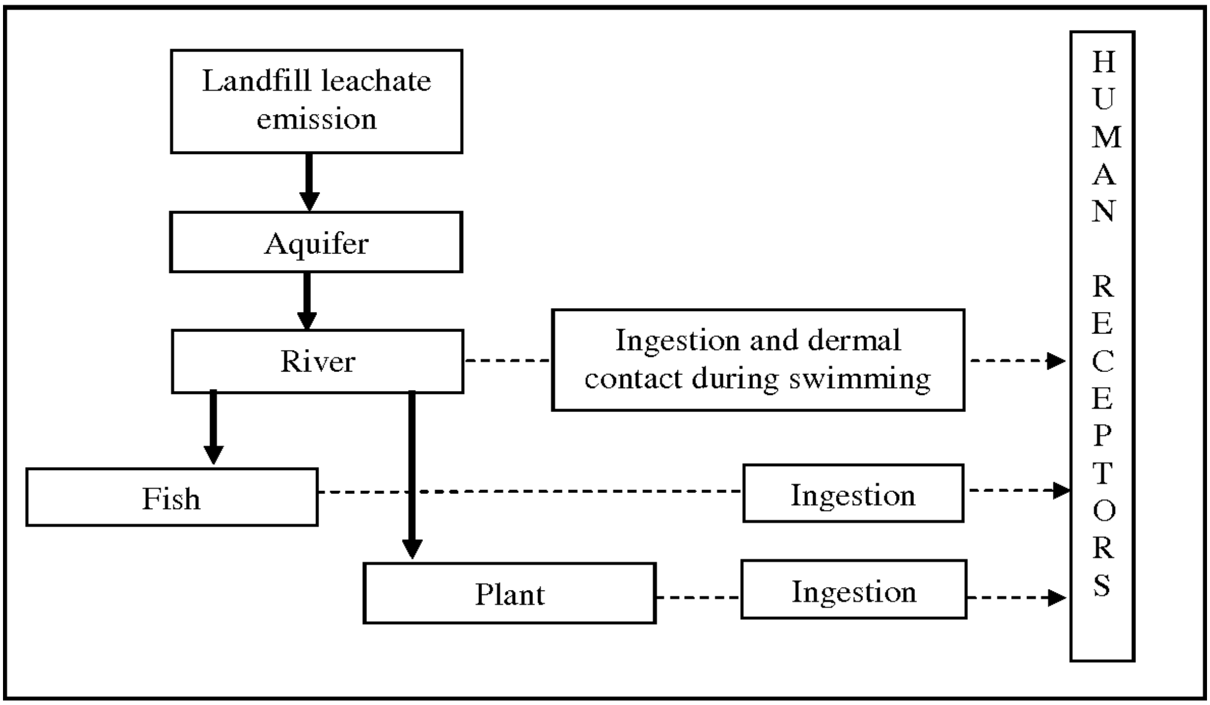


Figure 5.9: Leachate receptors

For a more in-depth look at the individual data for each facility please refer to the Appendix in the latter portion of this report.

6.0 Recommendations

6.1 GRREC

When examining this facility's results, it is clear that the IBA sample that is produced from this facility is very clean. There was hardly any exceedance and was not deemed to be too hazardous from an irritant, corrosive, carcinogenic or ecotoxic standpoint. It was also deemed safe for disposal in landfill specific for non-reactive hazardous waste. This indicates that their sample would be safe to be utilised in construction and road filing purposes. However, there is slight room for improvement to ensure that future samples are cleaner and safer. For instance, regarding the GRREC HP14 test, there were a few zinc oxide exceedances of the 1000mg/kg threshold. Even though this sample does not exceed the legal threshold of 2500 mg/kg it is still best to ensure safety by lowering the zinc concentration.

As it stands, the testing sample can be safely utilised under the law and requires no treatment whatsoever. However, for future samples, it is worth investing into metal recovery technology such as a magnetic separator and eddy current separator. The choice of technology would be dependent on which is the most financially reliable and efficient in producing bottom ash that is clean and applicable for utilisation purposes. As previously mentioned, a very notable way for facilities to earn money through metal recovery would be selling any valuable metals. However, if this option is not viable for GRREC then it is worth investigating the three aforementioned main factors that affect heavy metal concentration.

From a landfill perspective, the result indicate that the sample tested is suitable for non-reactive hazardous waste in non-hazardous landfill. This was due to the only exceedance of the inert waste landfill threshold from the antimony concentration which was 0.45mg/kg. Some form of remediation of the leaching mechanics could very well be an option to ensure that the bottom ash is also safe for inert waste landfill disposal. The overall recommendation options for GRREC is demonstrated in figure 6.1.

