Exploring beneficial uses of ferrochrome slag: A case study of a South African Ferrochrome industry

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Mini-dissertation accepted in partial fulfilment of the requirements for the degree *Master in Environmental Management with Waste Management* at the North-West University

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Graduation October 2020

23334118

PREFACE AND ACKNOWLEDGEMENTS

Before the enactment of the *Waste Exclusion Regulations* in South Africa, strict and burdensome legislative requirements to obtain a waste management license limited the progression of South Africa's waste economy and precluded industry from the potential social, economic and environmental benefits. Change in legislation, however made it possible for the beneficial use of Ferrochrome (FeCr) slag. Within this context, the Ferro Alloy Producers Association (FAPA) members drafted a motivational document on the beneficial use of FeCr slag in terms of the W*aste Exclusion Regulations.* They submitted the application to the Minister of Environmental Affairs to consider its exclusion. In January 2020, the Minister of Environment, Forestry and Fisheries (DEFF) approved the applications for beneficial use of FeCr slag.

This dissertation outlines the research done in support of the application submitted for the beneficial use of FeCr slag by a ferrochromium producer.

ACKNOWLEDGMENTS

I wish to extend my sincere gratitude to the following people:

- My Supervisor, Dr Claudine Roos for all the guidance, encouragement and wisdom throughout this journey. Thank you for trusting and believing in my potential.
- I would also like to thank FeCr industry experts who provided advice and support in this research.
- I would like to thank Mr. Riaan Grobbelaar for his valuable contribution and expert advice on my research. Thank you for your patience to my never-ending questions. I acknowledge the work he did on behalf of South African Ferrochrome Industry through FAPA towards the motivation for beneficial use of FeCr slag.
- I would also like to thank the postgraduate bursary fund of the NWU and my employer study assistance, for financial support
- I would like to thank my family, friends and colleagues who supported my studies by their encouraging words, guidance and showing interest to my research topic.
- I am particularly grateful to my children, Mulanga, Oemetswe and Rialivhuwa for your unwavering support and cheering throughout the journey. I thank you for being my motivation to finish my studies. I dedicate this research to you.
- Lastly, I would like to acknowledge God Almighty for granting me strength, wisdom and good health throughout my studies.

ABSTRACT

South Africa is the leading player in the international ferro-alloy industry due to its abundance of natural resources. Ferrochrome (FeCr) slag is a waste material obtained from the manufacturing of ferrochromium alloy. Typically, it contains 30% silicon dioxide (SiO_2), 26% aluminium oxide (Al_2O_3) and 23% magnesium oxide (MgO) in different phases such as spinel and fosterite, with minor traces of ferrous/ferric oxides, chrome oxides and 2% calcium oxide (CaO). Because of its constituents, the FeCr slag has value and can be used for beneficial purposes, however, if not managed correctly, it may have adverse impacts on health and the environment.

The South African National Waste Management Strategy advocates that waste is preferably re-used, recycled and recovered, and disposed to land as a last resort. However, the re-use, recycling and recovery of waste have, to date, not been implemented by industry as a preferred option to disposal. This is partly due to obstacles presented by waste management licencing requirements, financial implications and potential adverse impacts. Recently, the *Waste Exclusion Regulations*, have been promulgated, to promote the beneficial use of waste.

This study aimed to explore the beneficial uses of FeCr slag produced by a selected South African ferroalloy industry. In support thereof, the objectives of this study included: determining the properties of FeCr slag, the risks related to the beneficial use of FeCr slag, exploring the potential beneficial use of the FeCr slag and lastly determining the challenges of and opportunities for the beneficial use of FeCr slag. The results of the waste classification process, leachability test, and risk assessment performed in terms of the Waste Exclusion Regulations indicated that the FeCr slag is non-hazardous and presents a negligible risk to the environment and health of people.

There are several options within the South African context for the beneficial use of FeCr slag, which include the use of FeCr as aggregate, road construction material, construction material. The results of this study supports that reuse of FeCr slag has financial, environmental and business/operational benefits that will ensure sustainability of natural resources and circular economy.

Key terms: Ferrochromium; Ferrochrome slag waste; benefits; challenges; South Africa.

ABBREVIATIONS AND ACRONYMS

ASTM	American Society for Testing and Materials
ATE	Acute Toxicity Estimate
BIC	Bushveld Igneous Complex
CBR	California Bearing Ratio
CLSM	Controlled Low Strength Materials
Cr	Chromium
Cr(III)	Trivalent Chromium
Cr(VI)	Hexavalent chromium
DEA	Department of Environmental Affairs (now DEFF)
DEFF	Department of Environment, Forestry and Fisheries
DWAF	Department of Water Affairs and Forestry (now DWS)
DWS	Department of Water and Sanitation
FAPA	Ferro Alloy Producers Association
FeCr	Ferrochromium
GHS	Globally Harmonised System
H-codes	Hazard statement codes
H-C FeCr	High Carbon Ferro Chrome
HCFS	High Carbon Ferrochrome Slag
HNO_3	Nitric acid
IARC	International Agency for Research on Cancer
ICDA	International Chromium Development Association
ISSF	International Stainless Steel Forum
KOH	Potassium hydroxide
LC_{50}	Lethal concentration 50
LD_{50}	Lethal dose 50
M-C FeCr	Medium Carbon Ferro Chrome

MCFS	Medium Carbon Ferrochrome Slag
MoRTH	Ministry of Road Construction Transport and Highways
MR	Minimum Requirements (for the disposal of waste to land) (1998)
MSDS	Material Safety Data Sheet)
Mt	Mega tonnes
NEMWA	National Environmental Management Waste Act (59 of 2008)
NWMS	National Waste Management Strategy
OPC	Ordinary Portland Cement
PM	Particulate Matter
PPC	Portland Pozzolanic Cement
PSC	Portland Slag Cement
RO	Research Objective
SCM	Supplementary Cementitious Material
rpm	revolution per minute
SANS	South African National Standards
SDS	Safety Data Sheet (also referred to as MSDS)
SP	Significance points
TCLP	Toxicity Characteristics Leaching Procedure
US EPA	United States Environmental Protection Agency
XRD	X-ray Diffraction

DEFINITIONS

Bio-accessibility

The amount of a chemical that is available to interact with an organism's contact surfaces, and is therefore potentially available for absorption.

Van Niekerk, 2011

Bio-availability

The extent to which a substance can be absorbed by a living organism and reach the synthetic circulation.

Van Niekerk, 2011

Bio-elution

In-vitro extraction methods used to measure the degree to which a substance (e.g., metal or mineral ion) is dissolved in artificial biological fluids.

Van Niekerk, 2011

LD_{50}

Represents the amount of chemical, given all at once, which causes the death of 50 per cent of a group of test animals

OHSA, 2013

LC_{50}

Concentration of a chemical in air, which causes the death of 50 per cent of a group of test animals, exposed through inhalation within the stated study time.

OHSA, 2013

Controlled low strength Material (CLMS)

A mixture of soil or aggregate, cementitious materials, fly ash, water and chemical admixtures that hardens into material with higher strength than the soil.

Alizadeh *et al.,* 2014

Ferrochrome (FeCr)

A corrosion-resistant alloy of chrome and iron containing approximately 50% - 70% chromium by weight.

FeCr slag products

The FeCr slag products are granulated slag as well as classified slag products made by crushing and screening. A granule is tight and crystalline; typically, the granulated slag includes three different phases, which are amorphous glass phase, crystalline and zonal Fe-Mg-Cr-Al- spinals and metal drops.

Niemela *et al*., 2007

Particulate Matter

Particles, of any shape, structure or density, dispersed in the gas phase under the sampling conditions.

SANS 12141, 2019

PM_{10}

Particulate matter 10 micrometers or less in diameter **NEM: AQA, 2004**

Residue deposit

Any residue stockpile remaining at the termination, cancellation or expiry of a prospecting right, mining right, mining permit, exploration right, production right or an old order right.

Mineral and Petroleum Resources Development Act (28 of 2002)

Residue stockpile

Any debris, discard, tailings, slimes, screening, slurry, waste rock, foundry sand, beneficiation plant waste, ash or any other product derived from or incidental to a mining operation and which is stockpiled, stored or accumulated for potential re-use, or which is disposed of, by the holder of a mining right, mining permit, production right or an old order right.

Mineral and Petroleum Resources Development Act (28 of 2002)

Slag

Slag is another term referring unwanted solids substances released because of processes from industrial plants or various production mills

Yildiz, 2018

Waste

(a) Any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act; or (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette, but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste—(i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered; (ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered; (iii) where the Minister has, in terms of section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or (iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste.

National Environmental Management Waste Act (59 of 2008), as amended

Waste

Include any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted.

National Water Act (36 of 1998)

Waste classification

Establishing (a) whether a waste is hazardous based on the nature of its physical, health and environmental hazardous properties (hazard classes); and (b) the degree of severity of hazard posed (hazard categories). **GNR 634 of August 2013**

Pozzolanic material

A finely powdered material which can be added to lime mortar (or to Portland cement mortar) to increase durability.

Al-Jabri, 2018

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CHAPTER 1 INTRODUCTION

1.1 Introduction

Ferrochrome (FeCr) slag is a waste material or by-product generated during the production of ferrochromium alloy. The majority of the FeCr slag produced in South Africa is currently disposed to land, resulting in the build-up of large FeCr slag stockpiles and the unnecessary use of natural resources for construction purposes (Beukes *et al*., 2010, Erdem *et al*., 2005). Approximately three-quarters of the world's viable chromite ore reserves are located in South Africa, and the production of FeCr is steadily increasing. The management of FeCr stockpiles and FeCr slag thereof, is of importance to the FeCr industry (Beukes *et al*., 2010, Matinde *et al*., 2018).

Large FeCr slag volumes (which may have value/an alternative beneficial use) occupy thousands of hectares of land space, rendering that space unproductive (Lind *et al*., 2001). High – Carbon FeCr (HC FeCr) produces 1.1 – 1.6 slag/ton of metal with an annual global production of 13 Mt HC FeCr in 2018 (International Chromium Development Association, ICDA, 2019). It is, thus, imperative to explore beneficial uses of slag that will both reduce the space and reduce the utilization of virgin raw materials (Maier, 2012). Additionally, the alternative beneficial use of FeCr slag may be integrated to form a circular economy model that promotes waste avoidance, or reduce the amount of waste disposed to land, as required by the National Waste Management Strategy (NWMS) (DEA, 2011) and, ultimately, lead to the avoidance of disposal costs, and the reduction of environmental pollution. In the FeCr industry, this will mean that FeCr slag is not regarded as a waste but a product that can be recycled for beneficial use.

1.2 Problem statement

Prior to the promulgation on National Environmental Management Waste Act (NEMWA) in 2008, the *Minimum requirements (MR) for the handling classification and disposal of hazardous waste* (DWAF, 1998), classified FeCr slag as *hazardous waste* due to its physico-chemical characteristics, quality and large volumes that are produced. As such, there was limited use of FeCr slag commercially (Booysen, 2009). The MR document on waste disposal applied a precautionary principle especially in the industrial sector that waste is hazardous and toxic until proven otherwise. Thus, the re-use of such waste was dependent on the outcomes of the delisting process, but nonetheless the reclassified waste retained its legal status of being *waste*.

With the introduction of National Environmental Management Waste Act (59 of 2008) (NEMWA) in 2008, the previous legislation regulating waste management was reformed. The NEMWA deals with waste management and control in a comprehensive manner, and introduces the waste management hierarchy, with waste prevention as the preferred option followed by reuse, recycling, recovery, and as a last resort, safe disposal (RSA, 2008). In addition to NEMWA, a new system (waste classification and management system) for the classification of waste was introduced in August 2013. Moodie (2016) reflected on the application of this system as it relates to the classification of FeCr slag in South Africa, highlighting the beneficial uses, but also the limitations associated with the re-use of FeCr slag. There were, however, still limitations applicable to the beneficial use of FeCr slag, such as the risk of taking an approach that can be seen as advocative, that is collating available evidence or producing new information to support a pre-determined policy position (Moodie, 2016). Additionally, even if the FeCr slag could have been applied for a beneficial use, it was still legally regarded as being *waste*, until re-used, recycled or recovered in terms of the NEMWA definition[1].

In July 2018, however, new regulations were introduced in terms of the NEMWA, entitled *Regulations regarding the exclusion of a waste stream or a portion of a waste stream from the definition of waste* (GN 715 of 18 July 2018) (referred to as the *"waste exclusion regulations"*) (RSA, 2018). The purpose of these regulations is to- (a) prescribe the manner in which a person or a category of persons may apply to the Minister for the exclusion of a waste stream or a portion of waste stream for beneficial use from the definition of waste; (b) exclude permitted uses of a waste stream or a portion of waste stream from the definition of waste; and (c) promote diversion of waste from landfill disposal to its beneficial use (RSA, 2018b).

Should a waste stream be excluded from the NEMWA definition of waste, the requirements of the NEMWA are no longer applicable, and it may exempt that waste stream, for example, from the requirements of applying for a waste management licence, which may be regarded as a benefit to industry. Prior to the waste exclusion regulations being promulgated, strict and burdensome legislative requirements have discouraged industry from exploring the potential beneficial use of FeCr slag. The waste exclusion regulations are regarded as a mechanism to encourage industry to promote the circular economy, and support the implementation of the waste management hierarchy.

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[1] Waste means (a) any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act; or (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette, but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste—(i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered; (ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered; (iii) where the Minister has, in terms of section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or (iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste (RSA, 2008).

Note: *The research done as part of this study and reported in this dissertation, was used to motivate and support the application for the beneficial use of FeCr slag by a South African FeCr facility[2]. In April 2019, a notice of intention to take a decision on the application for the exclusion of a waste stream or a portion of a waste stream for beneficial use from the definition of waste was published for comment by the Minister of Environmental Affairs (GN. 535 of 3 April 2019) (RSA, 2019). The notice included several industries applying for the beneficial use of FeCr slag. The application for exclusion was approved in January 2020, as intended in GN 1077 of 16 August 2019.*

1.3 Rationale for the study

Several research studies have been undertaken on FeCr slag, which focus on potential environmental issues related to the weathering of slag dumps or on its utility as a construction material or the option of reprocessing for secondary metal recovery (Piatak et *al*., 2015). Moodie (2016) also focused on the benefits of using FeCr slag as waste aggregate in South Africa. However, limited studies have been done to explore added beneficial uses of FeCr slag, subsequent to the promulgation of the waste exclusion regulations.

The Waste exclusion regulations are perceived as a vehicle that South Africa will utilise to promote and encourage the circular economy, thereby driving economic growth and job creation, while reducing the dependence on natural resources as raw materials, and avoiding pollution and environmental damage.

1.4 Research aims and objectives

This study aimed to explore the beneficial uses of FeCr slag, in the context of the South African legal framework. The research objectives included:

- Evaluating the properties of FeCr slag and the risks related to its use;
    - ***Research question 1:*** *What are the properties (physico-chemical) of FeCr slag and the risks related to its use?*
- Based on the properties of the FeCr slag, explore the potential beneficial use of the slag;
    - ***Research question 2:*** *What are the potential beneficial uses of FeCr slag, based on its properties?*
- Determining the challenges of and opportunities for the beneficial use of FeCr slag.

[2] It was agreed that the name of the facility would be kept anonymous as part of a confidentially agreement, which formed part of the study.

- **_Research question 3:_** *What are the challenges and opportunities for the beneficial use of FeCr slag?*

1.5 Scope of the study

The study is based on the beneficial use of FeCr slag produced by selected South African FeCr industries. Classification results are based on samples collected during three sampling events (2011, 2015 and 2019).

The literature review focused on applications on FeCr slag from international producers and some research done within the South African context.

1.6 Assumptions and limitations of the study

The findings and conclusions of this study are based on the classification of FeCr slag samples, as required by GNR. 634 (Waste Classification and Management Regulations) (RSA, 2013a), according to SANS 10234 (the Globally Harmonized System (GHS) for the classification of chemicals) as required by South African waste legislation. Classification, as required by other countries' legislation, were not taken into account.

The results of the study are based on the GHS classification of FeCr from two FeCr producing facilities using samples analysed in:

- 2011 for the Ferro Alloy Producers Association (FAPA);
- 2015 as part of the requirements of Regulation 8(1)(a) of the W*aste Classification and Management Regulations* (GNR. 634 of 2013); as well as
- 2019 as part of the requirements of the *Waste Exclusion Regulations* (as explained earlier).

The researcher was involved in sample collection and preparation of the 2011 and 2019 samples. The laboratory analysis was performed by an accredited laboratory, while the results were interpreted by the researcher in the context of the research questions to inform the risk assessment and conclusions on the potential beneficial uses of FeCr slag.

The major contribution to knowledge of this research is the consolidation and evaluation of available data and information on FeCr slag characteristics and potential beneficial uses from international and South African literature, in the context of a new policy environment, where a waste stream (in this case FeCr slag) may be excluded from the definition of waste if it is suitable for a beneficial purpose.

The study was done in line with the requirements for risk assessment and the motivation of the beneficial use of FeCr slag, as required by the *Regulations regarding the exclusion of a waste stream or a portion of a waste stream from the definition of waste* (GN 715 of 18 July 2018), within the South African context.

1.7 Structure of this mini-dissertation

This mini-dissertation comprises of five chapters. Chapter 1 provides an introduction that gives a general overview including a background to the study, the problem statement, aim and objectives of the study. Chapter 2 provides details of the research methodology used to address the research aim and objectives and motivates the methodological choices made. Included in this chapter is a description of the methodology used, data collection procedures and the process of data analysis.

Chapter 3 outlines the literature review, specifically focussing on the beneficial use of FeCr slag, opportunities, challenges, and lessons learned. Chapter 4 presents the findings of this research study in line with the research aim and objectives. The findings were derived from the literature review and during dada analysis. Chapter 5 concludes the research and recommendations for further research.

1.8 Chapter summary

This chapter outlined the background of the study and presented the problem statement, where FeCr slag is currently regarded as a waste, but has the potential to be applied for beneficial use. The research aim and objectives were communicated. The next chapter provides an overview of the research methodology followed to address the research aim and objectives.

CHAPTER 2 METHODOLOGY

2.1 Introduction

The purpose of this study was to explore the beneficial uses of FeCr slag generated from South African industries. A mixed-methods approach was used, where information was gathered thorough literature review, and data gathered on the properties of the FeCr slag from laboratory analysis (waste classification according to SANS 10234), which informed the risk assessment.

2.2 Research design

A mixed-method approach was used to conduct the research (refer to Table 2-1). Mixed methods research design, according to Creswell (2003), is the concept of mixing different methods to answer the research question(s).

The research design was informed by the requirements of the *Regulations regarding the exclusion of a waste stream or a portion of a waste stream from the definition of waste* (GN 715 of 18 July 2018), which requires: the classification of the waste to determine hazardous properties, performing a risk assessment to determine the potential risks associated with beneficial use, and demonstration that the waste is being or has been or will be used for a beneficial purpose, either locally or internationally (RSA, 2018).

For certain of these requirements, existing information from processes in which the researcher was involved in earlier in her career, such as the classification of waste in terms of its hazard properties.

Although the laboratory analysis was not performed by the researcher herself, the researcher was involved in sample collection and preparation (of the 2011 and 2019 FeCr samples), evaluation of the laboratory results, performing the risk assessment, as well as collating and evaluating information obtained from the review of literature on the beneficial use of FeCr slag, to address the research questions.

Table 2-1: Outline of the research objectives and the methods used during this study

<table>
<tr><th>Research objective</th><th>Method used</th><th>Rationale</th></tr>
<tr><td>Research objective 1: Evaluating the (a) properties of FeCr slag and the (b) risks related to the use of FeCr slag</td><td>1. The properties of FeCr slag samples were assessed in accordance with SANS 10234. Note: The requirements for waste classification, in accordance with SANS 10234, is outlined in GNR. 634 of August 2013 (Waste Classification and Management Regulations). The classification results were evaluated in the context of FeCr use.
2. The potential risk properties of the FeCr slag was determined in terms of a risk assessment. The risk assessment was performed considering the significance of risk based on probability, magnitude, duration and scale.</td><td>1. According to Regulation 9(a) of the waste exclusion regulations (GN 715 of 18 July 2018), the risk management plan (submitted in support of an application for beneficial use in terms of these regulations) needs to contain a safety data sheet (SDS), which complies with the requirements of SANS 10234, to indicate the physico-chemical and hazardous properties of the FeCr slag.
2. According to Regulation 7(b) of the waste exclusion regulations (GN 715 of 18 July 2018), the applicant needs to undertake a risk assessment demonstrating that the intended use of the excluded waste can be managed in such a way as to ensure that the intended beneficial use will not result in significant adverse impacts on the environment. No specific methodology for risk assessment is proposed in the regulations.</td></tr>
<tr><td>Research objective 2: Exploring the potential beneficial use of the slag</td><td rowspan="2">Literature review:
Based on the outcomes of research objective 1 (properties of FeCr slag and risks related to beneficial use), literature was reviewed to determine the potential beneficial uses of FeCr slag. International and national literature were reviewed to determine the challenges and opportunities for the beneficial use of FeCr slag.
Key literature included: Moodie (2016); Sprinzl (2016); Matinde et al. (2018); Niemela & Kauppi (2007) as well as the SA legal framework and other sources. The results of the literature review are outlined in Chapter 3.</td><td>According to Regulation 7(a) of the waste exclusion regulations (GN 715 of 18 July 2018), the applicant needs to demonstrates that the waste is being or has been or will be used for a beneficial purpose either locally or internationally.</td></tr>
<tr><td>Research objective 3: Determining the challenges of and opportunities for the beneficial use of FeCr slag.</td><td>The feasibility to use FeCr slag is influenced by existing opportunities in the market, as well as challenges.
It is, therefore, important to understand these to enhance opportunities and to address challenges.</td></tr>
</table>

2.3 Data and information collection

According to the *Waste Classification and Management Regulations* (WCMR, 2013), waste must be classified according to GHS of classification and labelling of chemicals (SANS 10234). To address research objective 1, results from FeCr slag classification in accordance to the requirements of SANS 10234 to determine its hazardous properties were used.

The results on physico-chemical characteristics and hazards are based on the GHS classification of FeCr from two FeCr producing facilities using samples analysed in:

- 2011 for the Ferro Alloy Producers Association (FAPA)[3];
- 2015 as part of the requirements of Regulation 8(1)(a) of the W*aste Classification and Management Regulations* (GNR. 634 of 2013); as well as
- 2019 as part of the requirements of the *Waste Exclusion Regulations* (as outlined in a report prepared by JMA Consulting, as explained earlier).

The student was involved in sample collection and preparation in the FeCr slag analysis performed in 2011 and 2019, and provided inputs into the report prepared by JMA. The report (prepared by JMA Consulting) aimed to determine whether FeCr slag is hazardous or non-hazardous based on the GHS classification and labelling of chemicals following the assessment method as detailed in SANS 10234:2008. The results from this report was evaluated and represented in the context of this study.

The hazard properties informed the risk assessment, which considered the potential risks associated with the use of the FeCr slag. The risk assessment did not focus on any specific beneficial use categories, but rather the activities related to the use of FeCr slag, such as transportation, storage, handling, use, etc., using the criteria outlined in Table 2.2 of this dissertation.

Information related to research objectives 2 and 3 was gathered using literature reviews.

2.3.1 Determining the *properties* of the FeCr slag: SANS 10234

To address research objective 1 (a) (understanding the properties of the FeCr slag), the classification methodology proposed by South Africa's adopted national standard of the Globally Harmonized System for the Classification of Chemicals, SANS 10234: 2008 was adopted. GHS is an internationally accepted framework for standardizing and harmonizing the classification and

[3] The FeCr slag producer is a member of Ferro Alloy Producers Association (FAPA), and the results of the motivation report for beneficial use of FeCr slag that was prepared by JMA Consulting on behalf of FAPA members was utilized.

labelling of chemicals (Sprinzl, 2016) and the Waste Classification and Management System (GNR. 634 of 2013) requires the use of this system for the classification of waste in South Africa.

The GHS is based on a broad description of hazard classes in the main categories of physical hazards, health hazards and hazards to the aquatic environment (Van Niekerk & Fourie, 2011). Physical hazards refer to explosive properties, flammability, oxidizing properties, generation of hazardous or flammable gases when in contact with water and chemical properties that will materially damage, or even destroy metals (JMA, 2013). Hazard statement codes (H-codes) is developed for each hazard to assist in the classification, wherein each H-code relates to the intrinsic properties of a hazardous constituent in the material under assessment. For the assessment of the toxicity of chemicals, the lethal concentration (LC) and lethal dose (LD) is used, with LC_{50} and LD_{50} values used to define different hazard ratings (Sprinzl, 2016). There is a limiting concentration above which the material would classify as hazardous and below which it would be non-hazardous (Van Niekerk & Fourie, 2011). In South Africa, factor 0, 1 is used to set an acceptable risk level.

FeCr slag was sampled at FeCr producers and analyzed in 2011, 2015 and 2019, as explained in Section 1.6 of this dissertation. The researcher was involved in sampling and sample preparation of FeCr slag for the 2011 and 2019 analyses. The laboratory analysis was not performed by the researcher herself. The methodology for laboratory analysis are, however, outlined in the sub-sections of Section 2.3.1. For all three of the sampling and analysis events carried out, the same standardized procedures (as outlined in SANS 10234) were used.

2.3.1.1 Sample collection

FeCr slag samples were collected and prepared as per the requirements of the SANS standard for the sampling of aggregates (SANS 195:2006). Representative grab samples of approximately 2000 grams of FeCr slag were collected from a FeCr producer. These were collected from the current arising during the build-up of the FeCr slag stockpile. Three sample scoops at different points on the exposed face of the stockpile were taken, at the height of at least 1m from the ground. These samples were stored in a sealed, labelled sampling bag at room temperature, and sent to an accredited analytical laboratory for analysis. The samples were not mixed or diluted in any way prior to analysis.