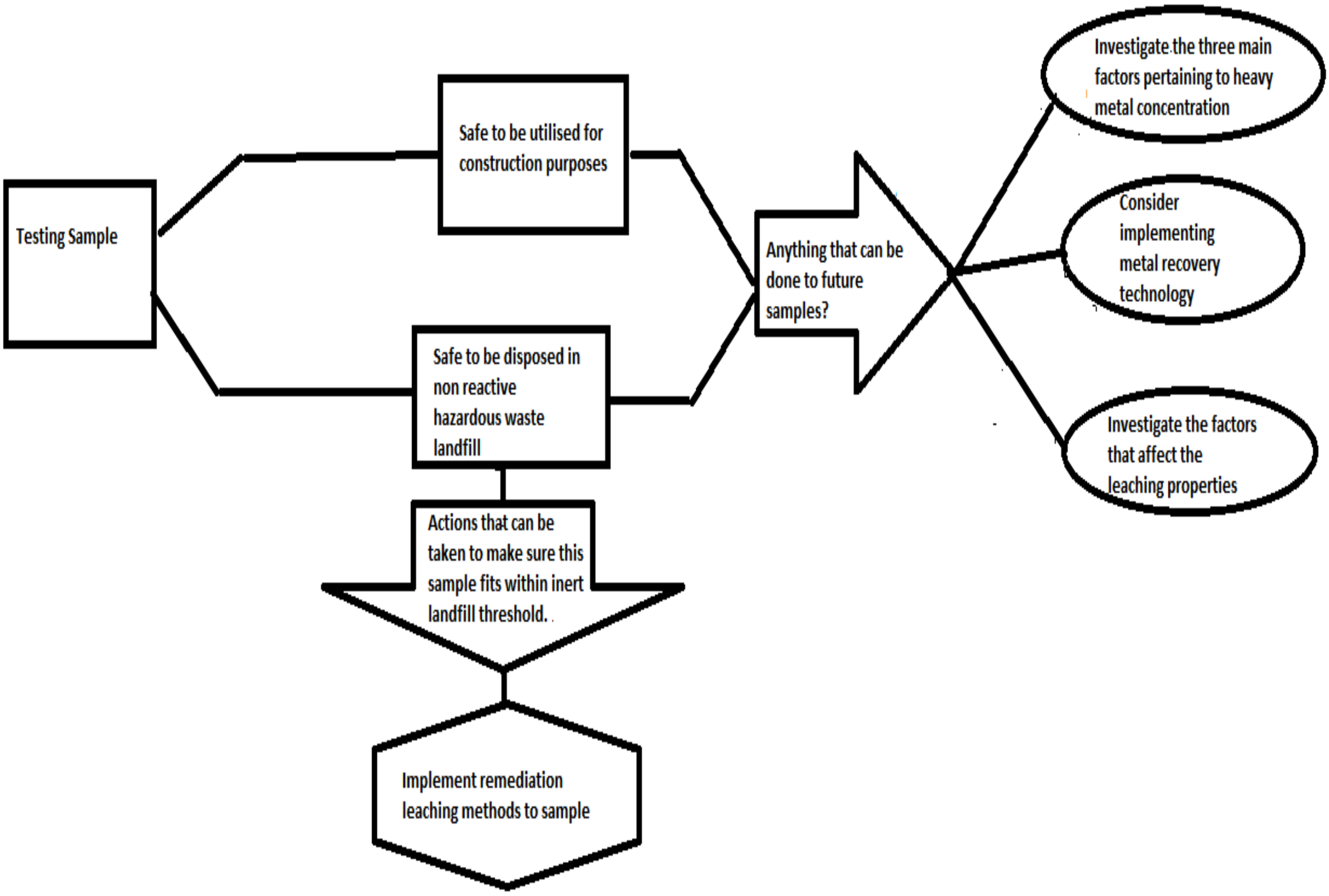


Figure 6.1: GRREC's recommendation graph

6.2 Millerhill & Dunbar

Millerhill's test sample did not experience any form of exceedances whatsoever in any of the hazard testing. This indicates that if utilised and applied in construction or road filing there would be no risk to the surrounding environment. It is also suitable to be disposed into a landfill for hazardous waste as the lead leachate is exceeding the non-reactive stable hazardous waste landfill threshold. If the facility wants this particular sample to fit within non-reactive hazardous threshold than some form of leaching remediation technique would be required. Some pre-emptive decisions can be made regarding the main factors that affect heavy metal concentration in order to make sure that future samples can fit within non-reactive hazardous waste landfill threshold. Other actions relating to factors affecting the rate of leaching can be investigated in order to reduce the amount of lead leachate in future samples. Moreover, due to its suitability to be utilised, utilisation would be the preferred option.

Dunbar's hazard testing would also indicate that their samples are also suitable for construction and road filing purposes due to its lack of exceedances of legal threshold. Overall, when observing the results, they are very clean of heavy metal contamination. Therefore, it is highly recommended that their sample is used for construction aggregate or road filing purposes. Unfortunately, Dunbar’s facility was not able to send any results regarding the landfill suitability of their sample, therefore a recommendation regarding this matter cannot be made.

6.3 Lerwick

Since only landfill suitability tests were conducted on Lerwick’s test samples means that a statement on its suitability in construction or road filing or any other form of utilisation/recycling cannot be made. Unfortunately, the results indicate that the sample tested is too hazardous for landfill disposal as previously mentioned. The concentration of the lead leachate surpasses the legal threshold for hazardous waste indicating that the leachate would pose a huge risk onto the surrounding environment. It is important to remember, as previously mentioned, there are several factors that affect the degree of leaching that occurs which are as follows:

- Ash behaviour
- Liquid to solid ratio (The leaching of heavy metal is typically done through solubility, therefore, ash with a liquid to solid ratio will accelerate the release of heavy metal)
- The impact of pH level
- Weathering and aging
- Use of chemical reagent
- Use of bacteria and fungi

A recommendation for Lerwick’s facility is to address this issue by investigating these factors when testing for the leachate content again. If this issue reoccurs when retesting after readjusting some of these factors then it is worth investigating the aforementioned factors that affect heavy metal concentration in bottom ash. Investigating these issues is a must as it will help to prevent this issue from reoccurring again in future samples. Another option would be installing a more modern comprehensive metal recovery technology as it is evidently clear that the magnetic separators are not efficient enough. If financially viable, then Lerwick should consider implementing eddy current separator technology and/or implementing pre-metal recovery treatment as these are more comprehensive ways to recover heavy metal

However, regarding the sample in question, a form of post treatment would be required because currently this sample is too hazardous for landfill disposal. As previously mentioned, there are many different methods that can be applied to bottom ash as a form of post treatment to remediate and prevent the leaching of harmful heavy metals in landfill. The following are the recommended procedures and methods to take to remediate and prevent the leaching of harmful heavy metals:

- Separation techniques
- Washing
- Electrochemical process
- Solidification & stabilization
- Vitrification
- Thermal treatment
- Accelerated carbonation
- Hydrothermal solidification
- Chemical stabilization
- Thermal treatment
- Melting/fusion

However, it must be said that these recommendations are a must and not a suggestion due to the fact that, as it currently stands, Lerwick’s samples are not suitable for landfill disposal and therefore require some form of treatment to reduce its leachate content so that it is within the thresholds for landfill disposal. The overall Lerwick recommendation options is demonstrated in figure 6.2.

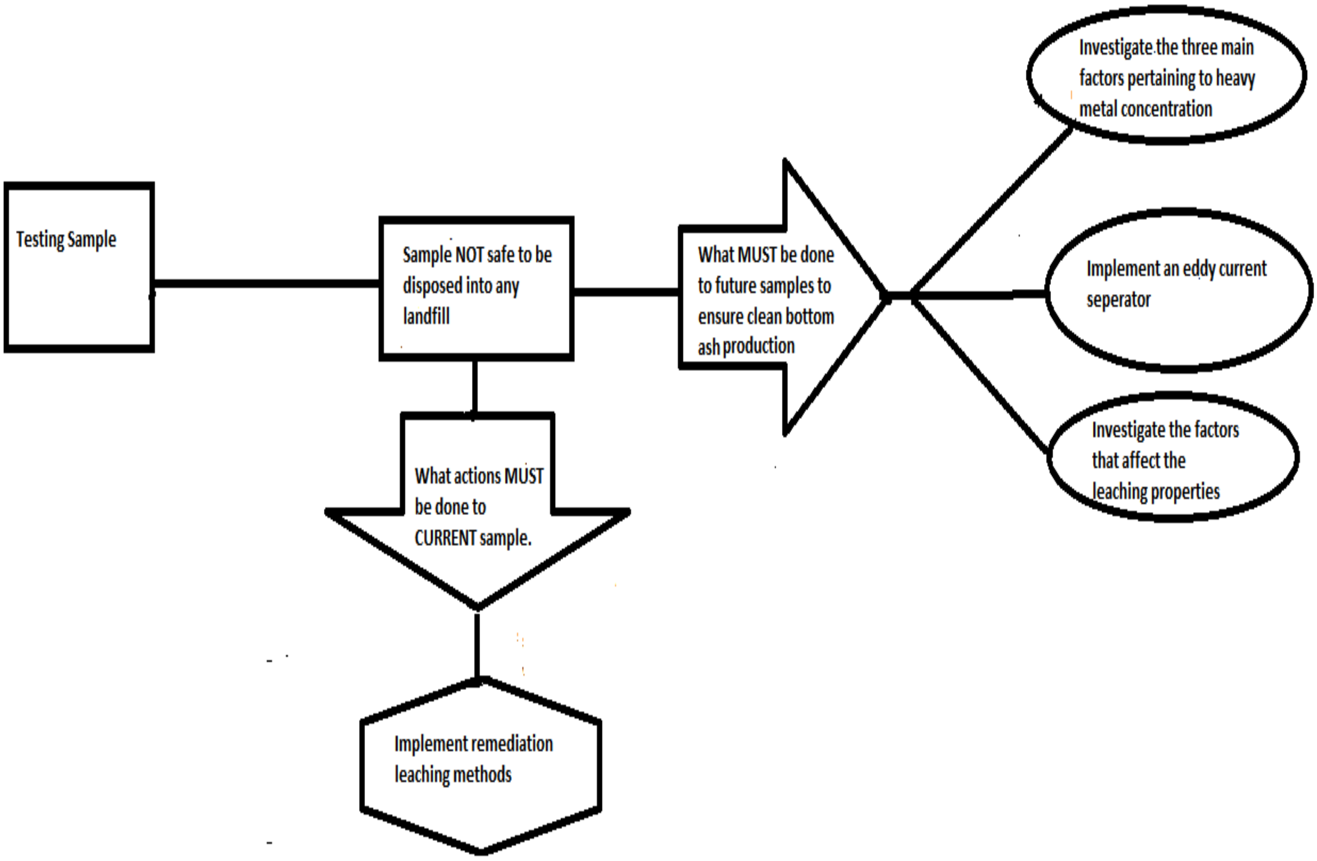


Figure 6.2: Lerwick's recommendation graph

6.4 Levenseat

Unfortunately, the only testing done to the Levenseat's sample were investigating its suitability in utilisation regarding heavy metal hazards. No landfill disposal testing was done, therefore, a statement or recommendations on its suitability regarding landfill disposal cannot be made. As previously mentioned, Levenseat experienced a lot of exceedances, however, it became an issue regarding the HP 14 hazard testing. More than 10% of its samples experienced exceedances over the legal threshold indicating that the ecotoxic risk posed to the surrounding environment is too great for the sample to be utilised or recycled in any manner.

Due to this exceedance, it is imperative that Levenseat investigates the viability of disposal to make use of this current sample. If the sample's leachate content is too hazardous for any landfill, then remediation measures must take place. In regards to utilisation hazards and not leachate hazardous, there are not any remediation measure that can be done to a bottom ash once it is produced. The only option is to take measures in lowering the risks of hazards regarding utilisation for future samples

A method that Levenseat can implement in order to reduce the risk of hazardous bottom ash being produced in the future is to incorporates metal recovery technology. The choice of metal recovery technology that can be implemented and the choice of implementing pre-metal recovery treatment is dependent on what is the most finically viable and efficient option. It is interesting to note when observing the HP 14 results it can be seen that the heavy metals that are of concern are mostly copper and zinc. Whilst the zinc market value may not be that high, the market value for copper is: it is reported to be 4€/kg in table 2.5. Therefore, it may be worth investing in high-end technology in the facility such as eddy current separators whilst incorporating pre-metal recovery techniques such as crushing and sieving. It is hard to make a definite statement on which metal recovery technology may be best suited for this facility due to the other unknown expenses they may have, although treating future samples is a high priority.

To ensure that future samples are safe for utilisation and recycling purposes it is also worth investigating the three primary factors affecting heavy metal concentration in bottom ash. To expand on these three factors, there are many examples on improving upon these factors to ensure safe bottom ash being produced. For instance, to ensure a cleaner input into a WTE facility, a process called "pre-sorting" can take place. This process would typically take place in a material recovery facility (MRF), where solid recovered fuel "SRF" would be produced as an input. A key difference between SRF and refused derived fuel (RDF), is that RDF doesn't have a strict definition nor is it subject to any strict standards or regulations. On the other hand, SRF is well defined and is typically produced from non-hazardous waste and must compile with European standard EN 15359 (Ragazzi and Rada, 2012). Due to the fact that RDF is not strictly defined by law, there comes an environmental risk with the application of it in WTE. One of the environmental risks that would arise would be the production of bottom ash that is highly contaminated with heavy metals. Therefore, to ensure a cleaner production of ash residue from energy recovery, it is imperative to consider the use of SRF.

The combustion process factor refers to the type of technology that a facility incorporates to produce its energy. There are three main types of combustion technology to choose from; incineration, gasification and pyrolysis. The incineration process (which Dunbar, Millerhill and Lerwick use) incorporates fully oxidised combustion, which results in energy production with a lot of ash residue production too. Unfortunately, there is a higher risk of hazardous ash residue production regarding incineration combustion (Samolada and Zabaniotou, 2014). Gasification technology refers to a facility that incorporates partial oxidation. This form of oxidation is typically more cleaner regarding its emissions and produces less hazardous ash residue (Samolada and Zabaniotou, 2014). Evidently the results would indicate that despite Levenseat using gasification technology the bottom ash produced is still very hazardous. This would indicate that the issue lies in the other two factors: waste input and the physiochemical condition of the facility. The overall Levenseat recommendation option is demonstrated in figure 6.3.