2.3.1.2 Laboratory analysis to determine the physical, health and environmental properties of FeCr slag

FeCr slag samples were analysed by an accredited laboratory in accordance with the requirements of SANS 10234: 2008 to determine total concentrations (TC), leachable concentrations (LC) and the related the physical, health and environmental hazardous properties related to the FeCr slag. The FeCr slag underwent a metal extraction process. A safety data sheet (SDS) was prepared by the laboratory, as required by GNR. 634 of August 2013 (the Waste Classification and Management Regulations).

In order to investigate the effects of weathering, a composite fresh FeCr sample was submitted to a series of weathering tests as per standard method as prescribed by the American Society for Testing and Materials (ASTM) in the USA (ASTM No D5744-07). Enhanced weathering was achieved by providing conditions conducive to sample oxidation and then leaching the sample with a fixed volume aqueous leach (750 mℓ). The procedure employed weekly cycles composed of three days of dry air and three days of water-saturated air circulated through the sample, followed by a leach with water on Day 7. Approximately 1 kg of FeCr slag with particle size < 6 mm was placed into each column, lightly pressed into position, and extracted with a 750 mℓ aqueous leach, which was analysed over 15 cycles to obtain better clarification of trends over time.

The analytical procedure (as prescribed by SANS 10234 to determine the properties of the FeCr slag) included nine parallel extractions of particle size reduced material at liquid-to-solid (ℓ/S) ratio of 10 mℓ extractant/gram of dry sample. According to Kosson *et al*. (2000), properties of surrounding materials in a particular use scenario may dominate contaminants release conditions, with external stresses (such as pH, redox gradients, and carbonation or mixing effects) which may lead to a significant deviation from slag's natural leaching characteristics. Therefore, an acid or base addition schedule was formulated for the extracts with final solution pH values between 2 and 12, through the addition of aliquots of HNO_3 or KOH as needed, with the pH range including the natural pH of the slag. The extractions were tumbled in an end-over-end fashion at 28 ± 2 revolution per minute (rpm). Contact time was calculated as a function of the selected maximum particle size, with an extraction period of 48 hours for the base case of 2 mm maximum particle size.

Following separation of the solids and liquid phases by centrifugation or settling, the phases were separated by vacuum filtration through 0,45 µm polypropylene filtration membranes. Analytical samples of the leach solutions were collected and preserved as appropriate for analysis determining the physical, health and environmental hazards.

2.3.1.3 pH dependence of leaching characteristics and ageing characteristics

The assessment of leaching characteristics of FeCr slag was carried out to ascertain whether there is a potential for serious leaching of hazardous elements and potential risks to human health and the environment with pH changes. To assess the ageing characteristics of ferrochrome slag, a composite ferrochrome slag sample was submitted to a series of laboratory weathering tests in accordance to the standard method ASTM requirements.

2.3.1.4 Determination of *physical* hazards of FeCr slag

According to GHS (SANS 10234, 2008 ed. 1.1) physical hazards refers to *explosive properties, flammability, oxidizing properties, self-reacting properties and self-heating characteristics, pyrophoric and oxidizing properties, generation of hazardous or flammable gases when in contact with water and chemical properties that will materially damage, or even destroy metals*.

Available literature (van Niekerk, 2011, Lind *et al*., 2001, Panda *et al*., 2013, Booysen, 2008, Niemela *et al*, 2007 and Gerricke, 1995) shows that FeCr slag from South Africa's ferrochrome producers is not classified as having any physical hazards, in accordance with the GHS classification system, and was not subjected to any physical hazard classification analyses.

2.3.1.5 Determination of *health* hazards of FeCr slag

The GHS (SANS 10234: 2008) provides for *acute toxicity, skin corrosion and skin irritation, serious eye damage and eye irritation, respiratory sensitization and skin sensitization, germ cell mutagenicity, carcinogenicity, reproductive toxicity, specific target organ toxicity (single and repeated exposure) and aspiration* hazards. Assessment of hazards to human health is based on total concentrations of chemicals in the material under consideration (SANS 10234, 2008 ed. 1.1). The default classification concerning health hazards is based on the total concentration of the substance, expressed as a percentage. It is known that certain challenges are encountered when classifying materials that are described as preparations such as metallurgical slag following the default classification in the GHS system (Van Niekerk & Fourie, 2011). The primary issue with preparations is how to assess the likelihood that toxic effects associated with their constituent metals would be exerted while there is a lack of toxicological information for the preparation as a whole.

A tiered approach was used to assess the exposure and health risks of FeCr slag. The Tier-1 assessment was conducted on the results of total elemental analysis, assuming that the constituents would be bio-accessible and bio-available. In Tier-2 assessments, bio-elution tests were conducted to determine bio-accessibility. For assessment of inhalation exposure, the test for bio-elution into alveolar fluid was applied.

In other words, if the slag were classified as hazardous to humans based on the total elemental content (Tier-1), further assessment through evaluation of bio-elution testing (Tier-2) was carried out. Bio-elution refers to *in vitro* extraction methods used to measure the degree to which a substance (e.g. metal or mineral ion) is dissolved in artificial biological fluids, that is to determine its bio-accessibility (Van Niekerk & Fourie, 2011).

In cases where results of both assessments were presented, the assessment based on the bio-elution tests was accepted as the final assessment, since bio-elution tests represent the physiological bio-accessibility of the relevant elements. (Van Niekerk & Fourie, 2011).

2.3.1.6 Determination of *environmental* hazards of FeCr slag

The GHS (SANS 10234) requires the determination of *acute and chronic toxicity* hazards to the aquatic ecosystem. Based on the standard, analytes are classified into chronic aquatic toxicity categories based on the acute category classifications. Acute category 1 analytes would thus be classified as chronic category 1 substances, and analytes not classified under acute toxicity would be classified as chronic category 4 substances. The standard provides guidelines on dealing with hazards to the aquatic ecosystem in the case of preparations that contain poorly soluble elements such as FeCr slag. According to SANS 10234: 2008, assessments of hazards to the aquatic environment requires a dissolution-screening test for transformation/ dissolution of metals and metal compounds in aqueous media. This test provided information on the proportion of metal, expressed as a mass percentage in the material, which would be available to exert its toxic effects on aquatic organisms.

2.3.2 Determining the *risks* related to the use of FeCr slag

To address research objective 1 *(b) determining the risks related to the use of FeCr slag*, a risk assessment was performed. The hazardous properties of the FeCr slag (as determined by the methodology outlined in Section 2.3.1) were used to inform the risk assessment. The risk assessment was not based on any specific beneficial use category of FeCr slag, but rather to the use of FeCr in general. The risk assessment was performed in line with the requirements of the *Waste Exclusion regulations* to determine whether the intended beneficial use of the FeCr slag would result in significant adverse impacts on the environment. The *Waste Exclusion regulations*, however, do not outline a specific risk assessment methodology.

2.3.2.1 Generic assessment of exposure of dust from FeCr slag

The potential for dust generation handling and use of FeCr slag forms part of the assessment of potential risks associated with the beneficial use of slag. Generic environmental (community) and occupational exposures scenarios were assessed. The assessment followed a conservative exposure scenario with the assumption that the community will be exposed to FeCr particulate matter (PM_{10}) slag dust at levels of the ambient air quality limit for chronic exposure. In contrast, vanadium was assessed in terms of averaged concentrations. Exposure concentrations of the elements in the dust were calculated from the total elemental concentration in the slag (van Niekerk, 2011).

2.3.2.2 Risk assessment methodology

The risk assessment was informed by the ISO 31 000: 2018 *Risk management – Guidelines*, which provides the principles, framework and a process for managing risk. The significance rating of the potential impacts (risks) was calculated to illustrate the importance of the impact (risk) itself, and expressed as significance points (SP) by means of the following equation:

Significance Points (SP) = (Magnitude + Duration + Scale) x Probability, where**:**

- *Magnitude* measures the size of the impact;
- *Duration* refers to the lifetime of the impact i.e. how long it will last;
- *Scale* refers to the extent of the impact; and
- *Probability* refers to the chance of impact to occur. The potential impact could be most likely to occur, unlikely, etc.

The criteria outlined in Table 2-2 were used to in the equation to calculate risk. Depending on the SP value, the "risk" related to beneficial use was rated as having a *high, moderate or low* significance, or having a *positive impact* (refer to Table 2-3).

Table 2-2: Criteria and values for the determination of the significance of risk (expressed as significance points or SP)

Criteria	
Magnitude (Severity)	**Duration**
10 - Very high	5 - Permanent (longer than 10 years)
8 - High	4 - Long-term (5 to 10 years)
6 - Moderate	3 - Medium-term (12 months to 5 years)
4 - Low	2 - Short-term (0 to 12 months)
2 - Minor	1 - Immediate
Scale	**Probability (Likelihood)**
5 - International	5 - Definite
4 - National	4 - Highly probable
3 - Regional	3 - Medium probability
2 - Local	2 - Low probability
1 - Site only	1 - Improbable
0 - None	0 - None

Table 2-3: Rating and description of risk, based on significance points (SP)

Rating		Description
SP >60	Indicates **high** environmental significance	An impact, which could influence the decision about whether or not to proceed with the activities regardless of any possible mitigation.
SP 30 – 60	Indicates **moderate** environmental significance	An impact or benefit which is sufficiently important to require management and which could have an influence on the decision unless it is mitigated.
SP <30	Indicates **low** environmental significance	Impacts with little real effect and which will not have an influence on or require modification of the activities.
+	**Positive impact**	An impact that is likely to result in positive consequences/effects

The risks related to the following activities associated with the beneficial use of FeCr slag were considered as part of the risk assessment:

- Transporting of slag;
- Handling of slag;
- Material storage;
- Material handling and processing of slag; and
- Environmental spillage.

The risk assessment considered the environment, members of the community and occupational exposure as the receptors exposed to potential risk.

The following exposure scenarios were taken into account:

- The potential for generation of dust during typical use or maintenance scenarios and associated exposure of members of the public or employees in occupational scenarios (van Niekerk, 2011);
- Generic environmental (and community) exposure scenario whereby the environment (air, water, land, biodiversity) and residents are exposed to airborne contaminants emanating from applications constructed using slag (such as unpaved roads); and
- Occupational exposure from slag products during handling of FeCr in application and maintenance scenarios (such as mechanical cutting, sanding or grinding).

2.3.3 Literature review

The literature review was conducted by utilising electronic, internet and library sources, with specific reference to international and national legislation, policy documents, academic sources and articles. The literature review focussed on the beneficial use of FeCr slag in construction, agriculture and other chemical and metallurgical industries. Scopus, Academia.edu and Google Scholar were used to identify and access academic publications.

The main aim of the literature review was to respond to research objectives 2 and 3 to:

- Explore the *potential beneficial use* of the slag; and
- Determine the *challenges of and opportunities* for the beneficial use of FeCr slag.

The results of the literature review are outlined in Chapter 3 of this dissertation. Key literature included:

- The dissertation by Moodie (2016);
- The dissertation by Sprinzl (2016);
- The publication by Matinde *et al*. (2018) entitled *Mining and metallurgical wastes: a review of recycling and re-use practices;*
- The publication by Niemela & Kauppi (2007) entitled *Production, characteristics and use of ferrochromium slags;*
- The South African legal framework applicable to the beneficial use of FeCr slag (waste); and
- Other sources of national and international literature as outlined in the bibliography.

2.4 Data analysis

The results of the laboratory analysis and the risk assessment were considered to inform the potential beneficial uses of FeCr slag. Data analysis was performed and summarized in tables.

2.5 Assumptions and limitations

The following methodological assumptions and limitations need to be taken into consideration:

- The physico-chemical characterisation and classification was based on one representative grab sample of approximately 2000 grams of FeCr slag collected and analysed during three sampling events in 2011, 2015 and 2019;
- The researcher was only involved in sample collection performed in 2019;
- Laboratory analysis was not performed by the researcher herself. The results of the laboratory analysis were assessed and evaluated within the context of the beneficial use

of FeCr slag within the South African regulatory context, as the main contribution of this study to knowledge.

- Exposure and health risks of FeCr slag were assessed in a tiered approach. The Tier-1 assessment was conducted on the results of total elemental analysis, assuming that the constituents would be bio-accessible and bio-available. In Tier-2 assessments, bio-elution tests were conducted to determine bio-accessibility. For assessment of inhalation exposure, the test for bio-elution into alveolar fluid was applied. In other words, if the slag were classified as hazardous to humans based on the total elemental content (Tier-1), further assessment through evaluation of bio-elution testing (Tier-2) was carried out;
- The risk assessment was performed by the researcher, and informed by a study conducted by Infotox to assess exposure to dust from FeCr slag as part of a FAPA motivational document (van Niekerk, Report 024-2011);
- The risk of exposure to ambient air quality (chronic exposure) was based on the assumption of exposure of FeCr PM_{10} slag dust to recipients (community members);
- The beneficial uses researched were based on reasonable uses, as outlined in the literature.

2.6 Ethical considerations

According to the North-West University (NWU, 2018), ethical considerations should be acknowledged and taken into consideration during research. The study was conducted based on laboratory analysis and secondary data gleaned from the literature, with limited human interaction (no interviews or other types of human interaction). The research proposal was submitted to the Scientific Committee of the Environmental Management Research Group (EMRG) in the Unit for Environmental Sciences and Management of the North-West University, Potchefstroom Campus for consideration. The scientific committee found that the project proposal was in accordance with the scientific method and adhered to the required standards as set out in the Academic Rules for Masters and Doctoral Students at North-West University. The Scientific Committee concluded that the proposed methodology did not pose any ethical risk hence exemption from further ethical approval was recommended for the study.

2.7 Chapter summary

This chapter outlined the research design and methodology for this study, detailing the methods followed for data collection and analysis, as well as outlining the limitations of the study.

The next chapter (Chapter 3) will provide a detailed literature review to inform the research questions.

CHAPTER 3 LITERATURE REVIEW

3.1 Introduction

The literature review aimed to identify historical data and research on the characteristics of FeCr slag and options for its beneficial application. The purpose was to identify the key considerations applicable to the beneficial use of FeCr slag and to identify “lessons learned” from South Africa and other countries, to provide context to the current study (to address research questions 2 and 3).

The main aim of the literature review was to:

- Outline the ferrochromium production process and its related wastes;
- Contextualize the legal framework applicable to the management of FeCr slag, and its potential beneficial use;
- Provide examples of the beneficial use options of FeCr and other metallurgical slags in South Africa and elsewhere in the world; and to
- Highlight the benefits and challenges applicable to the alternative use (beneficial application) of FeCr slag, locally and internationally.

This chapter provides an overview of the production process of FeCr, FeCr slag as a by-product. It elaborates on the national legislative framework for managing metallurgical waste, as well as beneficial uses of FeCr slag explored both nationally and internationally. It finally aims to provide context to the impact that the new waste exclusion regulations may have as far as the beneficial use of FeCr slag is concerned.

3.2 Ferrochromium in South Africa

South Africa is the leading player in the international ferroalloy industry due to its abundance of natural resources (Steenkamp & Basson, 2013). The existing exploitable reserves of platinum group metals (PGMs) are concentrated in narrow extensive strata called Merensky Reef, the Platereef, and the UG2 chromite layer found in the Bushveld Igneous Complex (BIC). The largest concentration of extractable chromite is found along the Merensky Reef which stretches from the west of Pilansberg southwards through the Bafokeng area and Rustenburg towards Marikana, parallel to the Magaliesberg (Coetzee *et al.*, 2018). The South African Bushveld complex’s chromite reserves constitute approximately 75% of global chrome ore reserves (DMR, 2018; USGS, 2019). The United States Geological Survey (USGS Mineral commodity summaries, 2019) states that world resources of chromite exceed 12 billion tonnes, sufficient to meet world demand for future generations. The major producers of FeCr are South Africa, China, Kazakhstan and India (Sprinzl, 2016).

South Africa produces high carbon FeCr or “charge chrome” produced from chrome with low carbon content, i.e. FeCr with 50% - 60% Cr in comparison to high carbon FeCr that is comprised 60% of Cr content, of which about 90% is used in stainless steel manufacturing. South African charge chrome is preferred for stainless steel production, above chrome with higher carbon content from elsewhere in the world. Western Bushveld Complex of South Africa produces a major amount of the world’s total ferrochromium (Coetzee *et al*., 2018). About 85% of FeCr from South Africa is consumed in the global stainless steel industry (Matinde *et al*., 2018). South Africa’s Ferro alloys industry has grown since 2018 to become the leading producer of bulk ferro-alloy globally (DMR, 2018). South African FeCr industry is export-oriented due to a small domestic stainless steel production, with country’s exports amounting to 4.7 Mt (49.2% global exports) in 2016 (DMR, 2018).

3.3 The ferrochromium production process

The production of ferrochromium is an energy-intensive process, which necessitates large amounts of electricity and fossil fuels. Ferrochromium is referred to as the principal alloy of iron and chromium that is manufactured pyrometallurgically by carbothermic reduction of chromite ore (Kumar *et al.,* 2014). The quality of raw materials and their pre-treatment condition, the utilization of reaction energies, and heat contents from the processes are all factors that affect energy consumption.

Figure 3-1 provides an overview of the FeCr production process, as explained by Niemela *et al*. (2007) and Daavittila *et al.* (2004). In short, raw materials used for FeCr production are beneficiated lumpy ore, ore fines and concentrates. Raw materials can be sintered or agglomerated by briquetting and pelletizing to convert ore fines and concentrates into more furnace usable lumpy material (Niemela *et al*., 2007).

Different types of carbon, such as metallurgical coke is used to reduce metal oxides in the furnace, with fluxing materials such as quartzite, dolomite and lime, used to get the right composition of the slag. (Niemela *et.al,* 2007, Sahu *et al*., 2016). International Organisation of Standardisation (ISO) differentiates between high, medium and low-carbon FeCr. High carbon FeCr metal is produced from the oxide of chromium ore in electro-arc furnaces by a carbothermal process with coke as the reducing agent at approximately 1700^{0}C (Zhou *et al*., 2017).

High-carbon FeCr has a chrome content between 60% and 70%, and carbon content of between 4% and 5% whereas charge chrome, an intermediate product in the stainless steel production has a chrome content between 50 and 55% and carbon content between 6 and 8% (Sprinzl, 2016). Medium and low low-carbon FeCr can be obtained by reducing chromites and iron using silicon as a reducer in the form of silicon-chrome in a shaft –type electric furnace lined with magnesia (Zhou *et al*., 2017).

The solid products from the smelting of FeCr are metal (product), slag and dust. In open-top and semi-closed furnaces the dust is collected as such in a bag filter plant, whereas in a closed top furnace, the dust is scrubbed in a venturi system and is produced as slurry. Electric submerged arc furnaces (that are either open, semi-closed) dominate the smelting of chromite ores and concentrates or closed units, as is the recognized production unit for ferrochromium alloys (Daavittila *et al*., 2004).

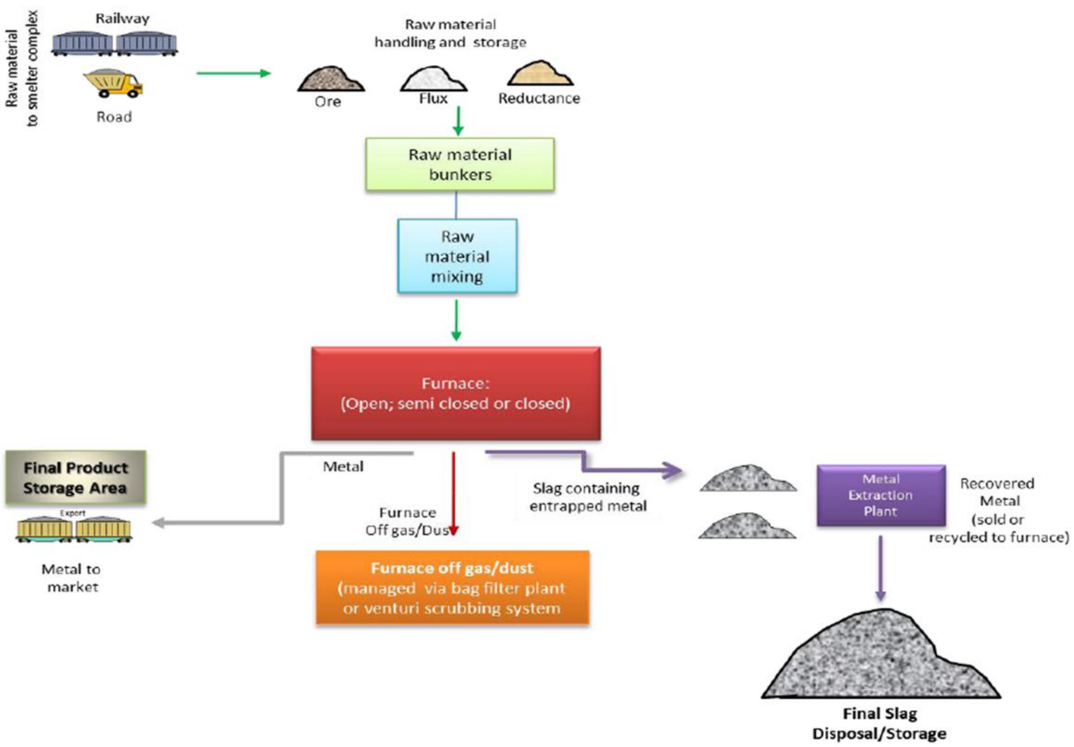

Figure 3-1: Typical illustration of a FeCr production process (JMA, 2013)

The FeCr production process produces significant amounts of solid wastes, such as slag (Matinde *et al.,* 2018). Global ferrochromium slag production is around 12 to 16 million tonnes per year (Richard, 2015). Section 3.4 discusses the waste produced during the ferrochromium production process.

3.4 Waste produced during the ferrochromium production process

During the smelting process, the total chromium fed is distributed into metal, slag and dust. Bag filter dust that typically contains higher concentrations of Cr(VI) is generated during the cleaning of off-gas in semi-closed and open furnaces or venturi sludge in scrubbing off-gases in closed furnaces. Slag forms the largest amount of waste generated by volume (Coetzee *et al*., 2018). Metallurgical extraction processes produce significant amounts of solid wastes such as slag (Matinde *et al.,* 2018). FeCr slag is a waste material obtained from the manufacturing of ferrochromium alloy (Sathwick *et al*., 2016). The slag is formed in a liquid form by physico-chemical processes at a temperature of 1700 ºC - 1750 ºC (Sahu *et al*., 2016). The FeCr slag typically contains 30% silicon dioxide (SiO_2), 26% aluminium oxide (Al_2O_3) and 23% magnesium oxide (MgO) as the main constituents in different phases such as spinel and forsterite, with minor traces of ferrous/ferric oxides, chrome oxides and 2% calcium oxide (CaO) (Kumar *et al.,* 2014, Coetzee *et al*., 2018). It is of importance to understand slag chemistry to ensure efficient FeCr production, and thus common phases in the slag are glass, spinels and forsterite (Niemela *et al.*, 2007).

The densities of metal and liquid are significantly different (FeCr slag density range is between 2.5 – 2.8 g/cm^3, and FeCr is 6.8 g.cm^3); therefore, the slag separates from the metal (Niemela *et al.*, 2007, Sahu *et al*, 2016). Unprocessed slag becomes aggregate when it passes through jaw crushers in the process of metal recovery. The slag produced from furnaces (unprocessed slag) is further processed to extract metals. The ferroalloy separation from the lumpy is based on magnetic separation, wherein the feed is crushed and screened to fractions of 0 - 4 and 4 - 22 mm. Coarser fractions are handled by a dense media separation with fine-grained material handled by magnet separator and spiral washing (Niemela *et.al*, 2007)

The product of slag processing to reclaim metal is either marketable metal or cycled to the furnace to re-melt with the goal to achieve maximum metal extraction (JMA, 2013). The FeCr slag products composed mainly of homogenous granulated slag which is the main part and classified slag that is produced through crushing and screening of air-cooled lumpy slag (Niemela *et al.*, 2007)

Ferro-alloy slag produced during FeCr production (referred to as *charge chrome slag*) is acidic with residual Cr that ranges between 8 and 12% (Jones, 2004, Niemela *et al*., 2007, Sathwik *et al.,* 2016, Coetzee *et al*., 2018). The slag material constitutes a significant portion of the solid waste that is disposed of as FeCr slag stockpiles every year. In Europe, 18.4 Mt of steelmaking slags were produced in 2016. FeCr slag production varies according to the type of FeCr produced. High carbon FeCr produces 1.1 – 1.6 tonnes of slag per tonne of metal produced depending on the feed material (Niemela *et al*., 2007, Nath, 2018). The annual global production of FeCr slag in 2018 was approximately 13 Mt (high carbon FeCr).

If not managed correctly, large quantities of slag containing hazardous elements have the potential to impact negatively on the environment (Saha *et al.*, 2019). Environmental issues associated with FeCr slag are mostly linked to chromium (Holappa & Xiao, 2004). Chromium (Cr) is commonly present in two oxidation states, namely Cr(III) and Cr(VI). The trivalent form, Cr(III), is a non-toxic , non-hazardous, essential trace element, whereas the hexavalent form Cr(VI) is highly toxic and is classified as hazardous material (Horckmans *et al.*, 2019). The oxidation state not only affects toxicology, but also the mobility and availability of chromium, with Cr(VI) compounds being more mobile and bioavailable than the stable and almost insoluble Cr(III) compounds (Kotas *et al*., 2000). Cr(VI) may leach into groundwater when FeCr slag is stockpiled or landfilled, due to its high solubility in water and mobility in soil (Saha *et.al*, 2019). Cr(VI) is also a known human carcinogen, (Garbers-Graig, 2006). Furthermore, Costagliola *et al.,* (2008), Ettler *et al.,* (2009b) and Piatak & Seal (2010) reported that some slags contain high concentrations of potentially toxic elements such as arsenic (As), barium (Ba), cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn), which could add to its toxicity.