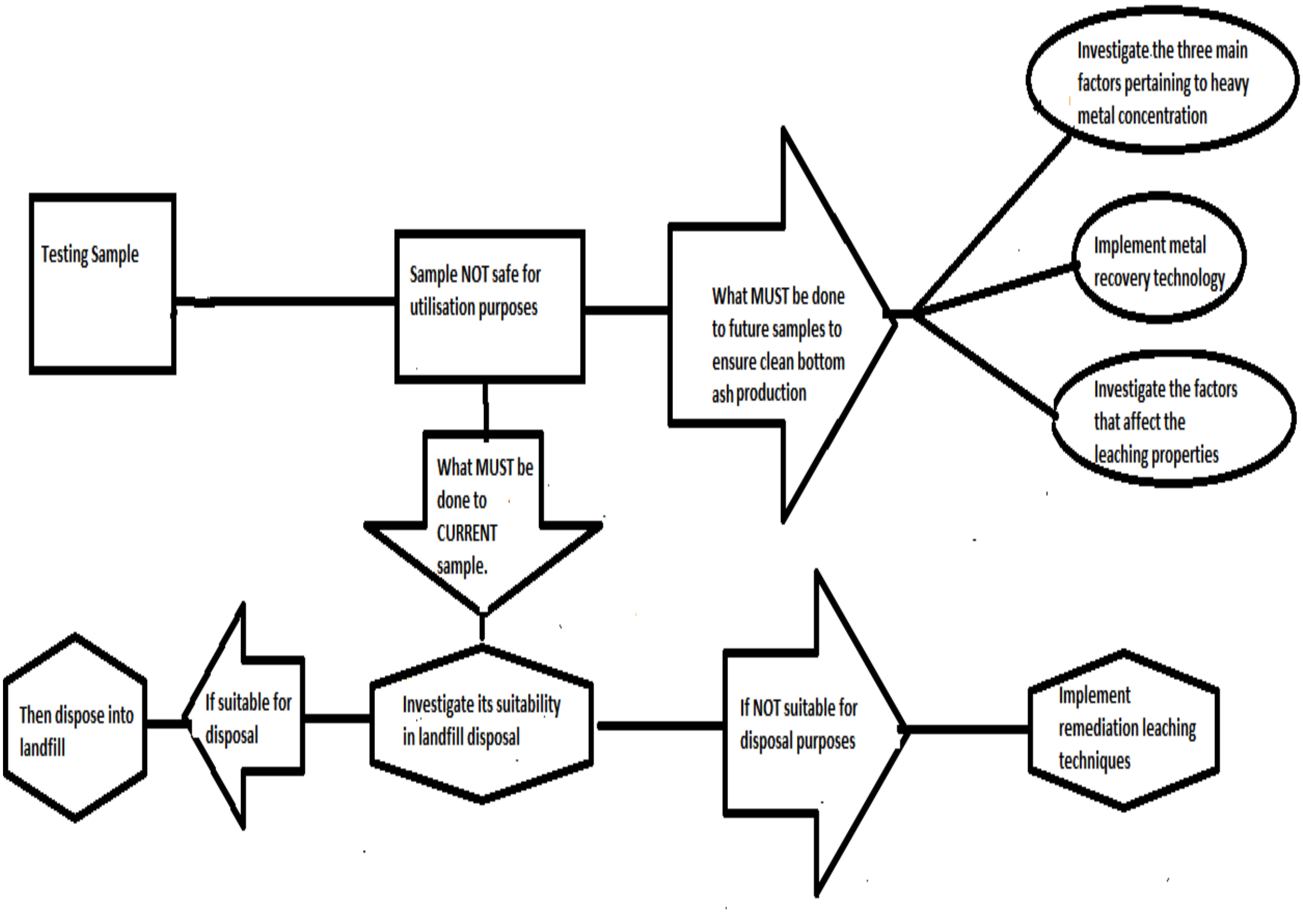


Figure 6.3: Levenseat's recommendation graph

7.0 Conclusion

They are many different hazards to look out for when considering the utilisation of bottom ash. These hazards are irritants, corrosion, carcinogenic and ecotoxic hazards, which all have major risks to the wider society and environment. There is even a risk that comes with landfill disposal regarding the hazardous level of heavy metal leaching. The heavy metal leachate has many different pathways that can be very damaging to public health and the environment. Therefore, it is essential that WTE facilities take the necessary precautions prior to their energy production to ensure that the bottom ash that is produced is not deemed too hazardous by law. It is also essential to apply proper remediation techniques and methods to bottom ash that has been tested to show high hazardous levels of harmful leachate.

This notion is evident through the analysis portion of this report. Taking data from different facilities opened an opportunity to showcase different bottom ash samples varying in their levels of hazardous contamination. This was helpful to show how heavy metal contamination can affect the utilisation of bottom ash, because different recommendations were made to different WTE facilities based on their bottom ash contamination. The difference in the recommendations is the true indication of how heavy metal contamination can affect the utilisations of bottom ash. In the case of this report, the Lerwick and Levenseat samples were above hazard thresholds and thus were *not* applicable to either landfill disposal or construction/road filing utilisation, respectively. In the case of Lerwick, it was recommended that remediation techniques and methods were done before their bottom ash is disposed into landfill to prevent extremely hazardous levels of lead leaching into the surrounding environment. Regarding Levenseat's samples, testing should be done to investigate its suitability for landfill disposal. Some of the same recommendations were made to the other facilities in this paper such as Dunbar, Millerhill and GRREC, however, these recommendations were only suggestions and not requirements. Even though some of these facilities may have experienced some exceedances, these exceedances were not surpassing legal requirements set out by SEPA and therefore were allowed to be utilised in construction and be disposed into landfill. In the case of Levenseat, their HP14 testing had over 10% of its samples exceeding the legal threshold thus indicating that their sample was too ecotoxic to be utilised. In the case of Lerwick, their lead leachate exceeded the threshold for hazardous landfill waste thus meaning it is too hazardous to be disposed in any form of landfill and thus require post treatment before disposal.