Although untreated pyro-metallurgical slag contains heavy metals, which can leach into the environment and cause pollution (Jones, 2014). Treatment processes, such as metal extraction, render the treated slag relatively “clean” to be used beneficially with minimal negative environmental impacts. Pyro-metallurgical slag, according to Jones (2014) is no longer regarded as waste fit for disposal in slag dumps, but must be regarded as a *potential economic resource* from which residual metals can be recovered. However, Saha *et al.* (2019) noted that only small quantities of waste slag from pyro-metallurgical production of FeCr are currently applied in other beneficial uses, still leaving significant quantities of slag discarded in slag dumps/stockpiles.

3.5 Managing ferrochromium wastes

In South Africa, mining and metallurgical wastes constitute approximately 80% of the waste (by volume) produced per year (SAWIC, 2018) and may contribute to environmental impacts and hazards to human health, if not managed properly (Matinde *et al.,* 2018), as mentioned earlier.

Contrary to the international practice of using metallurgical slag (including FeCr slag) in construction and other applications, metallurgical slag has been classified as mainly *hazardous waste* in South Africa (DWAF, 1998, and GNR 634 of August 2013), with the majority of slag being disposed to land in the form of *residue deposits and residue stockpiles*.

Recently, however, the *waste exclusion regulations* (2018) have provided alternative legislative measures, which allows the generator of waste to apply for the beneficial use of waste (as explained in Chapter 1 of this dissertation). However, in the pursuit of diverting FeCr slag from landfill by exploring its beneficial uses, there may still be a portion of slag that needs to be landfilled/stockpiled due to the instability or environmental issues caused by heavy metal leaching (Pan *et al*., 2016).

Section 3.6 provides an overview of the legislative framework for governing metallurgical wastes in South Africa, to provide context to this study.

3.6 An overview of the legislative framework for governing FeCr wastes

Over the years, environmental laws and social awareness programmes have been developed and promulgated universally to protect the environment and human health, and to promote business ethics regarding the disposal and/or re-use of metallurgical waste (Phadke *et al*., 2014, Kumar and Singh, 2013 and Ndlovu *et al.*, 2017).

In South Africa, the legal framework applicable to the management of metallurgical waste has evolved. With the promulgation of the National Environmental Management Waste Act (59 of 2008) in 2009, mining waste was included in the definition of waste, however, *"residue deposits" and "residue stockpiles"* were excluded in terms of Section 4. Until July 2015, the management of residue deposits and stockpiles were mainly dealt with in terms of the Minerals and Petroleum Resources Development Act (28 of 2002), while the waste classification aspect was addressed in terms of the National Water Act (36 of 1998) and the *Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste* (DWAF, 1998).

In July 2015, the *Regulations Regarding the Planning and Management of Residue Stockpiles and Residue Deposits from a Prospecting, Mining, Exploration or Production Operation* (GNR. 632 of 24 July 2015 in GG 39020) was promulgated. These regulations had the implication that residue deposits and residue stockpiles had to be classified, assessed and managed according to the waste classification and management system (as outlined in GNR. 634, GNR. 635 and GNR. 636). The regulations for residue deposits and stockpiles were, however, amended in September 2018 (GN. 990 of 21 September 2018 in GG 41920) to allow pollution control measures to be determined in line with risk analysis, with the requirements of GNR. 635 and GNR. 636, no longer being exclusively applicable to the disposal of waste (in the form of residue deposits and residue stockpiles) to land.

Table 3-1 provides an overview of some current waste-related laws and regulations from South Africa applicable to the management of metallurgical waste, with a specific focus on the management of FeCr slag, for its potential beneficial use. The aim of the table is not to be explicit in each piece of legislation applicable to the management of metallurgical waste, but to provide background and a conceptual understanding of some of the legislation applicable to the management of metallurgical waste.

Table 3-1: Overview of the legal framework applicable to the management of metallurgical waste

Legislation	Content
Bill of Rights, Section 24 of the Constitution (108 of 1996)	The universal right to environmental protection through reasonable and other measures that prevent pollution and secure ecologically sustainable development and use of natural resources while promoting economic and social development (RSA, 1996).
National Environmental Management Act (107 of 1998), as amended	Section 2 of the NEMWA provides the principle of sustainable development and imposes the duty of care (Section 28) and remediation of environmental damage. Section 23 provides for the application of various environmental management approaches (instruments), while Section 24 specifically refers to the requirement of applying for environmental authorisations, where necessary (RSA, 1998a).
National Water Act (36 of 1998), as amended	The NWA provides for the protection of the natural water resources in South Africa. It also provides a hierarchy of priorities for mine water management in terms of pollution prevention, water re-use or reclamation, and water treatment and discharge (RSA, 1998b).
Minerals and Petroleum Resources Development Act (28 of 2002), as amended	The MPRDA aims to make provision for equitable access to and sustainable development of the nation's mineral and petroleum resources; and to provide for matters connected therewith. The management of residue deposits and stockpiles are outlined in the MPRDA.
National Environmental Management Air Quality Act (No. 39 of 2004), as amended	Prescribes measures to control air quality, including, but not limited to, the emission of respirable and non-respirable dust and their control and minimisation through cleaner technologies and cleaner production practices.
National Environmental Management Waste Act (59 of 2008), as amended	The NEMWA aims to reform the law regulating waste management in order to protect health and the environment by providing reasonable measures for the prevention of pollution and ecological degradation and for securing ecologically sustainable development.

Legislation	Content
	The NEMWA provides for the National Waste Management Strategy (NWMS) and the waste management hierarchy. It also provides for regulations, norms, and standards to manage specific waste types and specific waste management activities.
• National Waste Management Strategy (NWMS) (2011)	The NWMS is a legislative requirement of the NEMWA. The purpose of the NWMS is to achieve the objects of the Waste Act. Organs of state and affected persons are obliged to give effect to the NWMS. The NWMS provides eight goals and measures to address these goals.
• Waste Classification and Management Regulations (GNR. 634 of August 2013)	GNR. 634 requires waste to be classified in terms of SANS 10234 (also known as the Globally Harmonized System of the Classification and Management of Chemicals, GHS). Waste classification provides information on the physical, health and environmental hazards associated with the waste (RSA, 2013a).
• List of waste management activities that have, or are likely to have, a detrimental effect on the environment (GN. 921 of 29 November 2013 in GG 37083), as amended	A listed waste management activity requires the application for a waste management licence, supported either by an environmental impact assessment (EIA) or basic assessment (BA) process. In July 2015, the list of waste management activities was amended and activities involving residue deposits and stockpiles were added. For example, *The establishment or reclamation of a residue stockpile or residue deposit resulting from activities which require a mining right, exploration right or production right in terms of the MPRDA.*
• Regulations Regarding the Planning and Management of Residue Stockpiles and Residue Deposits from a Prospecting, Mining, Exploration or Production Operation (as amended in 2018 by GN. 990 of September 2018)	Requires the identification and assessment of environmental impacts arising from the establishment of residue stockpiles and residue deposits, and requires pollution control measures to be determined as informed by the results of risk analysis. With the amendment of the regulations in 2018, GNR. 635 and GNR. 636 are no longer applicable to residue deposits and residue stockpiles (RSA, 2018a).
• Regulations regarding the exclusion of a waste stream or a portion of a waste stream from the definition of waste (GN 715 of 18 July 2018)	Allows the generator of waste to apply for a specific waste stream or portion of waste to be excluded from the definition of waste, based on the motivation for its beneficial use. The motivation needs to be informed by waste classification (according to SANS 10234) and the risks associated with the beneficial use of the waste (RSA, 2018b).

The focus of this study is mainly on the management of FeCr slag (waste) for beneficial purposes. This process is regulated under the National Environmental Management Waste Act (59 of 2008)

(NEMWA), and the remainder of this section will, therefore, focus on the NEMWA as it relates to the management (mainly the beneficial use) of FeCr slag.

3.6.1 An overview of the National Environmental Management Waste Act (59 of 2008) and its requirements, as it relates to the management of FeCr wastes

This section provides an overview of the NEMWA and its requirements as it relates to the management of FeCr slag.

3.6.1.1 Defining waste

According to the NEMWA (as amended in 2014) waste is defined as *(a) any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act; or (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette, but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste—(i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered; (ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered; (iii) where the Minister has, in terms of section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or (iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste.*

Prior to the amendment of NEMWA in 2014, the Act excluded *by-products* from the definition of waste, which meant that industries or generators of a by-product were afforded the opportunity to proactively find markets from by-products, instead of viewing it as waste and disposing of it. The 2014 amendment of the NEMWA, however, removed the definition of *by-product* from the Act and allowed for waste to "cease" being a waste, where "*the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste"* (as allowed for in terms of the w*aste exclusion regulations*).

FeCr slag is, therefore, considered to be waste in terms of NEMWA until it is excluded from the definition of waste (and ceases to be waste) by the Minister (as allowed for in terms of the *waste exclusion regulations*)

3.6.1.2 The waste management hierarchy

Mitigating the effects of metal and metallurgical manufacturing processes requires a holistic approach that involves the application of waste hierarchy principles, such as reducing the amount waste produced, in-process recycling, and finding new markets and applications in other sectors of the economy (Lottermoser, 2011).

The NWMS, as well as the associated norms and standards, are provided for in Section 6, Part 1 of the NEMWA. Waste management policies and legislation in South Africa, including NWMS has adopted the internationally accepted waste hierarchy approach which entails that re-use of waste would be expected to be a priority waste management option in South Africa (Oelofse *et al*., 2007). The waste management hierarchy (as outlined in the National Waste Management Strategy, 2011) (Figure 3-2) advocates the disposal of waste as a last resort, because of the adverse impacts of waste on the environment, including disposal of (for instance) FeCr slag to land.

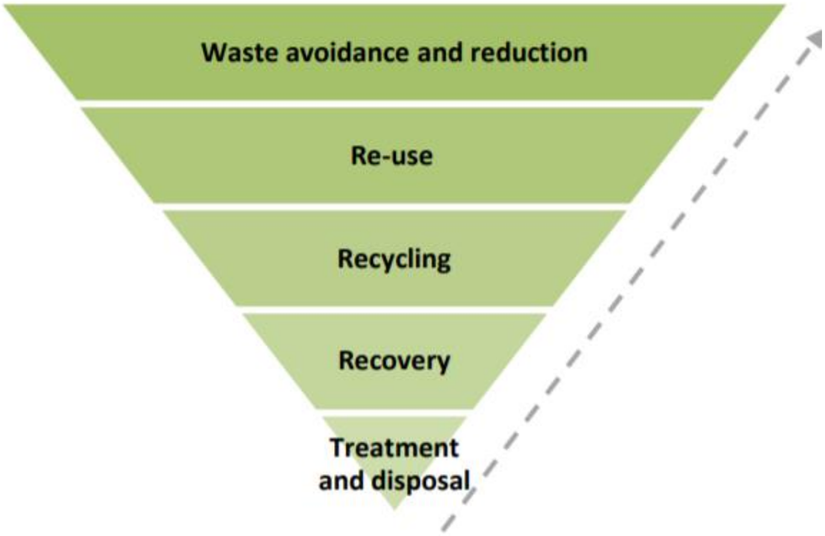

Figure 3-2: The waste management hierarchy, as proposed by the National Waste Management Strategy (DEA, 2011)

One of the aims of the waste exclusion regulations is to "promote diversion of waste from landfill disposal to its beneficial use", thereby promoting the waste management hierarchy.

3.6.1.3 Requirements for waste classification

As mentioned earlier, an application for the exclusion of a waste stream from the definition of waste, because of its potential beneficial use, needs to be supported by waste classification, according to SANS 10234 (as outlined in the Waste Classification and Management Regulations, GNR. 634 of August 2013).

Prior to the promulgation of the Waste Classification and Management Regulations in 2013, the DWAF *Minimum Requirements (*MR) classified FeCr slag as *hazardous waste* due to its quality and large volumes that are produced; and therefore, there was limited use of FeCr slag commercially (Booysen, 2009). The MR for waste disposal applied a precautionary principle, especially in the industrial sector, implying that waste is hazardous and toxic until proven otherwise, and thus, re-use of such waste was dependent on the outcomes of the delisting process. Even if delisted as being hazardous, the reclassified waste retained its legal status of being *waste*.

In July 2018, however, new regulations were introduced in terms of the NEMWA, entitled *Regulations regarding the exclusion of a waste stream or a portion of a waste stream from the definition of waste* (GN 715 of 18 July 2018) (referred to as the *"waste exclusion regulations"*) (RSA, 2018). Should a waste stream be excluded from the NEMWA definition of waste, the requirements of the NEMWA are no longer applicable, and, it may exempt that waste stream, for example, from the requirements of applying for a waste management licence, which may be regarded as a benefit by industry.

The regulations allowing the beneficial use of waste is applicable to waste that is non-hazardous and not harmful to the environment, health, and safety of people. The waste, therefore, needs to be classified, prior to it being deemed appropriate for application for beneficial purposes. The application for exclusion, therefore, needs to be supported by the *properties* of the waste, determined in terms of SANS 10234 (outlined in a safety data sheet), as required by Regulation 9(a) of the *waste exclusion regulations*. GNR. 634 of August 2013 outlines the requirements for determining the physico-chemical properties and hazard rating of the waste, in accordance with SANS 10234.

South Africa has adopted a Globally Harmonised System (GHS) of classification and labelling of chemicals (SANS 10234, 2008) that aims to harmonise criteria for classifying chemicals according to their physical, health and environmental hazards. The standard also aims to harmonise hazard communication requirements for labelling and safety data sheets (SDSs).

The GHS is based on a broad description of hazard classes in the main categories of physical hazards, health hazards and hazards to the aquatic environment. For each of the hazards, a series of hazard statement codes (H-codes) has been developed, to assist in the classification. For each of the hazard statement codes that relates to the intrinsic properties of a hazardous constituent in the material under assessment, there is a limiting concentration above which the material would classify as hazardous and below which it would be non-hazardous. (SANS, 2008)

The system provides for dealing with multi-component materials and additivity of concentrations for those hazards that are associated with more than one constituent in a material such as FeCr slag.

3.6.1.4 Regulations applicable to the beneficial use of waste (including FeCr slag)

As explained earlier, in South Africa there has been recent advancement in regulations for managing waste in terms of the *Regulation regarding the exclusion of a waste stream or a portion of a waste stream from the definition of waste* (GN. 715, 2018) that was promulgated in July 2018. The exclusion of a waste stream or a portion thereof for beneficial use will be considered by the Minister if the applicant can demonstrate that the waste is intended to be used beneficially either nationally and internationally. A risk assessment and risk management plan need to be submitted to substantiate that no adverse environmental impacts will result in the intended beneficial use for such waste stream, together with waste exclusion application forms.

Following the promulgation of the *waste exclusion regulations*, the Minister of Environmental Affairs gave notice of the intent on deciding on the applications for the exclusion of a waste stream or a portion of such a waste stream for beneficial use in April 2019 and was again published for public comment in August 2019 (GN 1077 of August 2019).

In January 2020, the Minister of Environment, Forestry and Fisheries (DEFF) approved the applications for beneficial use of FeCr slag to FeCr producers who applied for the exclusion of FeCr slag in terms of regulation 5 and 6 of the waste exclusion regulation. Only permitted uses that were applied for was excluded from the definition of waste. A Risk Assessment and Risk Management Plan submitted during the application was assessed to ensure the intended beneficial use cannot result in adverse impacts to the environment as per regulation 7,8 and 9 requirements of the waste exclusion regulation.

One of the studies conducted for FAPA motivation document for beneficial use of FeCr slag as aggregate was to evaluate classification of FeCr slag for landfill disposal (van Niekerk, 2011). The conclusions of the studies showed that FeCr slag is classified as non-hazardous according to GHS and SANS 10234 and therefore inert for disposal. An SDS is therefore not a requirement since FeCr slag is not classified as hazardous; instead, a product data sheet was developed by the FeCr producers to be available to the users of FeCr slag.

3.7 Benefits of using FeCr slag

The best strategy for solid waste management such as industrial by-products is to work towards achieving the so-called "5Rs" of reduction, recovery, recycling, reuse and research, thereby reducing their environmental problems associated with pollution and disposal (Su *et al*., 2001). The re-use of inert material, such as FeCr slag in applications such as road construction and as aggregates for cement and concrete can reduce the pressure on the reliance of natural resources (Oelofse *et al.,* 2007). This can be especially beneficial to developing countries such as South Africa, wherein economic growth necessitates the upgrade of road networks and the provision of low-cost, high-quality housing. The following sections highlight the financial, environmental and business benefits related to the re-use of FeCr slag.

FeCr slag is a chemically stable secondary resource that is well suitable for demanding structures and has found wide commercial application in the road and construction industries in countries such as South Africa, India, Norway, Turkey, East Europe, China, Sweden and USA (Al-Jabri, 2018). FeCr slag has been used for road construction, brick manufacturing and applications in cement industry as base layer material in road construction, pavement construction as engineering fill, sub-base and base as well as a hardener in the development of fire proof concrete (Al-Jabri, 2018).

3.7.1 Financial benefits

With the advancement in waste regulation, such as the enactment of *Waste exclusion regulations*, more beneficial uses of FeCr slag will emerge, as the market for the use of FeCr slag is further developed (JMA, 2013).

According to Moodie (2016), the financial benefits of FeCr waste slag usage include:

- The reduction of FeCr slag disposal costs, including the costs associated with stockpile design and monitoring;
- Alleviating the aggregate demand in the country, which may reduce the cost of aggregate (if demand is less than supply);
- Reducing the costs related to road construction; and
- Reducing the costs related to concrete production.

Other financial benefits include job creation, which is realised during crushing, screening, sorting and stockpiling of processed slag according to client's specification (JMA, 2013).

High-carbon FeCr slags that are usually dumped, if used in road construction reduces the cost of product and is environmentally friendly (Al-Jabri, 2018). Valuable metals such as FeCr can be recovered from slags, rendering the slag inert thereby making it available as construction material (Al-Jabri, 2018)

3.7.2 Environmental benefits

In South Africa, FeCr slag has, under certain circumstances, been classified as hazardous waste due to the large volumes produced and its potential for heavy metal leaching, potentially impacting on the water resource (DWAF, 1998). This has caused concern over the possible human health and environmental impacts of this waste stream in reuse applications. Studies on the re-use of FeCr slag, however, indicates minimal environmental risk (Pekka & Kauppi, 2007; Panda, *et al.,* 2013; Ananthi & Karthikeyan., 2015). According to these authors the mineralogy and microstructure of FeCr slag (with a highly stable spinal phase, which inhibits the release of FeCr under ambient conditions) is the reason why the slag leaching is significantly lower than expected when slag is recycled. There are environmental and economic advantages in utilising slag as a secondary resource than as a waste product (Al-Jabri, 2018).

The long term stockpiling and disposal of FeCr slag to land is a concern, due to its potential long-term negative impacts on land and the water resource. The limited space available for slag disposal, financial implications of the slag dumps and increase in land disposing costs influences slag management at FeCr producing companies (Al-Jabri, 2018, Saha *et al*.,2019). A large FeCr stockpile would continue to be a potential source of leachate until such time that the stockpile is either reused or lined, capped and closed for final disposal of slag or closure of the waste facility (Moodie, 2016). It is, therefore, argued that the re-use of FeCr slag would reduce the amount of waste being stockpiled, reducing the potential adverse environmental impacts in the long term.

In the construction industry, there is an increasing demand for natural aggregates due to infrastructure construction activities that leads to unsustainable quarrying of these aggregates (Kar, 2019). There is a need to explore the feasibility of replacing natural aggregate with alternative sustainable material. Replacing the use of natural aggregate with the re-use of waste is beneficial, since it reduces the extraction of natural aggregate (Moodie, 2016). The demand for naturally available aggregates is increasing due to the demand caused by growing population, housing demand, transportation and other amenities (Sathwik *et al*., 2016). Utilization of suitable by-products such as FeCr slag in the construction industry and other applications lightens the demands of natural aggregates as well as reducing the negative impacts on the environment caused by by-product stockpiles.

Other advantages of using waste beneficially include improvement of building materials, energy-saving, economy, environmental protection and rational use of natural resources (Yildiz *et al*., 2018). When FeCr slag is recycled through resource efficiency and circular economy, there is a decrease in the volume of space occupied by landfill waste and increase of revenue through selling of waste as a by-product. In cement manufacturing, 1 to 1, 5 tonnes of limestone and 0,5 tonnes of coal are used per tonne of clinker produced, replacement of clinker with industrial waste such as fly ash and furnace slag to produce blended cement assist in resource conservation, reduction in energy consumption and minimisation of CO_2 gases (Kumar *et al*., 2006, 2014)

3.7.3 Business/operational benefits

While Cr(VI) is a concern for human health and environment, chromium is a valuable metal, and therefore, FeCr slag can be considered a secondary source of metal (Shen & Forssberg, 2003). Johnson *et al*. (2006) have estimated that in 2000, 640-kilo tonnes of chromium were lost annually in FeCr slag. Therefore, the recovery of chromium from slags is beneficial for economic as well as environmental reasons.

With the advancement in waste regulation, such as the enactment of *Waste exclusion regulations*, more beneficial uses of FeCr slag will emerge, as a market for the use of FeCr slag is further developed (JMA, 2013). Commercial use of FeCr slag in civil engineering applications such as road construction, aggregate material in the concrete industry, brick manufacturing, pavement manufacturing as engineering fill and cement production are examples of beneficial use where the business benefits have been determined (Zelic, 2005, Gencel *et al*., 2012, Lind *et al*., 2001, Gerricke, 1995, Niemela *et al*., 2007).

FeCr re-use opportunities can create jobs for local communities, and the FeCr “waste products” can be utilized by various industries (especially the building industry).

3.8 Challenges and limitations applicable to the use of FeCr slag

While the majority of slags can find beneficial uses, a minor portion of slag will still need to be landfilled, which is due to volume instability associated with the presence of high free lime content or limitations to its use because of its heavy metal content, which may lead to environmental issues due to leaching (Pan *et al*., 2016). Other challenges associated with the use of FeCr slag are financial challenges and challenges related to the specifications of the FeCr slag product.

Challenges applicable to the specific beneficial uses identified as applicable to this study are further elaborated on in Chapter 4.

3.8.1 Waste characteristics and toxicity

The presence of entrained and/or dissolved toxic metal elements such as Cr(VI), as well as the build-up of harmful elements in FeCr slag, is a concern in the recycling and re-use of these materials (Matinde *et al*., 2017).

Environmental issues associated with FeCr slag that can deter its beneficial use, is mostly linked to chromium, which is present in FeCr slag (Holappa and Xiao, 2004). The speciation not only affects toxicology, but also the mobility and availability of chromium, with Cr(VI) compounds being more mobile and bioavailable than the stable and almost insoluble Cr(III) compounds (Kotas *et al*., 2000). Chemical analysis on various FeCr slag samples detected traces of heavy metals especially chromium oxide and Cr(VI) (Niemela *et al*., 2007; Das *et al*., 2017; Kumar *et al*., 2010 and Yilmaz *et al*, 2013). FeCr slag contains 8 - 12% chromium as chromium oxide with the potential to leach hazardous chromium compounds such as Cr(VI).

Various researchers (Gericke, 1995; Lind *et al.*, 2001; Yilmaz *et al*., 2013; Al-Jabri *et al*., 2013; Acharya *et al*., 2016; Sanghamitra *et al*., 2017) have conducted leaching tests according to Synthetic Precipitation Leaching Procedure (SPLP) to evaluate the potential hazards that may arise from the use of FeCr slag, also including FeCr slag in building applications. In all studies, the SPLP test results demonstrated that except for Cr(VI), the leaching of other heavy elements is negligible in terms of environmental impact. The Cr(VI) concentrations were slightly above the US EPA's 5mg/l target for chromium.

While most researchers suggest that the leaching of chromium from FeCr slag presents a low risk, some research suggests that Cr(VI) leaching to the environment presents a high risk in the long term because of the oxidation of Cr(III) to Cr(VI) in the presence of strong oxidants under laboratory conditions (Sahu *et al*., 2016). Studies have shown that natural leaching and environmental exposure of FeCr waste products such as FeCr smelter dust results in the formation and remobilization of Cr(VI) in the environment, which becomes a severe concern for groundwater pollution and soil contamination (Dhal *et al*., 2013; Satarupa & Paul, 2013). Despite the environmental concern about the content and leachability of toxic metals, FeCr slag has been classified as harmless in terms of International Agency for Research on Cancer (IARC) classification as the chromium exists in FeCr slags as Cr(III) (Saha *et al*., 2019).

To prevent and mitigate the potential risks related to the physico-chemical properties of FeCr, the South African regulations for the beneficial use of waste (including) FeCr, therefore, requires that the physical, health and environmental hazards related to the beneficial use are determined as part of the application for beneficial use.

3.8.2 Financial challenges

During the smelting process, vast quantities of FeCr slag is generated (slag: alloy = 1.1 -1.5:1), and thus it will be impossible to exhaust the entire volumes of slag generated locally (Sahu *et al*., 2016). The challenge is exacerbated by the fact that most metallurgical industries that generate metallurgical waste like FeCr slag are mostly located in remote areas where demand for construction material is low. The transportation of FeCr slag to other locations makes it uneconomical compared to the use of natural resources, which results in only a small fraction of FeCr slag being utilised.

Sprinzl (2016) in his dissertation carried out interviews with FeCr industry experts to evaluate their experience on FeCr slag. The FeCr producers who participated in the survey identified the barrier of the missing market for FeCr slag products due to abundant availability of crushed rock material from mining operations. Mining activities around the FeCr producers produce competitive materials such as crushed rocks that can be used as filler or construction materials. Another barrier identified is the geographical position and infrastructural circumstances of a FeCr producer due to the absence of a market of FeCr products. There is a financial challenge if FeCr slag products needs to be transported to potential customers. Most of the FeCr producing plants are located far from densely populated cities where there is a high demand for construction material.

Further processing and modification of FeCr slag for specific use makes the product uneconomical. A typical example is grinding, milling, shaping and high-temperature firing processing steps that are required for FeCr slag to undergo in order to be used in ceramics and refractory applications.