They are many recommendations that can made for future work within this topic. The first major recommendation would be regarding a first-hand laboratory experience in a post Covid-19 future. As mentioned earlier in this report, due to the newly implemented social distancing laws and the shutdown of universities, personally examining bottom ash was not possible and therefore required WTE facilities to send their results. The advantage of personally examining bottom ash in a laboratory setting is that it can allow for more freedom regarding experimenting with different physiochemical conditions of the bottom ash. For example, this means conditions and variables such as pH, BTEX (Benzene, toluene, ethylene and xylene) concentration and dioxins concentration can be experimented with and studied to see what their effect on heavy metal concentration would be. Another recommendation for the future is to build on previous works such as Linh et al. (2020), regarding weather conditions affecting landfill heavy metal leachate. The aforementioned study built a good foundation to build off of, as many avenues can be taken from this topic. These topics can vary from studying how weather affects the pathway of heavy metal leachate to studying more extreme weather conditions such as storms and snowfall effects on landfill leachate. Finally, the last suggestion would be studying the other forms of toxins in the bottom ash used in this report that were not mentioned. Since this report was focusing on heavy metal contamination, not much was mentioned on the other dioxins found in bottom ash or even the APC (air pollution control) effects on emissions reduction. A paper that specifically studies one of these issues with the same WTE facility results used in this paper would be very interesting and would help to build upon the body of literature on this topic.

Personally, tackling this topic has given me a lot of insight and knowledge into the world of waste management and the problems that surround bottom ash utilisation. Replacing natural aggregate with bottom ash aggregate can be very helpful in the global effort to lower carbon emissions, however existing laws regarding heavy metal concentration cannot be ignored. This is due to the fact that hazardous levels of heavy metal concentration can lead to many issues regarding public health and the environment. As a result, WTE facilities would need to conduct good practice within their operations and waste input to ensure safe bottom ash production to be utilised. The same can be said regarding bottom ash sent to landfill as there are many different remediation techniques and methods that can be applied to lower the heavy metal leachate content before it is sent to landfill. When reflecting on Britain’s perspective on bottom ash, it seems to be reasonable in comparison to other nations, as they appear to be striking a balance between what is safe to the public health and lowering the global carbon emissions.

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9.0 Appendix

9.1 GRREC Data

Sample Count	1/12 alkali reserve	Irritant / Corrosive (pH+1/12 alkali reserve)	Exceeds HP4 limit?* Irritant>11.50	Exceeds HP8 limit?* Corrosive>11.50
-	-	-	Yes/No	Yes/No
1	0.01	10.93	No	No
2	0.01	11.02	No	No
3	0.02	11.20	No	No
4	0.01	10.95	No	No
5	0.01	10.84	No	No
6	0.01	10.95	No	No
7	0.01	10.86	No	No
8	0.01	10.77	No	No
9	0.01	10.88	No	No
10	0.01	10.81	No	No
11	0.01	10.86	No	No
12	0.01	10.79	No	No
13	0.01	10.61	No	No
14	0.01	10.90	No	No
15	0.01	10.92	No	No
16	0.01	10.92	No	No
17	0.01	11.07	No	No
18	0.01	10.75	No	No
19	0.01	11.05	No	No
20	0.01	10.78	No	No
21	0.01	10.64	No	No
22	0.01	10.50	No	No
23	0.01	10.73	No	No
24	0.01	10.62	No	No

Appendix 9.1: GRREC HP4 & HP8 data

Sample Count	Nickel hydroxide	Exceeded HP7 Concentration limit? Ni(OH)$_2$>1000
-	mg/kg	Yes/No
1	257	No
2	90.7	No
3	95.8	No
4	117	No
5	89.5	No
6	106	No
7	105	No
8	81.3	No
9	71.1	No
10	87.0	No
11	98.8	No
12	75.6	No
13	74.4	No
14	90.6	No
15	89.7	No
16	106	No
17	100	No
18	110	No
19	152	No
20	94.0	No
21	94.3	No
22	91.3	No
23	125	No
24	87.8	No

Appendix 9.2: GRREC HP7 data

Sample Count	Lead	Nickel hydroxide	10% Copper oxide	30% Zinc oxide	Sum (if any >1000)	Exceeded HP14 Concentration limt?* Sum>2500
	mg/kg	mg/kg	mg/kg	mg/kg	-	Yes/No
1	276	257	683	1,131	1,131	No
2	155	90.7	567	755	0	No
3	171	95.8	565	943	0	No
4	62.9	117	505	547	0	No
5	81.9	89.5	514	480	0	No
6	153	106	447	1,172	1,172	No
7	139	105	464	940	0	No
8	234	81.3	398	813	0	No
9	88	71.1	299	454	0	No
10	249	87.0	566	1,106	1,106	No
11	283	98.8	492	912	0	No
12	123	75.6	338	899	0	No
13	96	74.4	268	580	0	No
14	174	90.6	433	816	0	No
15	141	89.7	441	974	0	No
16	316	106	670	1,309	1,309	No
17	211	100	472	833	0	No
18	152	110	548	1,165	1,165	No
19	159	152	677	1,175	1,175	No
20	78.2	94.0	302	668	0	No
21	158	94.3	482	885	0	No
22	142	91.3	320	808	0	No
23	156	125	499	807	0	No
24	142	87.8	384	782	0	No

Appendix 9.3: GRREC HP14 data

Parameter (mg/kg)	Inert Waste Landfill (mg/kg)	Hazardous Waste Landfill (mg/kg)	GRREC Sample (mg/kg)
TOC %	3	6	0.8
LOI %		10	6.74
BTEX	6		**11.2**
PAHs	100		6.36
PCBs	1		0
TPH C10-40	500		37.3
pH			10.9
ANC pH4 (mol/kg)			6.69
ANC pH7 (mol/kg)			4.96

Heavy Metals LS 1:10	Inert Waste Landfill (mg/kg)	Stable Non-reactive Hazardous Waste in Non-Hazardous Landfill (mg/kg)	Hazardous Waste Landfill (mg/kg)	GRREC Sample (mg/kg)
Arsenic	0.5	2	25	<0.05
Barium	20	100	300	0.3
Cadmium	0.04	1	5	<0.01
Chromium	0.5	10	70	<0.2
Copper	2	50	100	<0.05
Mercury	0.01	0.2	2	<0.01
Molybhedum	0.5	10	30	0.49
Nickel	0.4	10	40	<0.1
Lead	0.5	10	50	<0.05
Antimony	0.06	0.7	5	**0.45***
Selenium	0.1	0.5	7	<0.03
Zinc	4	50	200	<0.5

** indicates when a test sample exceeds the heavy metal leachate threshold for its disposal inert in a waste landfill*

*** indicates when a test sample exceeds the heavy metal threshold for its disposal stable in a non-reactive hazardous waste in non – hazardous landfill*

**** indicates when a test sample exceeds the heavy metal leachate threshold for its disposal in a hazardous waste landfill*