3.8.3 The challenge of meeting specifications in the final product

A study by Yildiz (2018) on the suitability of FeCr slag for brick production revealed that the inner structure of the FeCr slag had elevated proportion of magnesia (MgO) about 34 – 35 % which can limit bulk productions of concrete, rigid pavements and cement with FeCr slag (Yildiz *et al.*, 2018, Al-Jabri, 2018). This is mainly because elevated magnesia leads to undesirable expansion in concrete in the medium and long-term. In the same study, FeCr slag has been used successfully in the production of building material such as bricks and tiles due to its high strength, higher void rate and lower water absorption. Elevated magnesia can retard hydration of cement and increase its setting time, which can be eliminated by slag weathering in atmospheric conditions (Al-Jabri, 2018). However, it should be noted that elevated magnesia concentration in the FeCr bricks provides the bricks with lower water absorption rate thereby increasing their durability, as well as the potential for applications in ceramic industry and expanded cement production.

Al-Jabri (2018) carried out research on the use of FeCr slag in civil engineering applications and determined that the chemical composition of FeCr slag and summation of silicon, aluminium and iron oxides is about 60%, which is 10% lower than meeting the requirement to be classified as pozzolanic material. This shortfall will mean that FeCr slag is not chemically reactive material instead of cement due to insufficient lime (3.37%) to achieve hydration rate for early age strength. The FeCr slag can, however, be chemically activated using lime or cement by-pass dust (CBPD) to increase its pozzolanic activity.

The water absorption rate is relatively high in FeCr slag due to the porous nature of the slag (Al-Jabri, 2018). Physical properties of FeCr slag conducted by several researchers indicated that specific gravity (between 2, 84 g/cm^3 and 3.01 g/cm^3) and water absorption (between 0,25% and 2,3%) of slag is higher than that of limestone aggregate. The flakiness index, elongation index, impact value, crushing value and abrasion value percentages are lower than that of natural aggregate (Al-Jabri, 2018, Sanghamitra *et al.*, 2017, Yilmaz *et al*., 2013 Acharya *et al*., 2016). From the studies, FeCr slag satisfied all the requirements as per India's Ministry of Road Transport and Highways' (MoRTH) road safety engineering measures, for use in pavement layers (MoRTH, 2013).

Despite the challenges encountered in recycling and re-use of metallurgical slags, several researchers have focused on the application of metallurgical slag in other economic sectors such as application of processed slags as construction material (Euroslag, 2017), manufacturing of ceramics and other functional materials (Quijorna *et al.,* 2011) and also as geopolymer materials (Kalinkin *et al.,* 2014). Section 3.9 provides an overview of the potential beneficial uses of FeCr slag.

3.9 Exploring potential beneficial uses for FeCr slag: Learning from international examples

The circular economy model decrees the reduction, recycling and re-use of metallurgical waste (Matinde *et al*.,2018) in which metal extraction industries can integrate the model despite the environmental challenges associated with these waste streams (Lottermoser, 2011). Industrial solid waste, such as FeCr slag, is currently being explored worldwide for its beneficial use and constitute a high percentage of the alternative raw materials for the production of concrete (Awoyera *et al*., 2016). The use of FeCr slag as an aggregate in road construction is practiced worldwide in countries like Finland, Sweden, South Africa and India (Das, 2017).

This section provides an overview of the potential beneficial uses of FeCr slag, while a more detailed account is provided in Chapter 4 – Results and Discussion – which also elaborates on the opportunities and challenges related to each of the beneficial uses identified as potentially applicable within the South African context. Studies of slag re-use fall into the following four broad areas, namely, utilization of slag as a road and building construction material, ceramic and refractory application, metal recovery from slag, and slag use in environmental remediation applications (Piatak *et al*., 2015, Matinde *et al*., 2018).

Table 3-2 provides an overview of selected metallurgical slags, its mineral composition and its potential recycling and re-use opportunities.

Table 3-2: Properties, recycling, re-use opportunities of selected metallurgical slags (Matinde *et al*., 2018)

Category	Typical mineralogical composition	Recycling and re-use opportunities
Blast furnace slags	CaO-MgO-Al_2O_3-SiO_2 system. Crystallized mineral composition consisting mainly of melilite ($Ca_2MgSi_2O_7$–$Ca_2Al_2SiO_7$), and merwinite ($Ca_3MgSi_2O_8$)	Granulated and used as additives in Portland cement geopolymers, and other absorbents. Slow-cooled and used as and construction and soil aggregates.
EAF slags	$Ca_3Mg(SiO_4)_2$; β-Ca_2SiO_4; (Mg,Mn)(Cr,Al,Fe)$_2O_4$ spinel solid solution; $CaAl_2SiO_6$; (Fe,Mg,Mn)O wüstite-type solid solution; $Ca_2(Al,Fe)_2O_5$	Dissolved and/or entrained alloying elements. High level of impurities for refining slags. Recycled as pre-melted fluxes. Metal recovery and slag cleaning processes. Presence of elevated amounts of toxic alloying elements, e.g. Cr and Ni, limits their direct uptake in other sectors.
Steelmaking slags	Ca_3SiO_5; α-Ca_2SiO_4; $Ca_2Fe_2O_5$; β-Ca_2SiO_4; FeO–MnO–MgO solid solution; MgO; wüstite solid solution	
Stainless steel (AOD) slags	$FeCr_2O_4$; $FeFe_2O_4$; Ni–Cr–Fe solid solution; Ca_2SiO_4; CaF_2; $Ca_{14}Mg_2(SiO_4)_8$; Ca_2SiO_4; $Ca_4Si_2O_7F_2$; MgO; Fe–Cr alloy; Fe–Ni alloy	
PGM smelting and converting slags	Fayalitic ($2FeO·SiO_2$) slags with some dissolved magnetite. Chromium present as spinels (Fe, Mg) Cr2O4), particularly in furnaces smelting UG2 concentrates.	Slag cleaning and metal recovery. In-process build-up of converting slags Cr_2O_3 as spinels (Fe, Mg) Cr2O4) in UG2 concentrates limits recyclability and re-use.
Base metal slags (copper and nickel)	Fayalitic ($2FeO·SiO_2$) and FeO-CaO-SiO_2 slag systems with some dissolved magnetite.	Slag cleaning and metal recovery. Converter slag recyclable as pre-melted fluxes.
Ferroalloy slags	HCFeCr slags: Al2O_3-MgO-SiO_2-Cr_2O_3 system containing various phases such as MgO–MgO·Al_2O_3–2MgO·SiO_2–2CaO SiO_2, MgO·Cr_2O_3, (Mg$_2$ (Cr, Al, Si)$_2O_6$.	Slag cleaning and metal recovery. High leachability, mobility, and toxicity potential of entrained and/or dissolved Cr(VI) species limit the alternative applications.

3.9.1 Utilization of FeCr slag in road and building construction

FeCr slag is internationally recognised as a suitable material for use in road construction and as aggregate for concrete (Rossouw *et al*., 1981, Lind *et al*., 2001), and several international slag associations promote their value (JMA, 2013). FeCr slag is commonly used in construction, especially in road construction in countries such as India, Norway, Turkey, East Europe, China, Sweden and the USA (Al-Jabri, 2018).

In the USA, Japan, Germany and France, the fraction of FeCr slag being utilized has been close to 100%, where 50% of slag has been used directly as a road base, with the remainder used for sintering and iron making, or as a fertiliser (Euroslag, 2017). A number of states in Denmark, France, Germany, Netherlands and Sweden have passed legislation to assess the level of recycling within the highway environment, and passed agreements between states to allow reciprocity for beneficial use determinations, including the use of FeCr slag. (Holtz *et al*., 2000)

Outokumpu, Finland is the biggest producer of FeCr slag for commercial road construction and different other purposes (Niemela *et al.,* 2007). Outokumpu has been successfully selling FeCr slag as granulated insulating sand and various types of screened slags that are used in the foundations of buildings, in frost insulators, in street and road construction (JMA, 2013, Niemela *et al.,* 2007, Moodie, 2016). Due to FeCr slag superior physical properties over natural aggregates, roads can be built with thinner bases and sub-bases than when using natural aggregates (Das *et al*, 2017). FeCr slag products are reused in the production of asphalt, and limestone was replaced by refractory waste material in the manufacturing process (Sear, 2011). These achievements helped Outokumpu to gain its first International Stainless Steel Forum (ISSF) Sustainability award in May 2011. The FeCr slag products produced by the Outokumpu plant are quality assured and CE marked (CE marked the manufacture's declaration that the product complies with the essential requirements of the relevant European health, safety and environmental protection legislation) according to the standards EN13242 and EN13043. The main requirements for CE marking are the aggregate size distribution, resistance to fragmentation, durability against studded tyres and durability against freeze/thaw (Niemela *et al.,* 2007).

FeCr slag can also be used in civil construction as aggregate to develop high strength concrete with safe and less mobilization of hazardous chromium (Sahu *et al.*, 2016; Monosi *et al.*, 2015). Zelic (2005) assessed the performance of concrete pavements with FeCr slag as concrete aggregate in China. According to the research findings, air-cooled slag is suitable for concrete as per the relevant technical requirement of Croatian standard. From the study, it was reported that the mechanical properties of both slag and reinforced slag concrete had confirmed the advantages of slag over the limestone aggregate in all cases when higher quality is required from concretes than usual.

Blending of different ratios of fly ash as cement replacement with FeCr slag is another way of utilising a slag as construction material (Sahu *et al*., 2016). Gencel *et al*., 2012 studied the combined effects of fly ash and ferrochromium slag aggregate at the ratio of 10, 20, 30 wt % and coarse limestone aggregate by weight% in fresh concrete. From the study, it was found that fly ash lowers the properties such as compressive strength, wear resistance, tensile strength but increases the freeze-thaw durability. However, the use of FeCr slag increases the strength of concrete and abrasive wear resistance. The study concluded that the use of both fly ash and ferrochromium slag together as aggregate in concrete enhances overall properties.

Studies done by Song *et al.* (2004), Sahu *et al.* (2016), and Sanghamitra *et al*. (2017) found that the utilization of fly ash and ferroalloys slag in the manufacturing of construction materials reduces the disposal of solid waste from the power and ferroalloy industries significantly. The study further demonstrated that the profit of environment-friendly recycling processes compensates the operating expense of the environmental facilities, and enhances the competitive ability of the re-used products. These studies revealed that FeCr slag is suitable for pavement construction, concrete, riprap material and construction of stone columns in soft clay, as well as for ceramic and refractory applications. High-carbon FeCr slags are very refractory in nature and can find applications in bricks production as well as the production of ceramic components for in-plant use at ferroalloy enterprises (Zhuchkov *et al*., 2012, Kasheev *et al*., 2012, Dosekenov *et al*., 2013). The challenge however, is the low demand for these kind of refractories, which becomes uneconomical (Zhdanov *et al*., 2014).

In the African context, steel slag in Nigeria was considered as non-recyclable until recently. Recent research findings on different platforms have identified steel slag as a viable aggregate in concrete, sustainable material for soil modification and in bituminous pavement modifications (Netinger et *al*., 2011; Akimwumi *et al.,* 2016). The research did also identify that the utilisation of steel slag as coarse aggregate is a sustainable approach to preserve the depleting natural resources. Another benefit identified is that steel slag aggregate constitutes the potential for the provision of affordable housing in low-income communities (Ayowera *et al.,* 2016).

3.9.2 FeCr slag in ceramic and refractory application

The chemical composition of FeCr slag is similar to that of refractories comprised of high refractory phases spinel, fosterite and low melting phases enstatite, siliceous glass enriched with oxides of calcium, aluminium, chromium and iron (Sahu *et al.*, 2016). The presence of low melting phases decreases the melting temperature of the slag, and there are however many ways that can be utilised to improve the refractoriness of the slag by additives enrichment of alumina, magnesia and chromium oxide (Sahu *et al*., 2016). It was established that FeCr slag composition could be reengineered to develop refractory ceramic products that are suitable for high-temperature applications (Sahu *et al.,* 2016 and Sanghamitra *et al*., 2017).

Use of secondary resources such as FeCr slag in formulating castables solves the exploitation of natural raw materials and their associated costs of extraction, processing and thereby reduce their emissions (Kumar *et al*., 2014). The development of refractory castables is important due to their increasing applications in the cement, non-recovery coke ovens, chemical, metallurgical industries, ceramics, chemicals, oils/petrochemicals, etc. Kumar *et al*. (2014) developed a novel approach in preparing conventional castable and low cement castable using FeCr slag, calcined bauxite, high alumina cement and microsilica. The results exhibit good physico-mechanical and refractory properties. The less than 1% dimensional variation in prepared castables was due to the use of already heat-treated by-product (FeCr slag).

Pioro *et al.* (2003) and Bai *et al.* (2016) in experimental studies for reprocessing of metallurgical slag into materials for the building industry concluded that reprocessed blast-furnace slag could be poured into forms for the production of glass ceramic tiles. Kumar *et al.* (2014) revealed in his study that refractory castable made from FeCr slag has superior spalling resistance compared to conventional castables and it is being utilised in non-recovery coke oven doors for more than 90 cycles without repair.

Other applications of FeCr slag is in the manufacture of heat, fire and alkali resistant mineral wool by changing the viscosity of the slag and the addition of alumina and silica into the molten slag. Low temperature and high-temperature glass wools can be manufactured when certain ratios of alumina and silica are added to the ferrochromium slag (Sahu *et al.*, 2016).

Liu *et al.* (2016) investigated the properties of porous cordierite ceramics that are prepared by FeCr slag with commercial alumina and silica through a sintering technique without additional pore-forming agents. The phase evolution, porosity, microstructure, mechanical properties, thermal expansion property and leachability were investigated. Phase evolution analysis revealed that the internal oxidation of fosterite in the slag contributed to the glassy phases and synthesis of cordierite of the prepared ceramics. The iron oxides in the slag acts as a pore-forming agents. The Cr leachability of the ceramics was found to be half as high as that of the green samples, which supports another avenue for harmless treatments and resource use of FeCr slag.

3.9.3 Metal recovery from FeCr slag

Slags contain a valuable amount of metal that can be viewed as secondary resource of metals instead of being waste (Sripriyaka *et al*., 2003). According to Shen & Forsberg (2003), charge chrome slag contains high content of chromium, in the range of between 8 and 12 % with an estimated almost equal amounts of slag and metal produced in a charge chrome plant.

Pilot projects in South African, Indian and other African countries' ferroalloy plants, for commercial metal extraction plants as an integral part of their operation, have been reported (Khan *et al*., 2001; Salamon, 1995) Metal extraction process include magnetic separation and commercially viable option of simple physical gravity separation method such as crushing and jigging and tabling (Shen & Forsberg, 2003).

According to Sripriyaka *et al*., (2003), metal recovery from slag assist in reducing transportation costs and land space for dumping the slag, and also afford an opportunity for cleaning old slag dumps thereby reducing the environmental impact of the slag dumps. The benefit of metal recovery from slag dump is that it reduces the cost of production by allowing the plant to recover metal from the slag dump without running the furnaces during poor market conditions and enable them to sell the product to customers at smart prices. Metal-free slag is also sold out to customers as a construction material for roads, low-cost housing and many other applications.

3.9.4 FeCr slag in environmental remediation applications

Ferrous sulphate and ferrous chloride are popularly used by FeCr industries to reduce Cr(VI) to Cr(III). However, such chemical treatments are very costly and often result in secondary environmental problems such as high residual salts (Erdem *et al*., 2005; Gericke, 2001; Mulange & Garbers-Craig, 2012). Erdem *et al*. (2005) proved that FeCr slag could be used as a cost-effective alternative for the removal of hexavalent chromium from jigging water stream. From the study, it was demonstrated that the reduction of Cr(VI) and the precipitation of Cr(III) and Fe ions could be achieved by using fine FeCr slag and sulphuric acid, which is a cost-effective alternative.

Saha *et al*. (2019) researched on the utilization of FeCr slag for chromite mining wastewater treatment. The experimental results showed 99% removal of Cr(VI) from the mine water. In-situ generation of ferrous sulphate by addition of an oxidizing agent was the mechanism behind reduction reaction, which reduce Cr(VI) to Cr(III). The use of low carbon FeCr slag as an agricultural conditioner is not new (Senga *et. al.,* 1986). In South Africa, low carbon FeCr slags from a FeCr producer have been used for many years. It has been proven; through extensive tests, that low carbon FeCr slag as an agricultural conditioner poses no threat to the environment, and has proven beneficial to produce edible crops (Steyn, *et al.*, 1995).

3.10 South African examples on the beneficial use of FeCr slag

South African examples of beneficial use of FeCr slag are not well revealed/reported. However, there are pilot projects in which FeCr slag was successfully used as a replacement for natural aggregate (Moodie, 2016). FAPA, which is a member of the Steel and Engineering Industries Federation of South Africa appointed JMA Consulting to conduct a motivational report on the beneficial use of FeCr slag. The FAPA motivational document refers to pilot projects where FeCr was successfully used as concrete aggregate in RDP housing and in the manufacturing of cement bricks, as well as large-scale construction projects (JMA, 2013).

A number of novel applications for FeCr slag were established by a FeCr producer in South Africa (Gericke, 1998). A novel method of constructing low-income housing with a larger floor area was developed. Other uses include the patented production of fired-clay bricks incorporating slag and filter dust. The use of fine FeCr slag as blasting grit is one of the applications that was explored by the FeCr producer.

Low carbon FeCr slag and dust are being evaluated as cement extenders where mixtures of up to 70% slag and dust have been successfully used in mortars. Use of low carbon FeCr slag as a soil conditioner for acidic soils have also been established. Processed slag chips are also sold for road building and concrete work from the FeCr producers (Gericke, 1998; Moodie,2016).

Recently, another successful partnership has been established between a FeCr producer and a company that specializes in the rehabilitation of slag dumps. The FeCr slag processing plant capitalized on the fact that the construction industry uses aggregates as a viable alternative, due to the high cost of natural material and the rising emphasis on sustainable construction. FeCr slag has been successfully used in the following applications from this joint venture: road pavement layers, mechanical modification and chemical stabilisation, gravel roads, haul roads, fill applications, bedding material, backfill of storm water pipes, rehabilitation of mining sites, wash/parking bays, electrical kVA yards, stemming material, paving manufacturing, the reactive barrier to remove contaminants from water and increasing soil texture by breaking down clay-like soil (JMA, 2013).

According to JMA Consulting (Pty) Ltd as detailed in the FAPA motivational document, FeCr slag was identified as a versatile construction material during the construction phase of the N4 Toll Concession Contract, and was used for various purposes as described below (JMA, 2013):

- ***Drainage:*** Crushed slag, in excess of 400 m^3 (± 7 000t) was used for drainage construction along the N4 between Witbank and Middleburg, as well as for the widening contract between Wonderfontein and Belfast (JMA, 2013). The crushed slag was sieved out to comply with the COLTO, a Standard Specification for Road and Bridge Works for State Authorities 1998 specification for drainage aggregate.

- ***Layer for work material:*** The FeCr slag has been utilised successfully to enhance mixtures of natural soils and gravel layer work material. A volume of 5 500 m^3 (10 000 t) of FeCr slag mixed with in-situ gravel was utilised for rebuilding the shoulders along the N4 as well as sub-surface construction on N4/5 Wonderfontein to Belfast mixed with borrow-pit material (20 000 t)

- ***Asphalt:*** Asphalt manufacturing used far more FeCr slag during N4 construction than any other applications. Approximately 60 km of the N4/6N and N4/7N between Machadodorp and Montrose through Waterval-Onder was overlaid with 40mm of FeCr asphalt from Machadodorp.

  An ultra-thin friction course has been constructed on the N4/3 concrete road as an overlay using FeCr slag; a 35 mm asphalt surfacing was constructed for the widening of the toll road section between Wonderfontein and Belfast. (JMA, 2013).

  The quantities of FeCr slag asphalt outlined in Table 3-3 have been used on the N4 construction.

Table 3-3: FeCr slag asphalt used during N4 construction (JMA Consulting, 2013)

FeCr slag Application	Tonnages
Witbank N4/3 contracts – continuous medium grade asphalt	14 580 tons
N4/6-7X Elands valley	74 650 tons
N4/5 widening and rehabilitation contracts	59 900 tons
N 4/3 UTFC contract	25 900 tons
Total	175 030 tons

Seal work: The first stone application for a double seal was constructed using FeCr slag on N4/3, part of the N4/6; Eland valley has been sealed with a 13, 2 mm single seal using FeCr slag. With the advancement in waste regulation, such as the enactment of *Waste exclusion regulations* (GN 715 of 18 July 2018), more beneficial uses of FeCr slag will emerge, as a market for the use of FeCr slag is further developed. (JMA, 2013). The regulation is perceived as a vehicle that South Africa will utilise to promote and encourage the circular economy, thereby driving economic growth and job creation, while reducing the dependence on natural resources as raw materials, and avoiding pollution and environmental damage.

3.11 Chapter summary

The literature review aimed to identify historical data and research on the characteristics of FeCr slag and options for its beneficial application. The purpose was to identify the key considerations applicable to the beneficial use of FeCr slag and to identify “lessons learned” from South Africa and other countries, to provide context to the current study in terms of potential uses for FeCr slag, as well as opportunities and challenges related hereto (to address research questions 2 and 3). The potential beneficial uses are further evaluated in terms of its suitability within the South African context in Section 4.4 of this dissertation.

According to the best practices and lessons learned from South Africa and other countries, the following main aspects are deemed applicable to this study:

- South Africa is considered a leading player in the international ferro-alloy industry that produces "charge chrome" used in stainless steel manufacturing;
- FeCr slag or charge chrome slag is a waste material obtained from the manufacturing of ferrochromium alloy, which has the potential for beneficial re-use;
- The South African legislative framework provides an enabling environment for the re-use, recycling and recovery of waste through the application of the *Waste Exclusion Regulations* in terms of the NEMWA;
- To apply for the beneficial use of a waste stream in terms of the *Waste Exclusion Regulations*, the applicant needs to motivate the beneficial use applications and assess the risks related to the beneficial use of the waste;
- This chapter aimed to provide examples of FeCr slag waste beneficial use and application in South Africa and elsewhere in the world;
- International and national literature supports that reuse of inert material such as FeCr slag has financial, environmental and business/operational benefits that will ensure the sustainability of natural resources and circular economy;
- FeCr slag applications internationally fall under four broad categories namely, road and building construction, ceramic and refractory applications, metal recovery and environmental remediation applications;
- South African examples of beneficial use of FeCr slag are not well revealed/reported. However, there are pilot projects in which FeCr slag was successfully used as a replacement for natural aggregate and metal recovery;
- The main beneficial uses considered as viable within the South African context for this study included:
  - utilization of slag as a road and building construction material,
  - ceramic and refractory application,
  - metal recovery from slag, and
  - slag use in environmental remediation applications.
- With the advancement in waste regulation, such as the enactment of *Waste exclusion regulations* (GN 715 of 18 July 2018), more beneficial uses of FeCr slag will emerge, as market for the use of FeCr slag is further developed in South Africa.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter provides the results and discussion of the study, which relate to the three research objectives:

1. Evaluating the *(a) properties of FeCr slag and the (b) risks related to the beneficial use* of FeCr slag (Research Objective 1 or RO 1);
2. Based on the properties of the FeCr slag, *exploring the potential beneficial use* of the slag (Research Objective 2 or RO 2); and
3. Determining the *challenges of and opportunities for the beneficial use* of FeCr slag (Research Objective 3 or RO 3).

In summary, the results of the waste classification process, performed in accordance with SANS 10234 (2008) indicated that the FeCr slag presented no physical; health or environmental hazards (as described in Section 4.2). The tables with analytical results are provided in the sub-sections to Section 4.2, while the safety data sheet (SDS) as required as part of the SANS 10234 classification are appended as ***Annexure A.***

The risk assessment methodology followed also indicated that the significance of risk due to the beneficial use of FeCr slag is generally low, indicating impacts with little real effect and which will not have an influence on or require modification of the proposed activities (as described in Section 4.3). Literature determined that a number of potentially beneficial uses exist for FeCr slag in South Africa, including the use of FeCr as aggregate, road construction material, construction material, filtration media, and the production of cement, to name a few (as described in Section 4.4). Finally, the opportunities and challenges related to the beneficial use of FeCr slag are outlined in Section 4.4.

4.2 *Properties* of FeCr slag: SANS 10234 classification (RO 1a)

The analysis performed in 2011, 2015 and 2019 bared similar results and the values related to average concentrations are provided in the sections and tables below.

4.2.1 Results of total and leachable concentrations of major elements

The total concentrations (TC) of elements as determined by means of the *aqua regia* digestion analysis and leachable concentrations (LC) are presented in **Table 4-1** below. The results indicated very low concentrations of several hazardous elements such as arsenic, beryllium, cadmium, mercury and lead. The slag material used has gone through the metal extraction process. Elements near or below the analytical method detection limits are not expected to leach out of the slags at any levels that may pose hazards to human health and the environment.

Table 4-1: Average total elemental (TC) and leachable concentration (LC) composition of the FeCr slag from 2011, 2015 and 2019

Element	Elemental composition (average)	
	Total Concentration (TC) (mg/kg)	Leachable Concentration (LC) (mg/kg)
Ag (Silver)	141.40	Not detected
Al (Aluminium)	3 009.57	99.89
As (Arsenic)	0.80	Not detected
B (Boron)	217.79	Not detected
Ba (Barium)	324.89	9.39
Be (Beryllium)	<2.50[4]	Not detected
Bi (Bismuth)	2.79	Not detected
Ca (Calcium)	3 428.40	Not included in test[5]
Cd (Cadmium)	0.60	Not detected
Co (Cobalt)	10.77	Not detected
Cr (Chromium)	762.27	30.95
Cu (Copper)	39.9	18.70
Fe (iron)	6 055.05	993.33
K (Potassium)	378.34	Not included in test
Li (Lithium)	1.00	Not detected
Mg (Magnesium)	4 750.70	Not included in test
Mn (Manganese)	1420.40	174.48
Hg (Mercury)	0.64	Not detected
Mo (Molybdenum)	2.59	Not detected
Na (Sodium)	1 255.68	Not included in test
Ni (Nickel)	55.44	31.13
P (Phosphorus)	18.35	Not detected
Pb (Lead)	40.00	12.87
S (Sulphur)	100.92	Not included in test
Sb (Antimony)	9.97	6.26
Se (Selenium)	479	61.90
Si (Silicon)	1 160.95	585.60
Sn (Tin)	<2.50	Not detected
Sr (Strontium)	9.17	1.43
Ti (Titanium)	146.99	9.39
Tl (Thallium)	<2.50	Not detected
V (Vanadium)	4.59	Not detected
W (Tungsten)	2.59	1.26
Zn (Zinc)	229.76	37.56

[4] Elements that were not detected are indicated as below the analytical method detection limit by the symbol "<".

[5] *The solution applied in the LC test contains calcium, magnesium, potassium, sodium and sulphur and these elements are therefore not included in the results table.*

Element	Elemental composition (average)	
	Total Concentration (TC) (mg/kg)	Leachable Concentration (LC) (mg/kg)
Zr (Zirconium)	1.99	Not detected

Leachable concentrations of the major elements (Cr, Mg, Al, Fe and, to a lesser extent Ca), as determined by means of *aqua regia* digestion, are generally significantly lower than the total concentration levels reported for typical FeCr slag.

4.2.2 pH dependence of leaching characteristics and ageing characteristics of FeCr slag

As explained in Section 2.3.1.3 of this dissertation, the pH dependence of leaching characteristics and aging characteristics of FeCr slag were determined. Release estimates of contaminants in the slag for most situations assume that the slag controls release characteristics and associated design conditions of the application. However, according to Kosson *et al.* (2000), properties of surrounding materials in a particular use scenario may dominate the release conditions. External stresses (e.g., pH or redox gradients, carbonation, or mixing effects) may lead to substantial deviation from the slag's natural leaching characteristics. The solubility of many inorganic species may be strongly a function of pH, e.g., chromium, lead and manganese. The purpose of this assessment has been to assess whether there might be a potential for serious leaching of hazardous elements and potential risks to human health and the environment when the pH would change in use scenarios because of the surrounding environment.

Leaching of cobalt (Co) and manganese (Mn) (Figure 4-1) showed that the slag should not be used in scenarios where the surrounding environment could lead to low pH conditions.

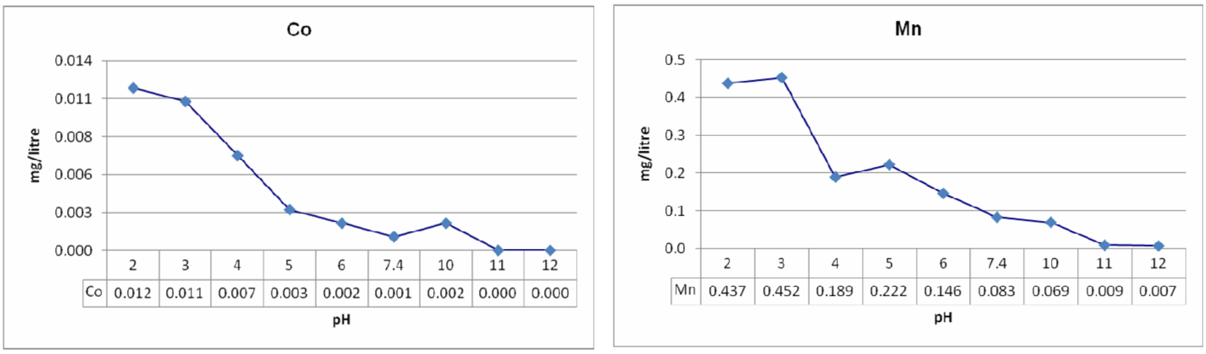

Figure 4-1: Leaching of Co and Mn according to pH level, where high leachable concentrations (mg/l) were detected at lower pH levels.

Leaching of lead (Pb) is not as clear in trend, but the data suggest that leaching would also be more pronounced at low pH (Figure 4-2).

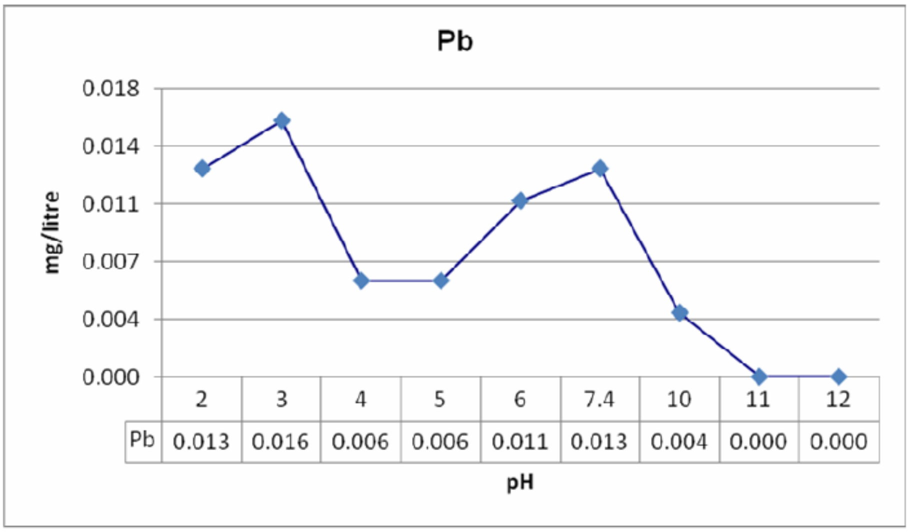

Figure 4-2: Leaching of Pb according to pH level, where higher leachable concentrations (mg/l) were detected at lower pH levels.

Leaching of chromium (Cr) indicated an increase in leaching as the pH drops to below the natural pH of the slag and there appears to be a peak in leaching around neutral pH (Figure 4-3).

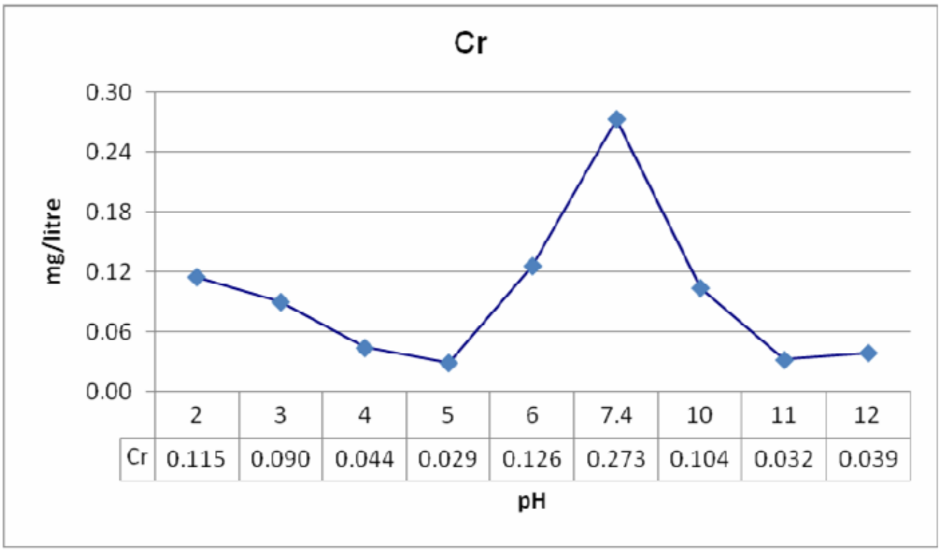

Figure 4-3: Leaching of Cr according to pH level, where an increase in leaching is observed as the pH drops to below the natural pH of the slag and there appears to be a peak in leaching around neutral pH

Results of the pH tests on leaching characteristics of the FeCr slag confirmed that changes in pH may affect the leaching potential of certain elements. It would be safe to use the slag under conditions of its natural pH or higher. Results of leach tests at different pH values indicated that, although there is a general trend of increasing leachability as the pH decrease in the range 12 to 2, the leachability of the majority of slag constituents is generally low (less than 0.5 mg/l) even at the lower pH levels.

In order to investigate effects of aging weathering, a composite fresh ferrochrome slag sample was submitted to a series of laboratory weathering tests. Elements which showed zero leaching over the completed enhanced weathering cycles include silver, cadmium, cobalt, copper, titanium and tungsten. As shown in Figure 4-4, the pH of extractions in the humidity cell tests dropped slightly over time from 8.2 to 7.8. This is regarded as insignificant in terms of pH-dependent leaching characteristics. These pH values are in the range of very low metals solubility. The pH is also not high enough to support any long-term oxidation of Cr(III) to Cr(VI).

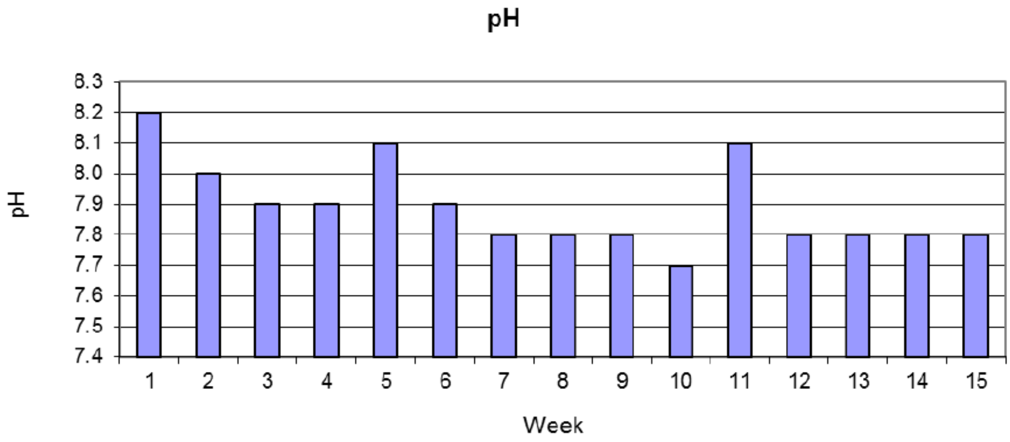

Figure 4-4: Change in pH over time (week 1 – 15) during the weathering test

The results of the humidity cell ageing tests indicated that, with the exception of sulphur, less than 5% dissolution of total leachable content occurred for the individual elements over a 15 week accelerated weathering period. Chromium was the only element, which showed a small but definitive increasing trend in mobility over the test period (Figure 4-5). It must be noted that the highest measured chromium concentration of 0.015 mg/litre (15 µg/litre) is very low (Figure 4-5). Cumulative leaching is low and it is unlikely that environmental concentrations would ever reach levels of concern. As expected, where a substance leaches out slowly over time, the cumulative leached concentration would increase. However, up to cycle 15 in the case of the FeCr slag, less than 0.004 per cent of the total *aqua regia l*eachable concentration of 762.27 mg/kg chromium has leached out during the ageing tests (Figure 4-5).

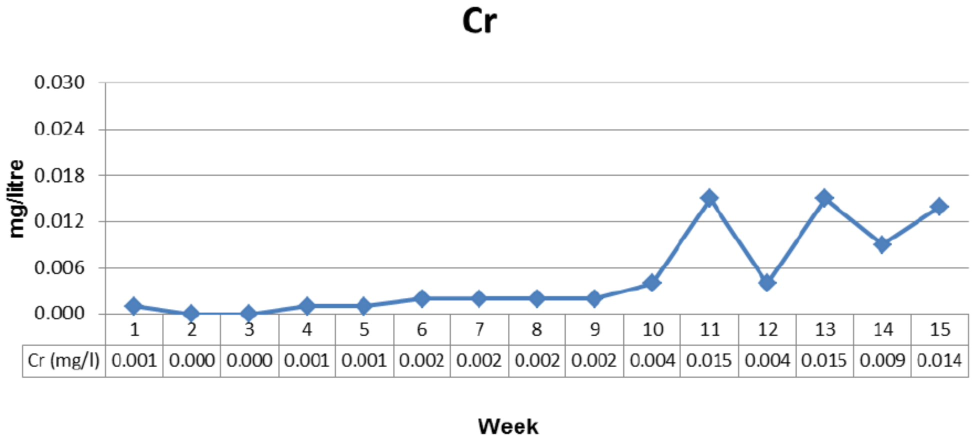

Figure 4-5: Concentration of Cr (mg/l) during 15-week ageing test.

4.2.3 Physical hazards of FeCr slag

According to GHS (SANS 10234, 2008 ed. 1.1) physical hazards refers to explosive properties, flammability, oxidizing properties, self-reacting properties and self-heating characteristics, pyrophoric and oxidizing properties, generation of hazardous or flammable gases when in contact with water and chemical properties that will materially damage, or even destroy metals. Available literature (van Niekerk, 2011, Lind *et al.*, 2001, Panda *et al.,* 2013, Booysen, 2008, Niemela *et al.*, 2007 and Gerricke, 1995) shows that FeCr slag from South Africa's ferrochrome producers is not classified as having any physical hazards, in accordance with the GHS classification system, and was not subjected to any physical hazard classification analyses.

4.2.4 Health hazards of FeCr slag

The bio-accessibility test results are outlined in Section 4.2.4.1, while the results of the generic human health hazard screening assessment are provided in Section 4.2.4.2 and the results on specific health hazards (as outlined in SANS 10234) are provided in the sub-sections to Section 4.2.4.3.

4.2.4.1 Bio-accessibility test results

Human bio-accessibility test results (average for extractions from 2011, 2015 and 2019) are shown in **Table 4-2**. The purpose of bio-accessibility test results is to inform the health hazards as outlined in SANS 10234, and for the purposes of this study, to inform the risk assessment process. Tests were conducted for elution into synthetic sweat, gastric fluid, intestinal fluid and alveolar fluid. The synthetic body fluids contain some of the elements in the list in Table 4-2 and these elements were not taken into account in the assessment and are indicated as such in Table 4-2.

Table 4-2: Concentration of analytes (mg/kg) indicating the bio-accessibility for different extraction fluids

Element	Concentration per extraction fluid (mg/kg)			
	Sweat	**Gastric**	**Intestinal**	**Alveolar**
Ag (Silver)	<2.50	<2.50	<2.50	<2.50
Al (Aluminium)	163	283	1	1
As (Arsenic)	1	10	8	1
B (Boron)	5	6	11	11
Ba (Barium)	3	3	57	60
Be (Beryllium)	<2.50	<2.50	<2.50	<2.50
Bi (Bismuth)	6	8	5	8
Ca (Calcium)	351	494	Constituent in extraction fluid	
Cd (Cadmium)	5	5	1	1
Co (Cobalt)	11	10	2	1
Cr^{3+}(Chromium)	125	181	24	11
Cr^{6+}(Chromium)	0.05	0.15	<0.05	<0.05
Cu (Copper)	2	3	1	1
Fe (iron)	7200	6650	4	6
K (Potassium)	18	15	Constituent in extraction fluid	
Li (Lithium)	<2.50	<2.50	<2.50	<2.50
Mg (Magnesium)	250	307	62	Constituent in extraction fluid
Mn (Manganese)	171	148	24	11
Hg (Mercury)	<1.0	<1.0	<1.0	<1.0
Mo (Molybdenum)	9	11	<2.50	<2.50
Na (Sodium)	Constituent in extraction fluid	61	Constituent in extraction fluid	
Ni (Nickel)	39	33	3	3
P (Phosphorus)	5	26	10	Constituent in extraction fluid
Pb (Lead)	<2.00	<2.00	<2.00	<2.00
S (Sulphur)	31	53	3070	675
Sb (Antimony)	<1.0	<1.0	<1.0	<1.0
Se (Selenium)	<2.00	<2.00	<2.00	<2.00
Si (Silicon)	355	545	53	87
Sn (Tin)	4	3	<2.50	18
Sr (Strontium)	<2.50	<2.50	<2.50	<2.50
Ti (Titanium)	10	15	<2.50	<2.50
Tl (Thallium)	<2.50	<2.50	<2.50	<2.50
V (Vanadium)	<2.50	<2.50	<2.50	<2.50
W (Tungsten)	1	1	<2.50	<2.50
Zn (Zinc)	5	6	8	10
Zr (Zirconium)	1	2	<2.50	<2.50

Table 4-2 indicates that the extent of dissolution of the slag component was generally low (mostly less than 5%) even under the relatively aggressive digestion conditions. This is consistent with the stable and inert nature of the mineral phases as determined by XRD (molten silicates, metal alloys and unaltered, or partially altered, spinels). As such, the aqua regia results both complement and validate the findings of the leachability test work (Section 4.2.1) and classification results outlined in the subsequent sections.

4.2.4.2 Generic human health hazard screening assessment of slag ingredients

As an initial Tier-1 approach, the standard *aqua regia* analysis results (Table 4-1) may be used for assessment according to the GHS. Should the screening assessment based on total elemental concentrations indicate that a slag is not classified as hazardous to human health no further work would be required. Should the screening assessment, however, indicate classification of a slag as hazardous due to one or more specific constituents for relevant toxic effects, this does not necessarily infer that the hazardous constituent can in fact be available to come into contact with vulnerable surfaces of the human body. In such cases bio-elution tests have to be conducted (as outlined in Section 4.2.4.1), The FeCr slag was classified with regard to hazards to human health related to each of the following hazard categories:

- Acute toxicity;
- Skin corrosion and skin irritation;
- Serious eye damage and eye irritation;
- Respiratory sensitization and skin sensitization;
- Germ cell mutagenicity;
- Carcinogenicity;
- Reproductive toxicity;
- Specific target organ toxicity — single and repeated exposure; and
- Aspiration hazards, as required by SANS 10234: 2008.

According to SANS 10234:2008, substances are allocated to one of five acute toxicity hazard categories based on acute toxicity (lethal dose data) by the oral, dermal or inhalation route of exposure. Acute toxicity values (LD_{50} for oral or dermal exposure, where the LD_{50} represents the amount of a chemical, given all at once, which causes the death of 50 per cent of a group of test animals, or the LC_{50} for inhalation exposure, where LC_{50} is the concentration of a chemical in air which causes the death of 50 per cent of a group of test animals exposed through inhalation within the stated study time) are required for classification purposes and are presented in Table 4-3.

Aspiration hazards are related to the potential entry of secretions or foreign material into the trachea (windpipe) and lungs. A substance or a mixture that poses an aspiration hazard causes severe acute effects such as chemical pneumonia, varying degrees of pulmonary injury or death following aspiration.

Table 4-3: Results of Tier-1 generic human health acute toxicity screening, applied for hazard assessment (Reference chemicals used are given in brackets)

Element	Acute toxicity values			Acute toxicity category[6]
	Oral LD_{50}	Dermal LD_{50}	Inhalation LC_{50}	
	mg/kg	mg/kg	mg/litre	
Ag (Silver)	32 ($AgNO_3$)	Not found[7]	Not found	Oral 2
As (Arsenic)	15, 44, 104 and 145 (As^{3+}; anions not specified)	Not found	Not found	Oral 2
Ba (Barium)	78 ($BaCl_2$)	Not found	Not found	Oral 3
Be (Beryllium)	203 ($BeCl_2$)	Not found	Generally toxic if inhaled	Oral 3, Inhalation 1, 2
Cd (Cadmium)	129 ($CdCl_2$)	Not found	Not found	Oral 3
Co (Cobalt)	42 (CoCl2)	Not found	Not found	Oral 2
Cr^{3+}(Chromium) Cr^{6+}(Chromium)	200 ($Cr(NO_3)_3 9H_2O$)	Not found	Not found	Oral 3
Cu (Copper)	280 ($CuCl_2$)	Not found	Not found	Oral 3
Mn (Manganese)	275 ($MnCl_2$)	Not found	Not found	Oral 3
Hg (Mercury)	26 ($HgCl_2$)	Not found	Not found	Oral 2
Ni (Nickel)	39 ($NiSO_4$)	Not found	Not found	Oral 2
Pb (Lead)	193 ($PbSO_4$)	Not found	0.058 ($Pb(NO_3)_2$)	Oral 3; Inhalation 2
Sb (Antimony)	281 ($SbCl_3$)	Not found	Not found	Oral 3
Se (Selenium)	4.4 ($Na_2SeO_3(H_2O)_5$)	Not found	Not found	Oral 1
V (Vanadium)	41 ($VNaO_3$)	Not found	Not found	Oral 2
Zn (Zinc)	293 (Zn(NO3)2)	Not found	Not found	Oral 3

The likely exposure scenarios related to ingestion of the slag is incidental ingestion of dust originating from the FeCr slag. This is by default a scenario involving small quantities of less than 200 mg dust per day, taken intermittently, that will exclude induction of vomiting as a practical remedy for ingestion of a potentially toxic substance. For this reason, the slag was not assessed in terms of aspiration hazards.

[6] Refer to descriptions of oral, dermal and inhalation acute toxicity categories as outlined in Section 4.2.4.3.1.
[7] Not found: Refers to the fact that no data exists on LD_{50} or LC_{50} on the specific substance.

4.2.4.3 Human health hazard screening assessment of FeCr slag

The human health hazard screening for the FeCr slag is provided in this section. The sub-sections contain the results related to the human health hazard categories as outlined in SANS 10234: 2008.

4.2.4.3.1 Acute toxicity

According to SANS 10234:2008, substances are allocated to one of five acute toxicity hazard categories based on acute toxicity estimate (ATE) values for acute toxicity (lethal dose data) by the oral, dermal or inhalation route, namely:

- ***Oral (mg/kg):***
    - Category 1: > 0 ≤ 5;
    - Category 2: > 5 ≤ 50;
    - Category 3: > 50 ≤ 300;
    - Category 4: > 300 ≤ 2000;
    - Category 5: > 2000 ≤ 5000;
- ***Dermal (mg/kg):***
    - Category 1: > 0 ≤ 50;
    - Category 2: > 50 ≤ 200;
    - Category 3: > 200 ≤ 1000;
    - Category 4: > 1000 ≤ 2000;
    - Category 5: > 2000 ≤ 5000;
- ***Dust/mist (mg/l):***
    - Category 1: > 0 ≤ 0.05;
    - Category 2: > 0.05 ≤ 0.5;
    - Category 3: > 0.5 ≤ 1.0;
    - Category 4: > 1.0 ≤ 5.0.

Table 4-4 is a summary of the acute toxicity classification of the slag ingredients, with the average mass per cent at which the ingredients occur in the slag. None of the elements were classified as acutely toxic through the dermal route of exposure. The data were used to calculate the Acute Toxicity Estimates (ATEs) of the slag with regard to oral and inhalation toxicity. The acute toxicity classification of the slag was based on the calculated ATEs.

Table 4-4: Hazard assessment for Ferrochrome Slag, based on the human health acute toxicity values for ingredients

Element	Acute toxicity category	Individual ingredient ATE (oral and dermal: mg/kg; inhalation: mg/litre)	Average mass %
Ag (Silver)	Oral 2	32	0.0141
Al (Aluminium)	Oral 3	261	0.3010
As (Arsenic)	Oral 2	44	0.0001
B (Boron)	Oral 4	510	0.0218
Ba (Barium)	Oral 3	78	0.0325
Be (Beryllium)	Oral 3 Inhalation1	203 0.005	0.0000
Bi (Bismuth)	Oral 5	2139	0.0003
Ca (Calcium)	Not classified[8]	6450	0.3428
Cd (Cadmium)	Oral 3	129	0.0001
Co (Cobalt)	Oral 2	42	0.0011
Cr (Chromium)	Oral 3	200	0.0762
Cu (Copper)	Oral 3	280	0.0004
Fe (iron)	Oral 4	462	0.6055
Hg (Mercury)	Oral 2	26	0.0001
K (Potassium)	Oral 4	528	0.0378
Li (Lithium)	Oral 2	50	0.0001
Mg (Magnesium)	Not classified	-	0.4751
Mn (Manganese)	Oral 3	275	0.0142
Mo (Molybdenum)	Oral 3	178	0.0003
Na (Sodium)	Oral 5	3000	0.1256
Ni (Nickel)	Oral 2	39	0.0055
P (Phosphorus)	Not classified	-	0.0018
Pb (Lead)	Oral 3 Inhalation 2	193 0.058	0.0000
S (Sulphur)	Not classified	-	0.0101
Sb (Antimony)	Oral 3	281	0.0010
Se (Selenium)	Oral 1	4.4	0.0005
Si (Silicon)	Oral 3	264	0.1161
Sn (Tin)	Oral 4	437	0.0000
Sr (Strontium)	Oral 5	2350	0.0009
Ti (Titanium)	Oral 4	500	0.0147
Tl (Thallium)	Oral 2	32	0.0000
V (Vanadium)	Oral 2	41	0.0005
W (Tungsten)	Oral 4	670	0.0003
Zn (Zinc)	Oral 3	293	0.0230
Zr (Zirconium)	Oral 4	1126	0.0002
Calculated slag ATE	**Oral (mg/kg)** **Inhalation (mg/l)**	**20 772** **145 406**	

[8] Not classified, refers to the fact that the element is not classified as hazardous, based on its concentration in the FeCr slag sample

4.2.4.3.2 Skin and eye corrosion and irritation

According to SANS 10234:2008, substances may be classified as skin corrosives or skin irritants, depending on the results of animal toxicity studies. Literature sources indicate that dermal exposure to silver nitrate (ATSDR 1990) may damage the skin. Although direct evidence indicating ocular damage is not available, it is reasonable to assume that this substance would also damage the eyes if direct exposure of the eyes would occur. Resultant GHS classifications are presented in Table 4-5. None of the substances under investigation in this report were classified as skin or eye irritants.

Table 4-5: Skin corrosive or skin irritant classifications of the FeCr slag

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
Ag (Silver)	0.014	Skin corrosive 1	Causes severe skin burn and eye damage	Not classified	1 ≤ Skin corrosive cat, 1 < 5

4.2.4.3.3 Respiratory sensitization and skin sensitization

None of the substances were reported to be respiratory sensitizers, but a number were classified as skin contact sensitizers, category 1 (Table 4-6). However, since the sum of classified ingredients was less than 0.1 mass percent, the FeCr slag was not classified as hazardous.