Appendix 9.4 & 9.5: GRREC WAC parameter & WAC table of results

9.2 Millerhill Data

Sample Count	1/12 alkali reserve	irritancy / corrosivity (pH+1/12 alkali reserve)	Exceeds HP4 threshold?* Irritancy>13.03	Exceeds HP8 threshold?* Corrosivity>14.5
-	-	-	Yes/No	Yes/No
1	0.12	12.74	No	No
2	0.11	12.69	No	No
3	0.08	12.56	No	No
4	0.06	12.44	No	No
5	0.12	12.71	No	No
6	0.11	12.63	No	No
7	0.06	12.42	No	No
8	0.11	12.70	No	No
9	0.08	12.59	No	No
10	0.08	12.59	No	No
11	0.11	12.75	No	No
12	0.05	12.45	No	No
13	0.13	12.82	No	No
14	0.12	12.80	No	No
15	0.12	12.78	No	No
16	0.11	12.83	No	No
17	0.09	12.64	No	No
18	0.10	12.63	No	No
19	0.11	12.70	No	No
20	0.11	12.69	No	No
21	0.11	12.73	No	No
22	0.11	12.68	No	No
23	0.11	12.75	No	No
24	0.12	12.73	No	No

Appendix 9.6: Millherhill HP4 & HP8 data

Sample Count	Nickel Hydroxide	Exceeded HP7 threshold? Ni(OH)2>1000
-	-	Yes/No
1	100	No
2	114	No
3	99.2	No
4	107	No
5	115	No
6	110	No
7	83.1	No
8	120	No
9	84.7	No
10	94.1	No
11	104	No
12	104	No
13	227	No
14	127	No
15	131	No
16	101	No
17	107	No
18	129	No
19	102	No
20	99.1	No
21	112	No
22	115	No
23	905	No
24	115	No

Appendix 9.7: Millerhill HP7 data

Sample Count	Lead	Nickel hydroxide	20% Copper hydroxide	Sum (if any >1000 mg kg^{-1})	Exceeded HP14 Threshold? Sum >2500 mg kg^{-1}
-	mg/kg	mg/kg	mg/kg	-	Yes/No
1	481	100	563	0	No
2	436	114	629	0	No
3	414	99.2	653	0	No
4	179	107	538	0	No
5	275	115	733	0	No
6	191	110	569	0	No
7	327	83.1	541	0	No
8	334	120	630	0	No
9	362	84.7	545	0	No
10	249	94.1	524	0	No
11	256	104	497	0	No
12	479	104	485	0	No
13	209	227	609	0	No
14	494	127	721	0	No
15	294	131	685	0	No
16	634	101	668	0	No
17	232	107	708	0	No
18	452	129	685	0	No
19	699	102	571	0	No
20	897	99.1	543	0	No
21	282	112	660	0	No
22	596	115	484	0	No
23	468	905	404	0	No
24	485	115	468	0	No

Appendix 9.8: Millerhill HP 14 data

Parameter (mg/kg)	**Inert Landfill (mg/kg)**	**Hazardous Landfill (mg/kg)**	**Leaching Sample 1 (mg/kg)**	**Leaching Sample 2 (mg/kg)**	**Leaching Sample 3 (mg/kg)**
TOC %	3	6	0.2	0.5	0.5
LOI %		10	0.58	1.51	2.22
Acid Neutralisation Capacity at pH 4			3.81	4.69	4.62
Acid Neutralisation Capacity at pH 7			3.39	4.24	3.85

Heavy Metals LS 1:10	**Inert Waste Landfill (mg/kg)**	**Stable Non-reactive Hazardous Waste in Non-Hazardous Landfill (mg/kg)**	**Hazardous Waste Landfill (mg/kg)**	**Millerhills Leaching Sample (mg/kg)**
Arsenic	0.5	2	25	<0.05
Barium	20	100	300	**48.4***
Cadmium	0.04	1	5	<0.01
Chromium	0.5	10	70	<0.2
Copper	2	50	100	0.87
Mercury	0.01	0.2	2	<0.01
Molybhedum	0.5	10	30	0.38
Nickel	0.4	10	40	<0.1
Lead	0.5	10	50	**10.9****
Antimony	0.06	0.7	5	**0.24***
Selenium	0.1	0.5	7	<0.03
Zinc	4	50	200	**6***

** indicates when a test sample exceeds the heavy metal leachate threshold for its disposal inert in a waste landfill*

*** indicates when a test sample exceeds the heavy metal threshold for its disposal stable in a non-reactive hazardous waste in non – hazardous landfill*

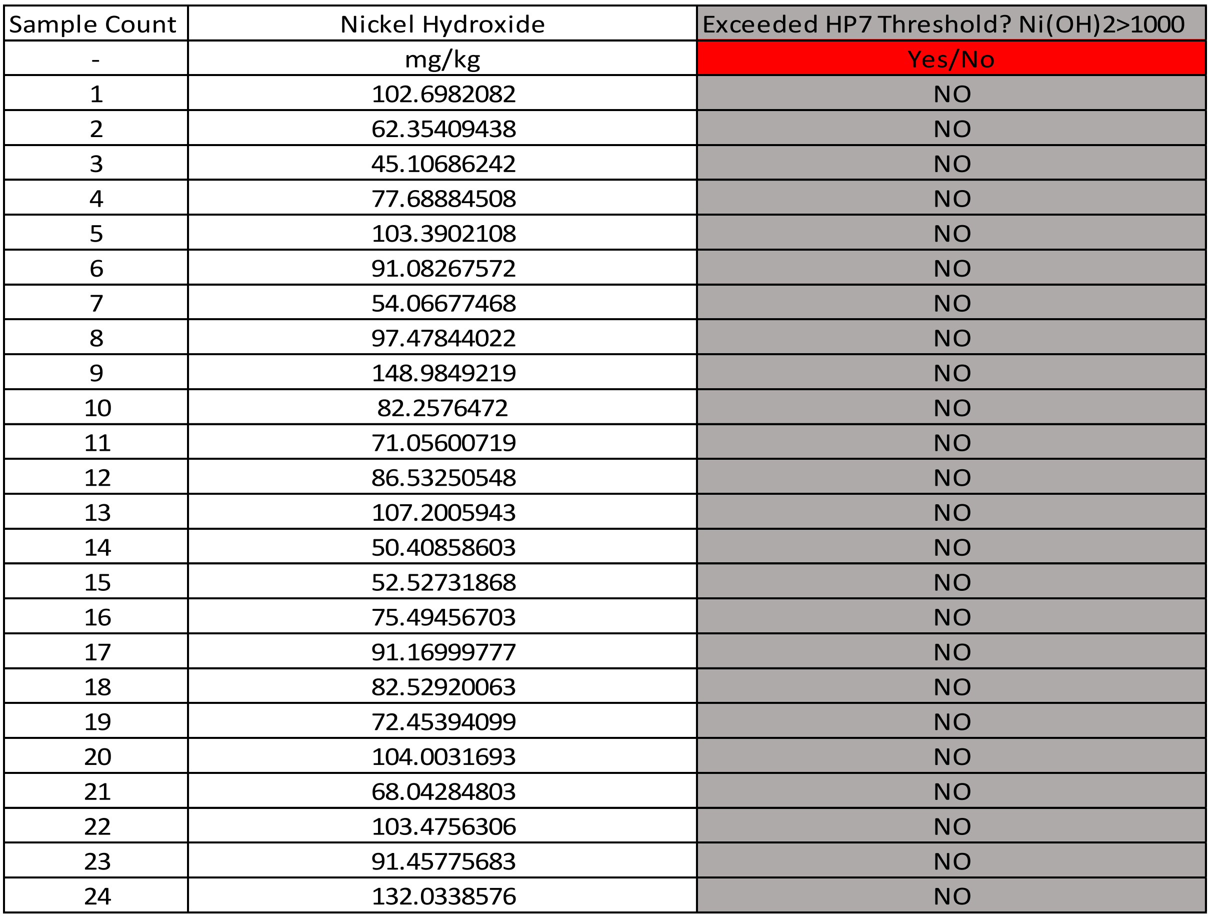
**** indicates when a test sample exceeds the heavy metal leachate threshold for its disposal in a hazardous waste landfill*