Table 4-6: Substances classified as skin contact sensitizers and the resultant classification of the FeCr slag

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
Be	0.0000	Contact sensitizer 1	May cause allergic skin reaction	Not classified	0.1%
Co	0.0011				
Cu	0.0004				
Ni	0.0055				
Se	0.0005				
Sum of classified ingredients: 0.007 mass %					

4.2.4.3.4 Germ cell mutagenicity

Germ cell mutagenicity covers chemicals that cause mutations in the germ cells of humans and that can be hereditary. Genotoxicity test results are usually taken as indicators for mutagenic effects. A germ cell mutagen can be classified in one of two hazard categories according to the weight of evidence available. For classification purposes, test results obtained by animal testing for mutagenic and/or genotoxic effects in germ cells and/or somatic cells are considered. Resultant GHS classifications are presented in Table 4-7.

Table 4-7: Substances classified as mutagenic and the resultant classification of the FeCr slag

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
Co	0.0011	Germ cell mutagen 2	Suspected of causing genetic defects	NA	-
Hg	0.0001				
V	0.0005				
Sum of classified ingredients: 0.002 mass %					

4.2.4.3.5 Carcinogenicity

Carcinogenic substances are classified based on the inherent properties of a substance and does not provide information on the level of the human cancer risk which the use of the substance may present. Classification of a product as carcinogenic, therefore, identifies a hazard, but does not involve or imply any classification of the potential risks associated with exposure. The evaluation is based on evidence from all existing, peer-reviewed published studies and additional data accepted by regulatory agencies. The resultant GHS classification based on the total elemental composition of the ferrochrome slag (*aqua regia* digestion) is presented in Table 4-8.

Table 4-8: Substances classified as carcinogenic, based on total elemental composition of FeCr slag (based on *aqua regia* results)

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
As	0.0000	1 – Known or presumed human carcinogen	May cause cancer	Not classified	0.1%
Be	0.0000				
Cd	0.0001				
Ni	0.0055				
Sum of ingredients in cancer hazard category 1: 0.0006 mass %					
Co	0.0011	2 – Suspected human carcinogen	Suspected of causing cancer	Not classified	0.1%
Pb	0.0000				
V	0.0005				
Sum of classified ingredients: 0.002 mass %					

Chromium (Cr^{6+}) is of concern in ferrochrome slag, since it may be expected to be present in concentrations not to be ignored for purposes of carcinogen classifications. However, aqua regia digestion may not be representative of conditions in body fluids. The assessment was thus repeated on the results of the bio-elution tests that included Cr^{6+} concentrations. The assessment based on the bio-elution results is presented in Table 4-9.

Table 4-9: Substances classified as carcinogenic and the resultant classification, based on the average bio-accessible mass % content of elements, determined from bio-elution extraction

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
As	0.0010	1 – Known or presumed human carcinogen	May cause cancer	Not classified	0.1%
Be	Not detected				
Cd	0.0005				
Cr^{6+}	0.00002				
Ni	0.0033				
Sum of ingredients in cancer hazard category 1: 0.0005 mass %					
Co	0.0011	2 – Suspected human carcinogen	Suspected of causing cancer	Not classified	0.1%
Pb	Not detected				
V					
Sum of classified ingredients: 0.001 mass %					

4.2.4.3.6 Reproductive toxicity

A mixture shall be classified as a reproductive toxicant when at least one ingredient has been classified as a category 1 or category 2 toxicant based on appropriate criteria, and is present at, or above, the concentration limit of 0.1 per cent. Adverse effects on sexual function and fertility include alterations to the female and male reproductive system, adverse effects on gamete production and transport, fertility or pregnancy outcomes. Developmental toxicity includes any effect which interferes with normal development of the offspring, either before or after birth. Resultant GHS classifications are presented in Table 4-10.

The assessment of health hazards based on the results of bio-elution testing (Table 4-11) is a refinement of the methodology based on assessment of the mass percentage content. It was explained earlier that the assessment based on the bio-elution tests is accepted as the final assessment and replaces the Tier-1 assessment based on the total elemental composition, since only the bio-elution test results represent the physiological bio-accessibility of the relevant elements.

Table 4-10: Substances classified as reproductive toxicants and the resultant classification of the FeCr slag. Classification based on the average mass % content of elements, determined from *aqua regia* extractions

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
Pb	0.0000	1 – Known or presumed human reproductive toxicant	May damage fertility or the unborn child	Not classified	0.1%
Co	0.0011	2 – Suspected human reproductive toxicant	Suspected of causing cancer	2 – Suspected human reproductive toxicant	0.1%
Cr	0.0762				
Ni	0.0055				
V	0.0005				
Zn	0.0230				
Sum of classified ingredients: 0.11 mass %					

Table 4-11: Substances classified as reproductive toxicants and the resultant classification of the FeCr Slag. Classification based on the average bio-accessible mass % content of elements, determined from bio-elution extractions

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
Pb	0.0000	1 – Known or presumed human reproductive toxicant	May damage fertility or the unborn child	Not classified	0.1%
Co	0.0010	2 – Suspected human reproductive toxicant	Suspected of causing cancer	2 – Suspected human reproductive toxicant	0.1%
Cr	0.0181				
Ni	0.0033				
V	0.0000				
Zn	0.0010				
Sum of classified ingredients: 0.023 mass %					

4.2.4.3.7 Specific target organ toxicity

According to SANS 10234:2008, classification of a substance or mixture as a specific target organ toxicant, depends on the availability of reliable evidence that exposure to the substance or mixture has caused consistent and identifiable toxic effects in humans and test animals, and that the effects are toxicologically significant; that is, the function and/or morphology of the tissue and/or organ is affected. The GHS provides for two specific target organ toxicity classes – single exposure and repeated exposure. Human data are the primary source of evidence and the route of exposure by which a substance produces specific target organ toxicity shall be identified. GHS classifications of target organ toxicity after *single exposure* are presented in Table 4-12, based on the mass percentage content, and based on the results of bio-elution testing in Table 4-13.

Table 4-12: Elements classified as single exposure specific target organ toxicants and the classification of the FeCr slag

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
As	0.0001	1	May cause cancer	1	1%
Ba	0.0325				
Cr	0.0762				
Cd	0.0001		Causes damage to lungs and other organs		
Hg	0.0001		Causes damage to kidneys		
Sum of classified ingredients: 0.011 mass %					
Co	0.0011	2	May cause damage to organs	Not classified	1%

Table 4-13: Constituent elements classified as single exposure specific target organ toxicants in FeCr slag and classification based on bio-elution extractions

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
As	0.0010	1	May cause cancer	Not classified	1%
Ba	0.0060				
Cr	0.0181				
Cd	0.0005		Causes damage to lungs and other organs		
Hg	0.0000		Causes damage to kidneys		
Sum of classified ingredients: 0.025 mass %					
Co	0.0011	2	May cause damage to organs	Not classified	1%

GHS classifications of target organ toxicity after *repeated* exposure are presented in Table 4-14, based on the mass percentage content.

Table 4-14: Elements classified as repeated exposure specific target organ toxicants and the classification of the FeCr slag

Element	Average mass (%)	Substance classification		Slag classification	
		Category	Description	Category	Limiting concentration mass %
As	0.0001		Causes damage to organs through repeated or prolonged exposure		
Be	0.0000		Causes damage to lungs through repeated or prolonged exposure		
Co	0.0011				
Cd	0.0001	1	Causes damage to lungs and kidneys through repeated or prolonged exposure	Not classified	1%
Hg	0.0001		Causes damage to kidneys through repeated or prolonged exposure		
Mn	0.0142		Causes damage to nervous system through repeated or prolonged exposure		
Pb	0.0000				
Sum of classified ingredients: 0.025 mass %					
Ba	0.033	2	May cause damage to organs through prolonged or repeated exposure	Not classified	1%

4.2.5 Environmental hazards

According to SANS 10234: 2008, environmental hazards include acute and chronic toxicity to the aquatic ecosystem, using surrogate aquatic species for fish (96-hr LC_{50}), crustaceans (48-hr EC_{50}); or algae or other aquatic plants (72-hr EC_{50}).

4.2.5.1 Generic assessment of hazards to the aquatic ecosystem

Hazards to the aquatic ecosystem may be assessed based on the mass percentage content of the slag. However, the GHS provides specific guidance in the case of preparations that contain poorly soluble elements, such as metallurgical slag. The GHS recommends the dissolution screening test for transformation/dissolution of metals and metal compounds in aqueous media. The leachable concentrations of FeCr slag elements are provided in Table 4-1.

Metal speciation is uncertain and it is not possible on the basis of the available information to determine whether effects would be acute or chronic. It was considered to be on the side of caution to assess the mixture for toxicity that includes the potential for long-term effects in the aquatic environment.

4.2.5.2 Assessment of hazards to the aquatic ecosystem

The list of elements of potential concern with regard to hazards to the aquatic ecosystem is presented in Table 4-15.

Table 4-15: Aquatic toxicity values applied in the acute aquatic toxicity hazard assessment and the resultant classifications

Element	Fish (LC_{50})	Crustaceans (EC_{50})	Algae (EC_{50})	Acute category
	mg/l			
Ag (Silver)	58	Not found	0.052	1
Al (Aluminium)	50	3.2	Not found	2
B (Boron)	105	133	34	3
Ba (Barium)	500	410	500	Not classified
Be (Beryllium)	1.5 – 32	2.5	100	2
Co (Cobalt)	50	Not found	0.6	1
Cr (Chromium)	18	0.05	17.8	1
Cu (Copper)	0.3	0.12	0.016	1
Fe (iron)	3	73	>50	2
Mn (Manganese)	13.1	28.7	8.3	2
Ni (Nickel)	13	1	1	1
Pb (Lead)	1 - 7	0.6 - >19.5	Not found	1
Sb (Antimony)	7	530	4.15	2
Se (Selenium)	2.3	0.57	Not found	1
Si (Silicon)	260	494	250	Not classified
Sn (Tin)	35	20	0.2	1
Sr (Strontium)	Not found	125	Not found	Not classified
Ti (Titanium)	155 (as $Ti(SO_4)_2$)	>1000	Not found	Not classified
V (Vanadium)	Not found	3	Not found	2
W (Tungsten)	420	83	Not found	3
Zn (Zinc)	0.093	Not found	0.040	1

The assessment was based on eco-toxicological data applicable to freshwater systems and may not be directly applicable to the marine environment. However, considering that products made from slags for application in the marine environment will be of monolithic nature, which generally shows much less leaching than percolation scenarios with materials having small particle sizes. Furthermore, the marine environment offers huge dilution factors which, in situations where leaching is diffusion-controlled, would in practice remove all substances very effectively from the surface release areas.

According to the GHS, components of a mixture in hazard category 1 with LC_{50} and EC_{50} well below 1 mg/litre might influence the toxicity of the mixture and must be given additional weight in the assessment. Substances with a classification in a high toxicity band, therefore, contribute to the classification of a mixture, even though all other substances in the mixture might be classified in a lower band. A multiplication factor (M-factor) is applied to account for such contributions. LC_{50} and EC_{50} [L(E)C50] categories and corresponding M-factors are listed in Table 4-16.

Table 4-16: Multiplication factors for highly toxic constituents of mixtures (SANS 10234:2008)

L(E)C50 value	Multiplication factor M
0.1 < L(E)C50 ≤ 1	1
0.01 < L(E)C50 ≤ 1	10
0.001 < L(E)C50 ≤ 0.01	100
0.0001 < L(E)C50 ≤ 0.001	1 000
0.00001 < L(E)C50 ≤ 0.0001	10 000
(Continue with factor 10 intervals)	

The classification of a mixture is dependent on the contribution of all classification categories. Therefore, the mass percentage contents of the various categories are summed (and multiplied with the M-factor if applicable, according to the equations in Table 4-17 for acute hazards and Table 4-18 for chronic hazards (SANS 10234:2008).

Table 4-17: Equations and limiting concentrations for classification of mixtures regarding acute hazards to the aquatic environment following the summation approach (SANS 10234:2008)

Sum of components for classification		Acute hazard category of the mixture
Acute 1 x M	≥ 25 %	1
[(M x 10 x Acute 1) + Acute 2]	≥ 25 %	2
[(M x 100 x Acute 1) + (10 x Acute 2)] + Acute 3	≥ 25 %	3

Table 4-18: Equations and limiting concentrations for classification of mixtures regarding chronic hazards to the aquatic environment following the summation approach (SANS 10234:2008)

Sum of components for classification		Chronic hazard category of the mixture
Chronic 1 x M	≥ 25 %	1
(M x 10 x Chronic 1) + Chronic 2	≥ 25 %	2
(M x 100 x Chronic 1) + (10 x Chronic 2) + Chronic 3	≥ 25 %	3
Chronic 1 + Chronic 2 + Chronic 3 + Chronic 4	≥ 25 %	4

The assessment of chronic aquatic toxicity was simplified by basing it on the acute assessment, assuming that all elements would bio-accumulate. Based on the SANS guidelines (SANS 10234:2008 Ed 1.1), analytes would therefore be classified in chronic aquatic toxicity categories based on the acute category classifications. Acute category 1 analytes would thus be classified as chronic category 1 substances, etc., and analytes not classified under acute toxicity would all be classified as chronic category 4 substances.

Based on the toxicological data and hazard classifications and work conducted by in 2011, 2015 and 2019 the FeCr slag used for chemical analysis and hazard assessment, following the approach and methods prescribed in SANS 10234:2008, is not hazardous to the aquatic environment.

4.2.6 Summary: Properties of FeCr slag

The FeCr slag was not classified as a physical, health or environmental hazard in terms of the Globally Harmonized System (GHS) classification due to the negligible risk posed to human health and ecosystems.

The results of classification of FeCr slag in accordance with SANS 10234:2008 (refer to Annexure A for a summary in SDS format) demonstrated that the FeCr slag samples were consistent with the physico-chemical characteristics and were non-hazardous in relation to all hazard classes.

The following key observations and findings should be considered, in combination with the classification results outlined in the sub-sections to Section 4.2 of this dissertation.

In accordance with the internationally recognized and accepted GHS classification performed according to SANS 10234: 2008, the FeCr slag samples investigated were classified as non-hazardous with regards to both human health and the aquatic environment. The results indicated that the health risks due to occupational exposure to dust generated by the FeCr slag samples are likely to be low to negligible, provided that dust levels are managed in accordance with national and international standards.

In summary, the studies conducted on FeCr slag pertaining the classification and leachability, have succeeded in demonstrating that the FeCr slag investigated poses a negligible risk to human health and ecosystems under non-aggressive conditions.

4.3 Risks related to the use of FeCr slag (RO 1b)

The risk assessment was performed by the researcher in terms of requirements as stipulated in Regulations 7 (b) of the *Waste exclusion regulations* following the guidance provided in ISO 31000: 2011 in accordance with the methodology outlined in Section 2.3.2 of this dissertation

4.3.1 Results of generic assessment of exposure to dust from FeCr slag

Table 4-19 outlines the estimated air concentration of hazardous air pollutants at the maximum air quality guidelines/standards for PM_{10}. This was used to inform the risk assessment.

The results shown in Table 4-19 indicate that cobalt was the only element that exceeded guideline concentration; however, a bio-elution test for inhalation exposure indicated very low bio-accessibility for cobalt, which confirmed insignificant exposure and associated health risks. It was thus concluded that use scenarios of FeCr slag that have a potential to generate dust would have insignificant effects on human health in communities if dust levels are managed within the South African ambient air quality standard PM_{10}. It was further demonstrated that occupational health risks associated with FeCr slag in typical use scenarios would be insignificant.

The results of the risk assessment are outlined in Table 4-20 and is based on the hazard properties of the FeCr slag (as outlined in Section 4-2 of this dissertation). In the assessment of potential risks associated with beneficial use of FeCr slag, dust generation during handling, crushing, screening, transportation as well as occupational and generic environmental exposure were considered. The exposure and health risks were assessed in a tiered approach, as explained in Chapter 2. For total elemental analysis, results showed low total concentrations of hazardous elements such as arsenic, beryllium, cadmium, mercury and lead, which means that probability of leaching of those elements from slag and pose hazards to human and environment, is very low (van Niekerk, 2011).

With the assumption that exposure of FeCr PM_{10} slag dust to recipients (community members) will be at the ambient air quality limit for chronic exposure, the results showed that with the exception of cobalt, all the elements were within the guideline concentrations (WHO, 2000, USEPA, 2010). Bio-elution tests, however, indicated low bio-accessibility of cobalt, which confirmed insignificant exposure and associated health risks.

Table 4-19: Estimated air concentration of hazardous air pollutants at the maximum air quality guidelines/standards for PM_{10} (van Niekerk, 2011, FAPA, 2015 & JMA, 2019)

HAP	AT	USEPA HAP	Concentration	WHO 2000	USEPA 2010
		µg/m³			
Ag			0.00566	No guideline	No guideline
Al	Annual		0.12038	No guideline	5.2
As	Annual	Yes	0.00003	0.00067	0.00057
B	Annual		0.00871	No guideline	21
Ba	Annual		0.01300	No guideline	0.52
Be	Annual	Yes	<0.00001	No guideline	0.001
Bi			0.00011	No guideline	No guideline
Cd	Annual	Yes	0.00002	0.005	No guideline
Co	Annual	Yes	0.00043	No guideline	0.00027
Cr	Annual	Yes	0.03049	No guideline	No guideline for total Cr
Cu			0.00016	No guideline	No guideline
Fe			0.24220	No guideline	No guideline
Hg	Annual	Yes	0.00003	No guideline	0.031
Mn	Annual	Yes	0.00570	0.15	0.05
Mo			0.00010	No guideline	No guideline
Ni	Annual	Yes	0.00222	0.0025	0.0094
Pb	Annual	Yes	0.00002	0.5	No guideline, calculate from USEPA models
Sb		Yes	0.00040	No guideline	No guideline: 0.21 for antimony trioxide
Se	Annual	Yes	0.00019	No guideline	21
Sr			0.00037	No guideline	No guideline
Ti			0.00588	No guideline	No guideline
V	Daily		0.00034	1.0	No guideline
Zn			0.00919	No guideline	No guideline
Zr			0.00008	No guideline	No guideline

Notes:
AT: Averaging exposure time applicable to the air quality standard or guideline used in the assessment.

It can thus be concluded that use scenarios of FeCr slag that have a potential to generate respirable dust would have insignificant effects on human health in communities if dust levels are managed within the South African ambient air quality standards of PM_{10}.

Occupational exposure to dust has been evaluated to not exceed occupational exposure limits for hazardous elements when dust is controlled within the occupational exposure limit for respirable dust. This would thus be insignificant occupational health risks associated with FeCr slag in typical use scenarios.

The reader is reminded of the criteria used for the risk assessment as outlined in Section 2.3.2 of this dissertation.

The results of the risk assessment (Table 4-20) indicated that the risks related to the handling, transportation, storage, processing, as well as accidental environmental spillage were all considered to be low, with significance scores ranging between 4 and 16. According to the methodology used (as outlined in Section 2.3.2), significance (SP) scores of less than 30 indicates low environmental significance, with *impacts with little real effect and which will not have an influence on or require modification of the activities.*

Table 4-20: Risk assessment for the use of FeCr slag

Activity	Risk Description	Environmental receptors	Impact	Assessment of the risk				
				Probability	Magnitude	Duration	Scale	SP score (Significance)
Transporting of slag	Potential for slag to become air-borne during transportation	Surrounding environment - Air - Roads - Other road users	Deterioration of air quality Damage to other vehicles	2	2	1	3	12 - low
Handling of slag	Potential for slag to emit dust during the loading and offloading of the slag	Air	Deterioration of local air quality	2	2	1	1	8 - low
Material storage	Potential for stockpiled material to enter the surrounding environment	Soil (primary) Surface water (secondary)	Slag spillage on soil Slag spillage in water causing siltation	3	2	1	1	12 – low
Material handling and processing	Potential for slag to emit dust during handling, crushing and screening activities	Air	Deterioration of air quality	2	4	2	1	14 – low

Activity	Risk Description	Environmental receptors	Impact	Assessment of the risk				
				Probability	Magnitude	Duration	Scale	SP score (Significance)
Material handling and processing of slag	Potential for skin exposure of humans whilst working with slag	Health - skin	Potential for skin irritation and abrasion	4	2	1	1	16– low
Material handling and processing of slag	Potential for eye contact exposure of humans whilst working with slag	Health - eye	Potential for eye irritation and abrasion	4	2	1	1	16– low
Material handling and processing of slag	Potential for inhalation of dust exposure of humans whilst working with slag	Health – respiratory system	Potential for respiratory irritation	4	2	1	1	16– low
Material handling and processing of slag	Potential for ingestion of slag dust by humans whilst working with slag	Health	Potential for irritation	2	2	1	1	8 – low
Environmental spillage	Potential for accidental release of slag into the environment during transport and material handling	Soil, surface water	Minor localised silt contamination Visual impacts	1	2	1	1	4 – low

4.4 Potential beneficial uses of FeCr slag in South Africa (RO2) and opportunities and challenges (RO3)

A number of potential beneficial uses (which are considered to be suitable within the South African context) were identified and are summarized in Table 4-21. The basis for identifying these uses as potentially beneficial applications of FeCr slag were based on the following:

FeCr slag material constitutes a significant portion of the solid waste that is disposed on landfill sites each year. Based on the analyses performed on the three slag samples, they were classified as non-hazardous based on leachable concentration values, as well as GHS hazard categories.

Insignificant leaching of the particular elements of concern (such as Fe, Cr, Co, Br, etc.) occurred. The further slag conforms to the definition of "inert", according to the definition of inert waste in the Waste Act – Schedule 3. Based on the physical properties, slag appears to be a good alternative material to conventional granular materials used in construction projects. Construction aggregate, or simply "aggregate", is a broad category of coarse particulate material used in construction, including sand, gravel, crushed stone, slag, recycled concrete and geosynthetic aggregates. Aggregates are the most mined material in the world and are a component of composite materials such as concrete and asphalt concrete; the aggregate serves as reinforcement to add strength to the overall composite material.

The beneficial use of FeCr slag is opposed to disposal of the slag material to landfills taking up many hectares of land. This further saves the natural resources currently mined as aggregate material and contributes to sustainability. The slag material can be an alternative aggregate material to supplement the growing demand for aggregate material.

Table 4-21 provides a summary of the potential beneficial uses of FeCr slag within the South African context as gleaned from literature and outlined in detail in Chapter 3 of this dissertation. The opportunities and challenges are also argued by the researcher in Table 4-21. In addition to the results provided in Table 4-21, results on overarching opportunities and challenges are also provided in Sections 4.4.1 and 4.4.2, respectively.

Table 4-21: Potential beneficial uses of FeCr slag in South Africa, with opportunities and challenges within the South African context

<table>
<tr><th>Beneficial use opportunities and advantages</th><th>References</th><th>Beneficial use challenges and disadvantages</th><th>References</th></tr>
<tr><td colspan="4">Aggregates and concrete aggregates
Suitability within the South African context: Suitable
Justification: Most cities and towns in South Africa mine natural aggregate for use in various construction applications resulting in the destruction of the natural environment. Large amounts of aggregate are required during the construction of pavements and roads in South Africa. As a result, there is a need for aggregate due to increased demand for housing for a growing population, transportation, and other amenities (Rajashekar & Reddy, 2015). Replacement of natural aggregate with FeCr slag saves landfill space and reduces the exploitation of natural aggregate. International and national research have shown that FeCr slag is a suitable natural aggregate replacement due to its physical/engineering properties, low leaching potential at its natural pH, versatility, low cost and durability (Priya et al., 2018; Dash et al.; Acharya et al., 2016 ; Kumar, 2014; Yilmaz, 2014; Gencel, 2010; Zelic, 2005). The studies further demonstrated that adding slag as mineral additive in concrete improves the workability, extends the set period, reduces the bleeding and permeability, increases resistance to sulphate, and reduces the concrete water requirement and thereby increasing the concrete strength. The concrete product with FeCr slag as a coarse and fine aggregate showed excellent results with respect to fresh and hardened concrete properties. FeCr slag as aggregate is, therefore, a financially viable and environmentally suitable solution to FeCr slag waste management in South Africa and is suitable for general-purpose concrete work.</td></tr>
<tr><td>Main constituent material in concrete production.</td><td>Priya et al., 2018; Dash et al., 2016</td><td>High water absorption due to porous nature of the slag.</td><td>Acharya et al., 2016; Zelic, 2005.</td></tr>
<tr><td>Possess excellent physical properties compared to other aggregates (good adhesion, good abrasion, rough/ porous surface and lacks clay and organic ingredients)</td><td>Acharya et al., 2016 ; Kumar, 2014; Yilmaz, 2014; Gencel, 2010; Zelic, 2005</td><td rowspan="2">Water absorption may increase weight, slump values, compressive and splitting tensile strength of concrete.</td><td rowspan="2">Ananthi et al., 2015</td></tr>
<tr><td>Displays better engineering properties (compressive strength, splitting tensile strength, bond strength, water</td><td>Acharya et al., 2018</td></tr>
</table>

<table>
<tr><th>Beneficial use opportunities and advantages</th><th>References</th><th>Beneficial use challenges and disadvantages</th><th>References</th></tr>
<tr><td>impermeability and acid resistance) than natural coarse aggregate</td><td></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>Versatile, economic, durable and ease of construction.</td><td>Ananthi et al., 2015</td></tr>
<tr><td>Relieve the pressure on reliance of natural resources as aggregates.</td><td>Oelofse et al., 2007</td></tr>
<tr><td colspan="4">Asphaltic concrete and other bituminous mixtures
Suitability within the South African context: Suitable
Justification: Natural supplies of high quality granular materials used in highways has become scarce worldwide (Yilmaz, 2012). A need for alternative materials that meet the requirements becomes a challenge that faces construction. Environmental and economic factors also contributes to the growing need for the use of reclaimed materials in asphalt pavements. The use of FeCr slag in asphalt works is the most common re-use scenario in South Africa. A FeCr slag/asphalt mixture was used during the upgrade of N4/3 toll roads (JMA, 2013). A study by CSIR on the use of charge chrome as an aggregate in hot-mix asphalt established the following unique properties of FeCr slag as aggregate: It is 20% heavier than alternative aggregate, porous, with 0.8 – 2.2 % intra-particle voids and high water absorption (JMA, 2013). The unique properties of FeCr slag improves its adhesion ability to the asphalt binder. With proper attention paid to the mix design and mixing, the authors concluded that FeCr slag could yield hot mix with satisfactory physical properties. Studies have shown that FeCr slag as aggregate affects mechanical properties of a hot bituminous mix in a positive way, and displays good physical and mechanical properties when utilized as granular layer during road construction (Kar, 2019). Laboratory tests carried out for FeCr slag (particle size analysis, specific gravity, SEM observation, chemical analysis) confirmed that asphalt mixtures containing FeCr slag filler are as good or better than those of limestone filler (Altan, 2012).Another advantage of utilizing FeCr slag and FeCr ash in concrete is that there is no adverse impact to the environment.</td></tr>
<tr><td>Commonly re-used scenario within the South Africa context.</td><td>NRA, 2013</td><td>Controversy of long term leaching of Cr(VI) in the asphaltic concrete and bituminous mixtures.</td><td>Kar, 2019</td></tr>
<tr><td>Provides stable, safe and durable road surface.</td><td>Yilmaz, 2012</td><td>Gaseous emissions during hot mix asphalt production.</td><td>Amelian et al., 2018</td></tr>
</table>

Beneficial use opportunities and advantages	References	Beneficial use challenges and disadvantages	References
Physical and mechanical properties good for alternative aggregate in bituminous materials.	Kar, 2019		
Road base and covering, road stabilisation **Suitability within the South African context:** Suitable **Justification:** FeCr slag has a widespread application in road construction as a material in base and sub-base layers in highway pavements and as embankment material. Studies have shown that FeCr slag produced in South Africa is considered a good alternative to large quantities of natural material required in the granular layers, capping and subbase layers of road structures, thus saving existing natural resources. The utilization of solid waste such as FeCr slag in the construction industry reduces the disposal cost of such waste and results in enhanced competitive ability of these products in the market. FeCr slag properties such as volume stability, high volume mass, good abrasion resistance to wear and crushability makes it a suitable material for road construction. FeCr slag has been evaluated for its suitability in road construction, and it was found that FeCr slag satisfies all the requirements for specifications for use in pavement construction. Higher bearing capacity and insulation capability properties displayed by FeCr slag results in reduced construction time due to smaller amounts of aggregate required, reduced transport costs and associated CO_2 emissions, compared to natural aggregate. FeCr slag as base material was successfully used in small quantities on the N4 between Belfast and Machadodorp (JMA, 2013). Due to FeCr slag superior physical properties in comparison to conventional aggregates, roads can be built with thinner bases and subbases that when using natural aggregates. Findings on studies for environmental impacts of using FeCr slag in road construction has shown that leaching of coarse FeCr slag is insignificant as it is a fused material at high temperatures (Lind *et al*., 2014).			
FeCr/OPC blend used as stabilised base and sub-base material in road construction and highway pavements.	Al-Jabri, 2018; Yilmaz *et al*., 2013; JMA, 2013.	Limited studies available on the use of FeCr slag in various applications.	Nath,2018
FeCr slag chip/tar blend used as top layer in road construction.	Al-Jabri, 2018	Application is still limited due to the environmental concern of Cr(VI) leaching potential from slag.	Priya *et al.,*2018

Beneficial use opportunities and advantages	**References**	**Beneficial use challenges and disadvantages**	**References**
Construction fill and construction of drainage systems **Suitability within the South African context:** Suitable **Justification:** In countries like South Africa, Norway, China, FeCr slag is utilized commercially in the road and construction industries as engineering fill for pavements construction due to its good mechanical properties and durability (Al-Jabri *et al.,* 2018). FeCr slag has been successfully applied as construction fill and construction of drainage systems during N4 construction toll-road. Soil conservation through construction of appropriate drainage system becomes paramount. FeCr slag has been applied successfully in agricultural drainage systems to control soil erosion. Due to FeCr slag properties such as less water absorption, high compressive strength, as well as the presence of large boulders, it has been found suitable for riprap and stone column application to stabilize slopes and soft clays.			
Can be used as modifiers (fillers) for infrastructure development.	Mahamaya *et al*., 2020; Galeev *et al*., 2016,	Basic nature of FeCr slag (pH 7,8 – 8) leads to formation of dense absorption and packed interface layers that decreases PVC strength if used as fillers.	Galeev *et al*., 2016,
FeCr slag/fly ash/cement blend can be used as structural fill material.	Mahamaya *et al*., 2020; Prioro *et al*., 2003		
Effective fillers for rigid and soft PVC than conventional fillers.	Galeev *et al*., 2016		
Concrete products **Suitability within the South African context:** Suitable **Justification:** Studies on the use of FeCr slag as aggregate substitute confirmed that concrete pavements prepared with FeCr slag aggregate displayed a higher compressive strength than that of limestone aggregate, when higher quality is required from concretes than usual. Concrete made from unscreened FeCr slag displays high compressive strength properties due to high intrinsic strength of the slag particles that improves binding with cement paste. These properties yields good quality concrete in terms of volume mass, water permeability, abrasion, low leachability, wear and frost resistance making the concrete suitable for applications requiring high performance concrete. Physical properties of FeCr slag such as Los Angeles (LA) abrasion value and CBR values, and high frost resistance meet the requirements of aggregates suitable for pavement layers. FeCr slag has been used successfully as a hardener in the development of fireproof concrete due to its properties of being hard, ceramic-like and chemically stable. FeCr slag based geopolymers concrete shows good fire resistance and less reduction in compressive strength compared to OPC based concrete samples (Türkmen *et al*., 2016). Studies have shown that FeCr slag can be considered as alternative to			

<table>
<tr><th>Beneficial use opportunities and advantages</th><th>References</th><th>Beneficial use challenges and disadvantages</th><th>References</th></tr>
<tr><td colspan="4">conventional aggregate in M50 grade concrete mix due to its higher strength achieved; higher specific gravity, impact strength, crushing strength and increase workability of M50 grade concrete. (Sathwik, et al., 2016)</td></tr>
<tr><td>Concrete based on FeCr slag is environmentally compatible, low impacts to soil and groundwater with excellent compressive strength.</td><td>Panda et al.,2013</td><td>Chemicals in FeCr slag can react with cement thereby reducing concrete life.</td><td>Ananthi et al, 2015</td></tr>
<tr><td>Good aggregate in pavement and road construction.</td><td>Gencel et al.,2012; Lind et al., 2001;Yilmaz and Karasahim, 2010</td><td>Durability studies for FeCr slag is a requirement despite better mechanical properties.</td><td>Ananthi et al, 2015</td></tr>
<tr><td rowspan="2">Increases concrete strength and abrasive wear resistance.</td><td rowspan="2">Nadeen et al., 2012; Panda, et al., 2013; Susheel, et al., 2016; Sathwik, et al., 2016</td><td>Higher specific gravity, bulk density and water absorption than conventional coarse aggregate.</td><td>Lakshmi and Anu, 2018; Rajasekhar and Reddy, 2015</td></tr>
<tr><td>Elevated magnesia in FeCr slag limits bulk production of concrete, rigid pavements and cement.</td><td>Yildiz, 2018</td></tr>
<tr><td colspan="4">Cement production
Suitability within the South African context: Suitable
Justification: During cement production, an intermediary product called cement clinker is produced causing significant amount of CO_2 emissions and consumption of natural resources as raw material and fuel (Acharya & Patro, 2018; Jena & Panigrahi, R., 2019). The demand for cement in South Africa is high, but its production can be reduced by using supplementary cementitious materials (SCMs) such as FeCr slag/ash as a replacement for clinker by up to 70% and more. Utilization of intermediate products/SCMs such as FeCr slag and -ash has an economic and environmental benefit in the developing economy like South Africa (Acharya & Patro, 2018). FeCr slag has displayed excellent engineering and mechanical properties when utilized as a coarse aggregate in geopolymer concrete in place of ordinary cement concrete (Jena & Panigrahi, 2019; Nath, 2018). Blending of different ratios of fly ash as cement replacement with FeCr slag is another way of utilising a slag as construction material. The FeCr slag properties increases the concrete strength and abrasive wear resistance whilst the fly ash increases the freeze-thaw</td></tr>
</table>

Beneficial use opportunities and advantages	References	Beneficial use challenges and disadvantages	References
durability, together enhancing overall concrete properties. Studies have confirmed that replacement of OPC up to 47% by FeCr ash and lime dust has comparable strength and appreciable impact on long-term properties of concrete.			
LC-FeCr slag good cementitious material due to its pozzolanic characteristics.	Zhou *et al.*, 2017		
LC-FeCr slag increases the capacity of cement production and significant reduction of greenhouse gas emissions.	Zhou *et al.*, 2017		
Can be used as partial replacement of sand in the production of cement mortars.	Al-Jabri *et al.,*2018		
Development of blended geopolymer cement increases both the thermal conductivity and specific heat effectively, and led to noticeable modifications in the microstructure characteristics of the hardened blends.	Jena & Panigrahi, R., 2019; Nath, 2018	Elevated temperatures during curing of FeCr slag/fly ash cement blend interferes with strength gain due to water evaporation from gel structure.	Nath, 2018
Effective in immobilizing Cr(VI) to Cr(III) compared to normal Portland cement and fly ash based cement in chromium containing aggregate concrete.	Lind *et al.*, 2001		
Reduces greenhouse gases (CO_2 , NOx and SO_3) emissions during cement manufacturing.	Acharya & Patro, 2018; Jena & Panigrahi, R., 2019		

<table>
<tr><th>Beneficial use opportunities and advantages</th><th>References</th><th>Beneficial use challenges and disadvantages</th><th>References</th></tr>
<tr><td colspan="4">Plaster and gunite sands
Suitability within the South African context: Suitable
Justification: In South Africa, the demand for sand is escalating at an alarming rate because of ever-increasing building construction projects and other infrastructural development, and the process of mining these aggregates has resulted to serious environmental impacts. Gunite refers to an artificial mixture of cement, water and sand that is applied to a mold to produce a dense hard protective layer. Gunite is used to line tunnels and structures and for construction applications, such as sealing cracks, fissures and areas that could be sources of leaks and/or structural instability. Due to the compressive strength of FeCr slag, it has found wide application as fine aggregate substitute to conventional sand in the cement mortar and concrete manufacturing (Dash et al., 2015; Panda et al., 2013; Priya et al., 2018). Partial replacement of conventional plaster and gunite sand with FeCr slag in the production of cement mortars has been studied and proven to result in improvement of thermal and mechanical properties (compressive and flexural strengths). The FeCr slag increase both the thermal conductivity and specific heat of the hardened blends.</td></tr>
<tr><td>Can be pertinently used as sand substitution material with chromium immobilization in concrete matrix, has been used successfully as sand or aggregate replacement in cement mortar and concrete.</td><td>Dash et al., 2015; Panda et al., 2013; Priya et al., 2018</td><td rowspan="3">There is however, less research work reported on FeCr slag used as sand substitution, further detailed investigation is still required.</td><td rowspan="3">Priya et al., 2018; Dash et al., 2016.</td></tr>
<tr><td>Exhibits similar comparative results as that with normal sand, when used as a substitution to conventional sand.</td><td>Panda et al., 2013</td></tr>
<tr><td>No significant change in compressive strength with the increment of slag up to 100% as compared with cubes with river sand as fine aggregate.</td><td>Panda et al., 2013</td></tr>
</table>

Beneficial use opportunities and advantages	References	Beneficial use challenges and disadvantages	References
Railroad ballast **Suitability within the South African context:** Suitable **Justification:** Railway transport is an integral part of South Africa's transport infrastructure for goods and commuting. Railroad ballast is a recycled product commonly made up of crushed limestone or other rock. It is primarily used during the construction and maintenance of railroads, holding the wooden cross ties in place and in turn, holding the rails in place. This product performs several additional functions for railroads. It distributes weight, provides drainage, hinders the growth of unwanted vegetation, and provides firm yet resilient support while allowing track maintenance to be performed more easily. Railroad ballast made up of recycled materials merits high priority both economically and environmentally in track maintenance planning. FeCr slag chips is a cost-effective alternative natural rock track ballast that will bear the load from railroad ties, thereby facilitating water drainage and to keep down vegetation that might interfere with the track structure.			
FeCr slag is used in civil construction applications such as embankments, railroad ballast, pavement granular base, concrete masonry, asphalt mixtures, due to its favourable physical and mechanical properties.	Amelian *et al*., 2018; Yilmaz *et al*., 2014	Less frequently used as ballast for railroad construction in developed countries compared to the use of FeCr slag as inert filling for asphalt and cement concrete.	Pugin *et al*., 2013
Roofing granules **Suitability within the South African context:** Suitable **Justification:** Many flat commercial roofs have asphalt shingles that contain roofing granules. Roofing granules are tiny particles made of natural rock constructed with a ceramic coating and covered by a silicate mixture. Natural stones used for roofing granules are mainly ground-up molten rock particles such as volcanic lava, basalt or granite that is durable, opaque and rust resistant. Currently, most of the industries manufacturing roofing granules are using natural rock. There is however emerging companies who are collaborating with FeCr to producers to recover metals and undertake commercialization of slag products as construction materials for the construction and road making industries. FeCr slag is a good alternative to natural stone to roofing granules due to its qualities to be utilized as surfacing on asphalt roofing. FeCr slag aggregate dark colour is ideal since the opaque nature will not allow solar rays to pass light through the granules, thereby protecting the asphalt coating of shingles from harsh UV light. FeCr slag contain trace amounts of ferrous oxides therefore its application as roofing granule material is ideal since a suitable iron content for a successful application is low iron content to prevent iron from leaking out of the granules, that can lead to rust on stains of roof.			

Beneficial use opportunities and advantages	References	Beneficial use challenges and disadvantages	References
The use of FeCr slag as a secondary material for manufacture of roof granules provides certain benefits to South Africa's commercial industries such as aesthetic beauty, cost-effective protection of asphalt coating of shingles from UV rays, fire resistance for shingles and lower utility bills for business due to a cooler roof.			
Metallurgical waste such as copper slag (CS) has been used in the manufacture of abrasive tools, abrasive materials, cutting tools, tiles, glass, and roofing granules.	Arunanchalam, 2014; Ananthi *et al*., 2015	Copper slag, unlike FeCr slag has been widely used in the manufacture of roofing granules.	Arunanchalam, 2014; Ananthi *et al*., 2015
Medium-grade abrasive and roofing granule products can be developed from all kinds of pyro metallurgical wastes including electric furnace dust, slag, spent refractory waste.	Fei *et al*.,2016	Studies and available information on using FeCr slag as roofing granules are limited.	Fei *et al*., 2016
Filtration media **Suitability within the South African context:** Suitable **Justification:** In South Africa's volatile ferrochrome industry market, reclaiming of metal entrapped in slag is an economic viable choice. However, during the metal extraction process, the outlet water from the jigging operation applied for FeCr reclamation from slag may contain Cr(VI) in significant levels. FeCr mining and smelting activities has the potential to contaminate groundwater and surface water. Another source of Cr(VI) will be during milling as well as in the bag filter dust and its sludge. The main environmental threat in the ferro-alloy industry is the Cr(VI) pollution. Cr(VI) contamination of soil and water is a significant problem due to its highly toxic, mutagenic and potentially carcinogenic to living organisms. Contamination of ground and groundwater due to leaching of Cr(VI) can be alleviated by the treatment of Cr(VI) contaminated water with fine FeCr slag as a filtration media.			
Fine FeCr slag with sulphuric acid has the potential of reducing Cr(VI) to Cr(III) as well as precipitation of Cr(III) and Fe ions.	Erdem *et al.,*2005; Saha *et al*.,2019	The only concern observed on the physical and geotechnical	Saha *et al*., 2019

<table>
<tr><th>Beneficial use opportunities and advantages</th><th>References</th><th>Beneficial use challenges and disadvantages</th><th>References</th></tr>
<tr><td>TCLP tests confirmed that solid residues of the Cr(VI) reduction process are environmental stable and can be used as landfilling material.</td><td>Erdem et al.,2005; Saha et al.,2019</td><td>characterization of FeCr slag is higher specific gravity than standard value.</td><td></td></tr>
<tr><td colspan="4">Backfilling, pipe filling, and hydroponic filling material
Suitability within the South African context: Suitable
Justification: In construction, backfill replaces soil that is removed during building construction, and it is used to strengthen and support a structure’s foundation. The use of commercial by-products, such as furnace slag or fly ash as backfill material, may be advantageous where such products are locally available and where suitable natural materials cannot be found. Controlled low strength material (CLSM) is a self-compacting, flowable, low-strength cementitious material used primarily as backfill, void fill and utility bedding as an alternative to compacted fill.
Conventional CLSM mixtures usually consist of water, Portland cement, fly ash or other similar products, fine or coarse aggregates or both. CLSM made aggregate such as FeCr slag, cement and fly ash blend can be used as a replacement for compacted backfill for building excavations, utility trench, retaining walls, structural fill for footings, road bases and utility bedding etc. (Alizadeh et al., 2014).
Commercial by-products such as FeCr slag is cost-effective alternative backfill material that can be applied as backfills to high walls or as additives to highly plastic clay. Fine grained and coarse FeCr slag can serve as a cost-effective, environmental –friendly alternative to conventional filler materials (Yilmaz et al., 2012).</td></tr>
<tr><td>FeCr slag can be used as an aggregate for CSLM.</td><td>Alizadeh et al., 2014</td><td rowspan="3">Slag content above 7% decreases the density thereby increasing deformation of samples when used as filler material.</td><td rowspan="3">Yilmaz et al., 2012</td></tr>
<tr><td>Fine-grained FeCr slag could be used as fill and embankment material whereas coarse FeCr slag can be used as pavement material.</td><td>Das, 2014</td></tr>
<tr><td>Provides economic and environmental benefits in comparison with conventional filler materials.</td><td>Yilmaz et al., 2012</td></tr>
</table>

<table>
<tr><th>Beneficial use opportunities and advantages</th><th>References</th><th>Beneficial use challenges and disadvantages</th><th>References</th></tr>
<tr><td colspan="4">Construction of drainage systems
Suitability within the South African context: Suitable
Justification: Slag cement has already proven itself to be a massive contender when it comes to cementitious materials (Kim et al., 2019). One of the greatest aspects of slag cement is being a recycled material. As a byproduct, the production of Slag cement does not contribute to carbon emissions in and of itself. However, the benefits of slag cement far exceed that of simply being a recycled material. Several studies have confirmed that Slag Cement can improve water flow, strength (Kim et al., 2019) and fineness of surface (Norrarat et al., 2019). Studies by Kim et al. (2019) and Norrarat et al. (2019) has proven that slag cement reduces the porosity of any cement mixture, a highly bonding material reducing voids created in conventional Portland cement. It is therefore evident that slag cement can make a huge difference in improving any city's sewer and drainage system as well as communities around the world. Ideally, placing a greater emphasis on including slag cement in cement mixtures will offset the heavy necessity placed on Portland, thereby reducing carbon emissions from cement production altogether.
FeCr slag from a South African FeCr producer was successfully used as drainage material, as layer work material, for asphalt manufacture and for seal work during N4 toll road construction. Approximately 7 000 tons of ferrochrome slag were used as drainage material on the N4 between Witbank and Middleburg. The slag fulfilled all the requirements of the Standard Specification for Road and Bridge Works for State Authorities 1998 (COLTO,1998)</td></tr>
<tr><td>Over and above the application of FeCr slag in applications such as civil engineering, road construction and production of refractory material granulated FeCr slag can be used as subsurface drainage material.</td><td>Niemela and Kauppi, 2007</td><td rowspan="2">Reuse of mining and mineral-processing wastes may minimize the environmental impacts related to disposal; however, some reuse and recycling measures may actually cause new and serious environmental problems.</td><td rowspan="2">Bian et al., 2012.</td></tr>
<tr><td>FeCr slag has been used successfully as drainage material, layer work material, for asphalt manufacture and for seal work during N4 road construction.</td><td>JMA, 2013</td></tr>
</table>

Beneficial use opportunities and advantages	References	Beneficial use challenges and disadvantages	References
The FeCr fulfilled all the requirements of the standard specification for road and bridge works for State Authorities 1998 (COLTO).	JMA, 2013		
Blasting grit **Suitability within the South African context:** Suitable **Justification:** A relatively new use for charge chrome slag in South Africa is as a blasting grit (Gerricke, 1998). Extensive tests by independent laboratories have indicated that the material is safe to use and poses no threat to the environment either, provided normal precautionary measures are followed, such as wearing the necessary protective clothing. EPA TCLP extracts for the following elements are all within the threshold levels: arsenic, barium, cadmium, chromium, lead, mercury selenium and silver. Because of its relatively low cost, hardness and angular shape, it is forecast that the use of charge chrome slag as a blasting grit will find increasingly wider applications.			
Blasting grit is being used in Finland and Japan and is currently being explored in South Africa. Fine charge chrome slag is also finding applications as a blasting grit in South Africa.	Gericke, 1998	All potential uses for waste products will increasingly be subjected to an evaluation of their impact on humans and the environment and only applications which meet these criteria will find acceptance.	Gericke, 1998
Because of its relatively low cost, hardness and angular shape, it is forecast that the use of charge chrome slag as a blasting grit will find increasingly wider applications.			
Agricultural soil conditioners **Suitability within the South African context:** Suitable **Justification:** The use of low carbon FeCr slag as an agricultural soil conditioner is not new. In South Africa, the LCFeCr FeCr producers within South Africa has already utilized low carbon FeCr slag as an agricultural soil conditioner. However, there was a concern on the environmental impact of the use of such slags, prompting the FeCr producers to undertake extensive tests to determine the effect of the water soluble Cr^{6+} on the environment in terms of potential uptake of Cr^{6+} in the food chain). The results showed that the slag addition rate is below 10 tons/ha (1			

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<tr><td colspan="4">kg/m^2). In conjunction with the Institute for Soil, Climate and Water, soils from areas where LCFeCr slag had been applied for periods of up to eight years, were sampled and analyzed. This was compared to soils where slag had never been applied. It was found that the level of plant - available chromium was less than 0,4 mg/kg, thus well below the proposed limit of 50 mg/kg soil. The conclusions drawn were that the use of LCFeCr slag from a FeCr producer as an agricultural soil conditioner poses no threat to the environment. In fact, in chrome-deficient soils, LCFeCr as a liming agent may even prove beneficial to provide edible crops (e.g. maize) with sufficient chromium to satisfy the minimum dietary requirement of chrome in humans. The nutritional role of chromium in man has been well described by World Health Organization (WHO). It has been shown that small amounts of chromium could lead to an improvement in impaired metabolism of glucose (Gerricke, 1998).</td></tr>
<tr><td>The use of low carbon FeCr slag as an agricultural conditioner is not new In South Africa, low carbon FeCr slags from a FeCr producer have been used for many years.</td><td>Senga et. al., 1986</td><td rowspan="3">Chemical analysis on various FeCr slag samples has detected traces of heavy metals specially chromium oxide and Cr(VI).</td><td rowspan="3">Niemela et al., 2007; Das et al., 2017; Kumar et al., 2010 and Yilmaz et al, 2013</td></tr>
<tr><td>FeCr slag, as an agricultural conditioner poses no threat to the environment, and has proven beneficial to produce edible crops.</td><td rowspan="2">Steyn et.al., 1995</td></tr>
<tr><td>Tests conducted on soil samples with low carbon FeCr slag shows the level of plant-available chromium below 0,4 mg/kg which is significantly less than the proposed limit of 50 mg/kg soil.</td></tr>
<tr><td colspan="4">Ceramic and refractories applications
Suitability within the South African context: Suitable
Justification: Environmental and ecological consideration necessitates the use of industrial waste due to scarcity of natural resources and to optimize recycling of chromium slag.Very limited studies have been conducted to investigate FeCr slag feasibility in high temperature applications,</td></tr>
</table>

<table>
<tr><th>Beneficial use opportunities and advantages</th><th>References</th><th>Beneficial use challenges and disadvantages</th><th>References</th></tr>
<tr><td colspan="4">such as in refractory products. Karhu, (2020) and Kumar (2014) published an article on preparation of conventional castable and low cement castables utilizing FeCr slag, calcined bauxite and micro silica. Conventional and low cement castables prepared from FeCr slag, calcined bauxite, high alumina cement and micro silica exhibit good physico-mechanical and refractory properties (Karhu, 2020; Kumar et al., 2014). The superior mechanical strength of the castable is was due to high amount of in situ acicular mullite formation. FeCr slag had been successfully implemented as conventional castables (25 wt. % slag + 75 wt. % Al2O3) for non-recovery coke oven door, which completed 90 cycles successfully without any repair. Using approximately 50% FeCr slag as an aggregate in conventional castables saved around the 40% production cost per ton. Glass ceramics has been successfully been prepared from blending high-carbon FeCr slag and waste glass (Bai et al., 2016). FeCr slag is a cost-effective alternative secondary material with wide application in the production of ceramic and refractories materials due to good physico-chemical and refractory properties and spalling resistance (Kumar et al., 2014)..</td></tr>
<tr><td>Development of refractory casteless.
Exhibit good physico-mechanical and refractory properties;
Exhibit superior spalling resistance than conventional castables; and
Saves 40% - 45% of production cost per ton as an aggregate in castables development.</td><td>Kumar et al., 2014; Karhu, 2020.</td><td rowspan="3">Low melting phases of FeCr slag decreases the melting temperature of the slag and lowers its refractoriness.</td><td rowspan="3">Sahu et al., 2016</td></tr>
<tr><td>Can be used in the manufacture glass-ceramics.</td><td>Prioro et al., 2003; Bai et al., 2016</td></tr>
<tr><td>FeCr slag/alumina blends makes porous cordierite ceramics.</td><td>Liu et al., 2016</td></tr>
<tr><td colspan="4">Metal recovery from FeCr slag
Suitability within the South African context: Suitable
Justification: Most ferroalloy plants loose considerable metal in the unprocessed slag/slag-metal mix, which serves as a potential source of income from their slag dumps. South Africa’s ferroalloy producers has metal recovery plants that serves to improve total ferrochrome recovery whilst maintaining high-quality product. There are environmental and economic advantages to see FeCr slag as a useful resource rather than</td></tr>
</table>

<table>
<tr><th>Beneficial use opportunities and advantages</th><th>References</th><th>Beneficial use challenges and disadvantages</th><th>References</th></tr>
<tr><td colspan="4">waste. FeCr slag has a metallic content of approximately 4% that can be recovered, rendering the residual slag inert and available for construction material and other applications. With the challenges faced by the FeCr industry due to volatile market prices and electricity hikes, metal extraction plants dilutes the cost of production considerably. Over and above cost dilution, a producer can shut down furnaces and rely on the low-cost metal from slag product to remain viable during times of low prices (Sripriya & Murty, 2004).In South Africa, virtually all charge chrome plants are using crushing/jigging process to recover chrome alloy from both stockpiled and currently produced slag. Studies shows that crushing of mixed metal and slag to below 10 mm followed by jigging of the -10+ 1mm material recovers 10 tons per day of metal from 18 tons per day of mixed metal (Sripriya & Murty, 2004). Recovery of metals from slag and utilisation of slags serve the dual purpose of saving metal resources as well as conserving the environment (Shen & Forssberg, 2003). Studies were done for the dissolution and reduction of chromite ore in ferrochromium slags to recover chromium losses as chromite particles trapped in the slag (Kucukkaragoz & Eric, 2018). According to the results obtained, considerable amounts of chromium and iron was recovered from FeCr slag using carbon as a reductant. Pilot projects at South Africa’s ferroalloy plants have successfully recovered FeCr fines (-1mm metal from slag) by using traditional spirals (70% recovery of metal) and the Apic classifiers (90% recovery) (Van Reenen et al., 2004).</td></tr>
<tr><td>Secondary resource of metals, which reduces the cost of production</td><td>Shen & Forssberg, 2003; Johnson et al.,2006; Al-Jabri et al., 2017</td><td rowspan="3">Oxides with beads of metals cannot be removed by magnetic separator</td><td rowspan="3">Zhdavov et al., 2016</td></tr>
<tr><td>Chromium content between 8 and 12 % that can be recovered</td><td>Coetzee et al., 2018;</td></tr>
<tr><td>Reduces transportation costs and land space for dumping the slag; and
Affords the opportunity for cleaning old slag dumps</td><td>Sripriyaka et al., 2003</td></tr>
</table>

4.4.1 Overarching opportunities for the beneficial use of FeCr slag

Apart from the specific opportunities related to a specific beneficial use of FeCr slag, there are also certain generic, overarching opportunities for the beneficial use of FeCr slag in the South African context.