Appendix 9.9 & 9.10: Millerhill WAC parameter & WAC table of results

9.3 Dunbar’s ERF data

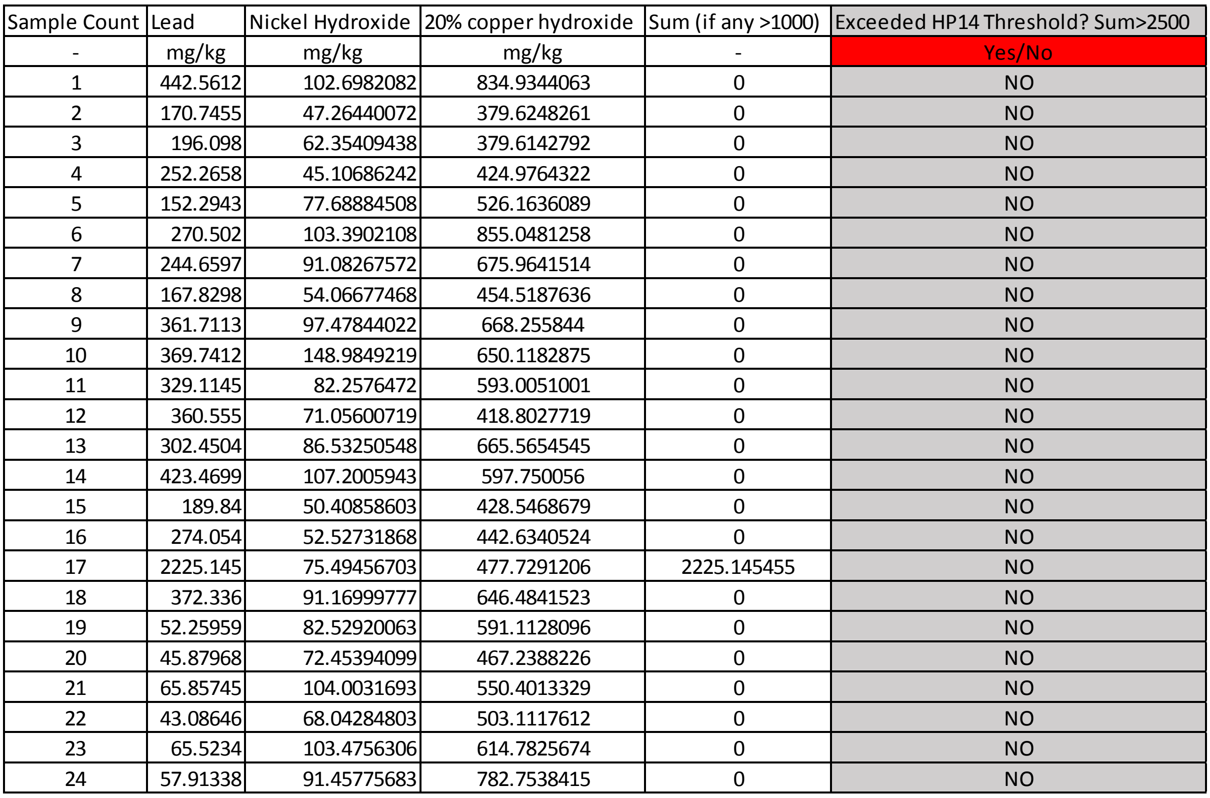
Sample Count	1/12 alkali reserve	Irritancy / corrosivity (pH+1/12 alkali reserve)	Exceeds HP4 threshold? Irritancy > 13.03	Exceeds HP8 threshold? Corrosivity>14.5
-	-	-	Yes/No	Yes/No
1	0.05	12.52	NO	NO
2	0.108333333	12.775	NO	NO
3	0.108333333	12.84166667	NO	NO
4	0.116666667	12.78333333	NO	NO
5	0.116666667	12.85	NO	NO
6	0.091666667	12.75833333	NO	NO
7	0.083333333	12.75	NO	NO
8	0.133333333	12.83333333	NO	NO
9	0.125	13.00833333	NO	NO
10	0.116666667	13	NO	NO
11	0.116666667	13.01666667	NO	NO
12	0.108333333	12.80833333	NO	NO
13	0.108333333	12.90833333	NO	NO
14	0.108333333	13.015	NO	NO
15	0.108333333	12.80833333	NO	NO
16	0.116666667	12.91666667	NO	NO
17	0.116666667	12.95	NO	NO
18	0.041666667	12.74166667	NO	NO
19	0.025	12.39166667	NO	NO
20	0.025	12.425	NO	NO
21	0.025	12.15833333	NO	NO
22	0.025	12.05833333	NO	NO
23	0.008333333	12.075	NO	NO
24	0.008333333	12.00833333	NO	NO

Appendix 9.11: Dunbar’s HP 4 & HP 8 data



Sample Count	Nickel Hydroxide	Exceeded HP7 Threshold? Ni(OH)2>1000
-	mg/kg	Yes/No
1	102.6982082	NO
2	62.35409438	NO
3	45.10686242	NO
4	77.68884508	NO
5	103.3902108	NO
6	91.08267572	NO
7	54.06677468	NO
8	97.47844022	NO
9	148.9849219	NO
10	82.2576472	NO
11	71.05600719	NO
12	86.53250548	NO
13	107.2005943	NO
14	50.40858603	NO
15	52.52731868	NO
16	75.49456703	NO
17	91.16999777	NO
18	82.52920063	NO
19	72.45394099	NO
20	104.0031693	NO
21	68.04284803	NO
22	103.4756306	NO
23	91.45775683	NO
24	132.0338576	NO

Appendix 9.12: Dunbar HP 7 data



Sample Count	Lead	Nickel Hydroxide	20% copper hydroxide	Sum (if any >1000)	Exceeded HP14 Threshold? Sum>2500
-	mg/kg	mg/kg	mg/kg	-	Yes/No
1	442.5612	102.6982082	834.9344063	0	NO
2	170.7455	47.26440072	379.6248261	0	NO
3	196.098	62.35409438	379.6142792	0	NO
4	252.2658	45.10686242	424.9764322	0	NO
5	152.2943	77.68884508	526.1636089	0	NO
6	270.502	103.3902108	855.0481258	0	NO
7	244.6597	91.08267572	675.9641514	0	NO
8	167.8298	54.06677468	454.5187636	0	NO
9	361.7113	97.47844022	668.255844	0	NO
10	369.7412	148.9849219	650.1182875	0	NO
11	329.1145	82.2576472	593.0051001	0	NO
12	360.555	71.05600719	418.8027719	0	NO
13	302.4504	86.53250548	665.5654545	0	NO
14	423.4699	107.2005943	597.750056	0	NO
15	189.84	50.40858603	428.5468679	0	NO
16	274.054	52.52731868	442.6340524	0	NO
17	2225.145	75.49456703	477.7291206	2225.145455	NO
18	372.336	91.16999777	646.4841523	0	NO
19	52.25959	82.52920063	591.1128096	0	NO
20	45.87968	72.45394099	467.2388226	0	NO
21	65.85745	104.0031693	550.4013329	0	NO
22	43.08646	68.04284803	503.1117612	0	NO
23	65.5234	103.4756306	614.7825674	0	NO
24	57.91338	91.45775683	782.7538415	0	NO

Appendix 9.13: Dunbar HP 14 data

9.4 Lerwicks Data

Parameter (mg/kg)	Inert Landfill Waste (mg/kg)	Stable Non-reactive Hazardous Waste in Non-Hazardous Landfill (mg/kg)	Hazardous Waste Landfill (mg/kg)	Lerwicks Leaching Sample
TOC %	3	5	6	0.82
LOI%			10	5.8

Heavy Metals LS 1:10	Inert Waste Landfill (mg/kg)	Stable Non-reactive Hazardous Waste in Non-Hazardous Landfill (mg/kg)	Hazardous Waste Landfill (mg/kg)	Millerhills Leaching Sample (mg/kg)
Arsenic	0.5	2	25	0.01
Barium	20	100	300	1.9
Cadmium	0.04	1	5	<0.0001
Chromium	0.5	10	70	0.17
Copper	2	50	100	**7.26***
Mercury	0.01	0.2	2	0.006
Molybhedum	0.5	10	30	0.74
Nickel	0.4	10	40	0.06
Lead	0.5	10	50	**92.7*****
Antimony	0.06	0.7	5	<0.01
Selenium	0.1	0.5	7	0.05
Zinc	4	50	200	**10.87***

** indicates when a test sample exceeds the heavy metal leachate threshold for its disposal inert in a waste landfill*

*** indicates when a test sample exceeds the heavy metal threshold for its disposal stable in a non-reactive hazardous waste in non – hazardous landfill*

**** indicates when a test sample exceeds the heavy metal leachate threshold for its disposal in a hazardous waste landfill*

Appendix 9.14 & 9.15: WAC parameter & WAC table of results

9.5 Levenseat Data

Sample Count	Nickel Hydroxide	Exceeded HP7 concentration limit? $Ni(OH)_2$>1,000
	mg/kg	**Yes/No**
1	103	No
2	371	No
3	357	No
4	321	No
5	196	No
6	273	No
7	630	No
8	558	No
9	518	No
10	315	No
11	538	No
12	386	No
13	407	No
14	405	No
15	365	No
16	331	No
17	359	No
18	313	No
19	1,261	**Yes**
20	305	No
21	278	No
22	321	No

Appendix 9.16: Levenseat HP 7 data

Sample Count	Lead	Nickel Hydroxide	100% Copper hydroxide	100% Zinc hydroxide	Sum (if any >1000)	Exceeded HP14 concentration limit? Sum>2,500
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	**Yes/No**
1	120	103	3,888	2,587	6,475	**Yes**
2	177	371	7,823	3,795	11,618	**Yes**
3	183	357	8,218	4,050	12,267	**Yes**
4	213	321	8,086	3,747	11,833	**Yes**
5	123	196	6,899	2,540	9,440	**Yes**
6	124	273	10,100	2,553	12,653	**Yes**
7	301	630	7,312	3,745	11,057	**Yes**
8	256	558	8,349	3,671	12,019	**Yes**
9	284	518	7,897	3,440	11,337	**Yes**
10	205	315	7,501	3,200	10,701	**Yes**
11	334	538	7,492	3,903	11,395	**Yes**
12	319	386	7,377	4,033	11,410	**Yes**
13	179	407	12,901	3,311	16,213	**Yes**
14	168	405	12,501	3,203	15,704	**Yes**
15	171	365	22,995	3,789	26,784	**Yes**
16	162	331	18,050	3,661	21,711	**Yes**
17	227	359	17,602	3,114	20,717	**Yes**
18	200	313	14,194	2,806	17,000	**Yes**
19	184	1,261	12,184	2,302	15,748	**Yes**
20	181	305	11,781	2,664	14,445	**Yes**
21	240	278	13,393	3,089	16,482	**Yes**
22	231	321	12,305	3,027	15,331	**Yes**

Appendix 9.17: Levenseat HP 14 data