4.4.1.1 Sustainable business opportunities

The beneficial use of FeCr slag may lead to sustainable business opportunities. In 2019, a South African FeCr producer signed a 10-year FeCr slag reclamation agreement with a notable reclamation company that specialises in the reclamation and remediation of mine site waste and process slag (www.eestechinc.com). Such a partnership has significant positive impacts on the world's mining and resource industries by increasing productivity, reducing energy demands, delivering significant economic benefits and environmental sustainability.

Post-process tailings will be transformed into environmentally stable, inert, sand products suitable for a wide variety of commercial applications. Sand products will be marketed as foundry sand suitable for export to the world's metal-casting industry.

The FeCr producer produces more than 1,7 million tons of FeCr per annum with 2, 2 million tons of slag production. The reclamation facility has the capacity to process up to 900 000 tons of FeCr slag per annum to recover all residual chrome units. This will establish new industry standards for mine waste and process slag management.

With this project, waste is totally transformed into value-added products to deliver zero-waste outcomes wherein industries benefits, government compliance is realised and environmental sustainability is achieved.

4.4.1.2 Wide application in the building industry

One of the major potential opportunities for the re-use of FeCr slag is in the building industry (also refer to specific examples in Table 4-21). A study was done in 1981 already, where charge chrome slags from a FeCr producer was subjected to tests by the National Building Research Institute (NBRI) of the South African Council for Scientific and Industrial Research (CSIR) to determine its suitability as concrete aggregate (Rossouw *et al.,* 1981) indicated that charge chrome slags were within all specified limits with the exception of relative density that exceeded the preferred value of 3.0 (SABS Test Method 844, 1992) by only 10%.

The suitability of FeCr slag as an alternative in the building industry gave rise to several opportunities:

- **Low cost housing:** Low cost housing that are bigger in size were constructed as part of Reconstruction and Development Programme (RDP) by the city Council of Witbank, with the free supply of washed, sized charge chrome slag from a FeCr producer (Gericke, 1998) The construction method entailed the following: the foundation slab was cast using a mixture of slagment (Portland blast furnace cement) and FeCr slag as aggregate to a strength of 15 MPa. A volume of 18 m^3 aggregate was used per house with 15 800 m^3 for the first phase of the project.

- **Construction of roads:** Construction of proper roads using FeCr slag (a mixture of 60% slag, 40% gravel by volume for the construction of a 150 mm sub base layer). This is topped with gravel/clay mixture for the base layer followed by a slag chip/tar sprayed top layer.

- **Brickmaking:** A FeCr producer collaborated with Material Science and Technology Division of the CSIR to embark in a programme to utilise waste FeCr slag and filter dust for the production of fired bricks (Boucher. *et al*., 1995). Two South African patents were granted for the production of fired bricks with slag and filter dust (Gericke, 1998).

- **Cement extenders:** Both low carbon FeCr slag and bag filter dust are being evaluated in terms of their suitability as cement extenders. Test cubes were made from mixtures containing up to 70% low carbon FeCr slag in combination with varying levels of Ordinary Portland Cement (OPC) and low carbon FeCr dust, and allowed to cure for 7 to 28 days. Compressive strengths were between the specifications for OPC (16 MPa @7 days; 32 MPa@28 days) and rapid hardening cement (33 MPa@ 7 days; 47 MPa@28 days) (Schaekers, 1997). Cubes were crushed and subjected to the US EPA TCLP test. Results indicated that the leachate contained lower concentrations of the eight EPA defined elements than the TCLP limits.

4.4.2 Overarching challenges for the beneficial use of FeCr slag

In addition to the specific challenges related to a specific beneficial use of FeCr slag (Table 4-21), there are also certain generally applicable challenges for the beneficial use of FeCr slag in the South African context.

4.4.2.1 Potential for the leaching of chrome into the environment

Although the FeCr slag has excellent properties, its application has been limited due to its potential of leaching chromium compounds to the environment (Sathwik. *et.al*. 2016). Disposal of slag comprises of short-term emissions to water from leachate as well as long-term emissions from landfill to ground water (Abubakar, 2018). According to Coetzee *et al.* (2018), chromite mining and FeCr industries pollutes the land, water and contributes significantly to air pollution.

Despite the environmental concern about the content and leachability of toxic metals, FeCr slag has been classified as harmless in terms of International Agency for Research on Cancer (IARC) classification as the chromium exists in FeCr slags as Cr(III) (Saha *et al*., 2019).

4.4.2.2 Negative perceptions regarding the use of waste materials

Oyedele *et al.* (2014) found out that recycled materials are rarely used in the construction industry due to inadequate information about the recycled product, negative perception about the products. Recycled products are perceived as second-class materials of low standard and short-lifecycle period that cannot serve the required purpose. That being said about some users' perceptions towards recycled products, the producers and companies responsible for manufacturing products from the waste, many times share a different view in that they are proud of manufacturing or using recycled products as it enhances their brand value in the sustainability-driven global environment (Oyedele *et al*., 2014).

The identified reluctance to use recycled products is often due to insufficient information about the availability, durability, qualities and effectiveness of the products for construction projects (Cappuyns *et al*., 2015). Cappuyns *et al*. (2015) researched consumer's perceptions around possibilities and barriers of using green products/secondary resource as a brick-making material. The responses on the risk perception showed that more than 60% had insufficient information available on the product despite the fact that 60% of the respondents had a higher education degree. This lack of information highlights the challenge of assessing demand for an innovative, unfamiliar product. The research further showed that consumer risk perception is determined by the possibility of a bad bargain (bricks of inferior quality) and the connotation with chemical contamination. This is influenced by factors such as the age of the respondents, environmental awareness and the respondent's belief in their ability to influence environmental problems. Consumers indicated that technical quality, safety and environmental impact are the most important characteristics of building bricks, for this reason sensitization and provision of information is imperative that the end-users through different platforms such as workshops, leaflets and newspapers to make green products successful (Cappuyns *et al*., 2015). Environmental certification of building products would be a step forward in informing consumers on the environmental impacts associated with bricks.

Another research article by Metson *et al.* (2015), on evaluating key barriers and facilitators for achieving recycling of organic waste, revealed that despite an enabling legislative environment, mandating 100% recycling of organic matter, there is a barrier in terms of the lack of shared vision about the role of government, private sector and citizens. Other barriers identified are cultural disinterest, lack of knowledge and lack of infrastructure. These barriers can, however, be overcome by investing in increasing social capital, linking key stakeholders to co-create shared visions.

Sprinzl (2016), in his dissertation, highlighted the challenge of finding a consensus between different stakeholders in the beneficial use of FeCr slag, i.e. the producer, buyer and the government. The producer as the only stakeholder with the influence on the production of FeCr slag, will be driven by minimizing the slag volumes due to high landfilling costs. On the other hand, the buyer is looking for a cheaper alternative for raw materials. The main government drive is to protect the ecosystem. The challenge, therefore, becomes understanding the producer's point of view in terms of the production process, technology and the effect on slag, at the same time taking cognisance of waste management legal requirements and how sustainable development can increase motivation for utilization of FeCr slag.

Klauber *et al.* (2009) reiterated that from the viewpoint of residue utilization and public perception, the terminology such as "waste" or "hazardous material" has a negative connotation, which deters the consumers from exploring beneficial use of such material.

Therefore, communication on environmental impacts associated with beneficial re-use of wastes, relevant roles and responsibilities, as well as the benefit to all stakeholders, should be as evident as providing information on technical and safety characteristics.

4.4.2.3 High cost compared to the use of natural raw materials

The use of FeCr slag as an alternative to raw materials may have unexpectedly high cost compared to virgin materials (Oyedele *et al*., 2014). Unlike high carbon FeCr slag that is versatile in the application of bricks and ceramics, low-carbon FeCr production needs to be enriched with boron-bearing materials to counteract its disintegration properties before it can be used as an aggregate for construction (Zhdanov *et al*., 2014). This will increase the cost of processing the FeCr slag to a usable state. Although high carbon FeCr slag has high versatility in applications such as bricks and ceramic components, the challenge is the low demand for such refractories (Zhdanov *et al.*, 2014).

Studies have shown that recycled products, especially construction products are more expensive, despite the fact that recycled construction products perform well in addressing environmental issues (Essoussi and Linton, 2010; Oyedele *et al*., 2014). This challenge has hindered the wider acceptability of using recycled construction products. It is evident from the findings that material selection of green products over their conventional counterparts is rather influenced by cost not by the amount of recycled content or environmental friendliness of such material, especially in the construction projects. Governments in the developed and developing world must therefore not only advocate an increase in recycling, but strive to develop the market for recycled products through cheaper prices for such products as incentive.

Corporate social responsibility aims to promote sustainability of communities beyond closure of operations and reduce their liability through identification of income-generating opportunities of unwanted products such as FeCr slag (Ferraz, 2016). Although the potential for socio-economic development by promoting enterprise development and job creation is possible, however there are constraints that can hinder this opportunity to be realised. There is a geographic constraint for material take-off since FeCr slag is stockpiled on the FeCr producer's lease area. Another challenge to be realised is that repurposing or beneficiation activities should not interfere with the routine operations of the FeCr producer.

4.5 Chapter conclusion

The results of the waste classification process, leachability test, and risk assessment performed in terms of the Waste Exclusion Regulations indicated that the FeCr slag is non-hazardous and presents a negligible risk to the environment and human health. There are several options within the South African context for the beneficial use of FeCr slag. These include the use of FeCr as aggregate, road construction material, construction material, filtration media, and the production of cement, to name a few. Each of the beneficial uses has opportunities and challenges – some more than others.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Chapter 5 concludes the research findings (presented in Chapter 4) in relation to the research objectives. The chapter also contains recommendations for further research.

5.1.1 Conclusions related to Research Objective 1: Determining the (a) properties of FeCr slag and the (b) risks related to the use of FeCr slag

To address research objective 1, FeCr slag (waste) from a FeCr producer in South Africa was classified in accordance with requirements of SANS 10234 to determine the hazard properties. The results of FAPA motivational report for assessment of FeCr slag indicated that the FeCr slag presented no physical, health or environmental hazards. These findings support the findings by other researchers reviewed in the national and international literature. As far as determining the potential risks related to the beneficial use of FeCr slag, the generic assessment of exposure to dust emanating from FeCr slag was investigated together with pH dependence of leaching characteristics and ageing characteristics of FeCr slag.

The results indicated that the health risks due to occupational exposure to dust generated by the FeCr slag samples are likely to be low to negligible, provided that dust levels are managed in accordance with national and international standards. The only element of concern as far as exposure to dust is concerned was the amount of cobalt (which exceeded the guideline concentration); however, a bio-elution test for inhalation exposure indicated very low bio-accessibility for cobalt, which confirmed expected insignificant exposure and associated health risks. It could thus be concluded that use scenarios of FeCr slag with a potential to generate respirable dust would have insignificant effects on human health, if dust levels are managed within the South African ambient air quality standards of PM_{10}. At the time of this study, occupational exposure to dust (surrounding the site of the FeCr producer) has been evaluated to not exceed occupational exposure limits for hazardous elements when the dust is controlled within the occupational exposure limit for respirable dust. When mitigated, typical FeCr slag beneficial use activities should not pose an unacceptable risk in typical use scenarios.

Several authors express concerns regarding the leaching of Cr(VI) from FeCr slag into the environment (which may have negative environmental and health impacts); while others reported that, the risk is negligible. For this study, a direct comparison of leachate concentration values of FeCr slag with US EPA drinking water standards emphasizes the low human health risks associated with FeCr slag, with only chromium, lead and manganese exceeding these limits to a marginal extent and only at certain pH values.

The risk assessment, performed in terms of requirements of Regulations 7 (b) of the *Waste exclusion regulations* following the guidance provided in ISO 31000: 2011, indicated that the significance of risk due to the activities related to the beneficial use of FeCr slag (such as handling, transportation, storage, etc.) is generally low, indicating insignificant impact, which will require basic mitigation measures.

In summary, the results of the hazard classification and leachability tests, which informed the risk assessment performed during this study, have demonstrated that the physico-chemical characteristics of the FeCr slag investigated poses a negligible risk to human health and ecosystems under non-aggressive conditions anticipated during the storage, transportation, handling and use of FeCr slag during its potential beneficial use. These assessments concluded that FeCr slag could be considered as non-hazardous and relatively non-reactive (i.e. inert), with insignificant risks to human health and the environment.

5.1.2 Conclusions related to Research Objective 2: Exploring the potential beneficial uses of FeCr slag (RO 2)

In South Africa, the literature on case studies of FeCr slag re-use, published on accessible platforms is limited. The FAPA motivation document on the beneficial use of FeCr slag provided successful re-use scenarios for the building industry, where FeCr slag was used as drainage material and layer work material, for asphalt manufacture and seal work (JMA, 2013).

Based on the review of national and international literature on the potential re-use of FeCr slag, the following potential beneficial uses for FeCr slag was identified within the South African context:

- Aggregates and concrete aggregates;
- Asphaltic concrete and other bituminous mixtures;
- Road base and covering, road stabilisation;
- Construction fill and construction of drainage systems;
- Concrete products;
- Cement production;
- Plaster and gunite sands;
- Railroad ballast;

- Roofing granules;
- Filtration media;
- Backfilling, pipe filling, and hydroponic filling material;
- Dam construction and stabilisation material;
- Blasting grit; and
- Agricultural soil conditioners.

Despite its wide scope of potential re-use opportunities, some challenges still exist with its implementation.

5.1.3 Conclusions related to Research Objective 3: Determining the challenges of and opportunities for the beneficial use of FeCr slag (RO 3).

Each of these potential beneficial uses of FeCr slag has specific related opportunities (such as the replacement of non-renewable resources, financial savings, process optimisation) and challenges (related to technical specification, leaching of elements, potential environmental risks, etc.). Apart from the specific opportunities related to a specified potential beneficial use of FeCr slag, there are also certain generic, overarching opportunities and challenges related to the beneficial use of FeCr slag in the South African context.

Because of its characteristics, FeCr slag has wide application in the building such as low cost housing, construction of roads, brickmaking and cement extenders; and other industries such as agriculture where it could be used as a soil conditioner. Sustainable business opportunities exist wherein FeCr slag producers partner with businesses such as slag reclamation companies, and socio-economic development enterprises, where FeCr slag as waste is totally transformed into value-added products to deliver zero-waste outcomes wherein industries benefits, government compliance is realised, and environmental sustainability is achieved.

There are also certain generally applicable challenges for the beneficial use of FeCr slag in the South African context. Although the FeCr slag has good properties which suit its potential for re-use, its application has been limited due to its potential of leaching chromium compounds to the environment. Despite the environmental concern about the content and leachability of toxic metals, FeCr slag has been classified as harmless in terms of International Agency for Research on Cancer (IARC) classification as the chromium exists in FeCr slags as Cr(III).

The negative perception around using waste material is that recycled products are perceived as second-class materials of low standard and short-life cycle period that cannot serve the required purpose. The identified hesitance to the use of the recycled products is generally due to insufficient information about the availability, durability, qualities and effectiveness of the products for construction projects.

Another challenge identified is finding a consensus between significant stakeholders (producers, buyer and government) in the beneficial use of FeCr slag. The challenge, becomes understanding the producer's point of view in terms of the production process, technology and the effect on slag, at the same time taking cognisance of waste management legal requirements and how sustainable development can increase motivation for utilization of FeCr slag.

Studies have shown that recycled products, especially construction products, are sometimes more expensive, even though recycled construction products perform well in addressing environmental issues. This challenge has hindered the wider acceptability of using recycled construction products. It is evident from the findings that material selection of so-called "green products" over their conventional counterparts is rather influenced by cost not by the amount of recycled content or environmental friendliness of such material, especially in the construction projects.

5.2 Recommendations

Before the *Waste Exclusion Regulations* being promulgated, strict and burdensome legislative requirements have discouraged industry from exploring the potential beneficial use of FeCr slag. These regulations are regarded as a mechanism to encourage industry to promote the circular economy and support the implementation of the waste management hierarchy.

An important aspect related to the optimisation of FeCr slag re-use will be to create a market that wants to use the material. This can be achieved by providing information on the product to change possible negative perceptions around its re-use.

Socio-economic development, through promoting business development and job creation, is possible through projects such as building roads, pavements, houses and infrastructure to uplift communities in the surroundings of the smelters. This corporate social responsibility will promote sustainability of communities beyond the closure of operations and reduce their liability through the identification of income-generating opportunities of unwanted products such as FeCr slag. If the focus is placed on the re-use of FeCr slag, the opportunity for job creation over time will be realised.

Opportunities may exist for the government to support beneficial use initiatives by introducing incentives in a form of market-based instruments that will promote the re-use of secondary raw materials rather. For these initiatives, the South African Waste Information System (SAWIS) may be useful to monitor the amounts of waste re-used to inform the awarding of incentives.

5.3 Suggestion for future research

Further research is recommended to collect empirical data around opportunities and challenges for FeCr slag re-use, as well as to determine the perceptions of potential secondary users of FeCr slag waste. Further research and monitoring are also recommended to determine the actual impacts related to the beneficial re-use of FeCr slag on health and the environment to inform future risk assessments.

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Annexure A: FeCr Aggregate Product Specification sheet

SECTION 1. IDENTIFICATION OF SUBSTANCE AND COMPANY

1.1 Product Identifier	Ferrochrome slag
1.2 Approved uses of the substance and uses advised against	This material may ***only*** be used for the approved beneficial waste uses in the following processes: ▪ Use as aggregates ▪ Concrete aggregates ▪ Road base and covering and road stabilization ▪ Asphaltic concrete and other bituminous mixtures ▪ Construction fill ▪ Concrete products ▪ Plaster and granite sands ▪ Railroad ballast ▪ Roofing granules ▪ Filtration media ▪ Pipe filling material ▪ Backfilling ▪ Dam construction and stabilisation material ▪ Construction of drainage systems ▪ Hydroponic filling ▪ Material ▪ Production of cement
1.3 Details of supplier of the safety data sheet	
1.3.1 Name of supplier	▪ FeCr Producer
1.3.2 Emergency telephone number	**SITE NAME: CONTACT NUMBER**

SECTION2: HAZARDS IDENTIFICATION

2.1 Classification of the substance	This product is not hazardous and as a waste is classified as a type 4 waste according to the National Environmental Management: Waste Act 59 of 2008, its amendments and relevant regulations as at date of revision.
2.2. Label elements	This product is not hazardous. Labeling is not required.
2.3 Other Hazards	Though not considered to be hazardous, material should be handled with due considerations to industrial and personal hygiene. See section 8 for personal protection.
2.3.1 During handling	If a significant amount of dust is present, precautions should be taken to limit this exposure through normal control procedures such as respiratory protective equipment (RPE).
2.3.2 During use	See guidance on safe use throughout the SDS relative to the points below.

GHS* hazard statement code	Hazard statement
Physical hazards	None
Human health hazards	H320: Causes eye irritation
Environmental hazards	None

SECTION3: COMPOSITION INFORMATION ON INGREDIENTS

3.1 Substances			
Component	**CAS Nr**	**Amount (%)**	**Symbol**
Chromite	1308-31-2	8.94	$Fe\ Cr_2O_4$
Diopside	14483-19-3	21.71	$MgCaSi_2O_6$
Forsterite	15118-03-3	4.24	Mg_2SiO_4

Iron alpha (Ferrite)	7439-89-6	1,69	Iron alpha (Ferrite)
Spinel	12068-51-8	41.5	$MgO \cdot Al_2O_3$
Amorphous	none	21.92	Amorphous
Additional Information: Amounts indicated are typically generalised and do not represent a specification.			

SECTION 4: FIRST AID MEASURES

4.1 Description of first aid measures	
Inhalation	Move out of dusty conditions into fresh air. Take precautions to minimize dust formation (e.g. wetting of the product) and use appropriate personal protective equipment to prevent dust inhalation. If respiratory problem persists, seek medical attention.
Skin contact	Special attention other than routine personal hygiene not required. Wash with water and soap.
Eye contact	Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Seek medical attention if irritation persists.
Ingestion	Wash out mouth with water. No known effects.
4.2 Most important symptoms and effects, both acute and delayed	This product is considered as non-hazardous.
4.3 Indication of any immediate medical attention and special treatment needed	No relevant information has been identified. Potential symptoms/effects of over-exposure: • None specific to the product. • Inhalation of dust may produce the same effects as inhalation of nuisance dust, e.g. slight irritation of the upper respiratory tract.

SECTION 5: FIRE-FIGHTING MEASURES

5.1 Extinguishing media	Product is not combustible
5.2 Special hazards arising from the substance or mixture	Product is not combustible

5.3 Advice for fire-fighters	Product is not combustible

SECTION 6: ACCIDENTAL RELEASE MEASURES

6.1 Personal precautions, protective equipment and emergency procedures	Eye protection and respirators should be worn where dust is a potential hazard. Gloves should be worn when handling this material because of the risk of contact with sharp particles. Do not ingest.
6.2 Environmental precautions	Avoid deposition outside areas of intended use. Spillage can be reclaimed for use; however it can have a limited impact depending on the degree of weathering that has taken place, the quantity of the spill and the area of the spill. It should be recovered and removed within a 24 hour period.
6.3 Methods and material for containment and cleaning up	Remove with mechanical equipment, shovels or brooms, appropriate to the size of the spilt material. Follow good housekeeping. Avoid excessive dust generation. Material may be reclaimed for re-use.

SECTION 7: HANDLING AND STORAGE

7.1 Precautions for safe handling	There are no special instructions before use.The product is a heavy and dense material.. If dusty conditions occur, wear suitable protective clothing, e.g., eye/face protection and respiratory protection. Wash hands and face thoroughly after handling.
7.2 Conditions for safe storage, including any incompatibilities	Special precautions not needed. The product is stable in storage. Product usually sold in large volumes for which packaging is impractical. Smaller volumes may be packed in metal drums or robust bags. Avoid deposition outside areas of intended use. Avoid storage conditions that may generate dust.
7.3 Specific end use(s)	See section 1.2 above

SECTION 8: EXPOSURE CONTROL / PERSONAL PROTECTION

8.1 Control parameters	
8.1.1 National occupational exposure limit values* (mg/m^3)	5 - Limit for inert respirable dust in air.

*Promulgated by the SA Department of Labour under the Occupational Health and Safety Act, 1993 (Act No. 85 of 1993).	
8.2 Exposure controls	
8.2.1 Appropriate engineering controls	None
8.2.2 Individual protection measures, such as personal protective equipment	
Eye/face protection	Safety goggles and face shield if the potential exists for the generation of sharp, small chips, sharp flakes or excess dust.
Skin	Overalls and safety boots; gloves for hands, where applicable.
Respiratory	If exposure is above the Occupational Health limits, respirators as approved by national authorities should be used.
Thermal hazards	Not identified
8.2.3 Environmental exposure controls	Do not wash spilled materials into drainage system, material may block drains.

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

9.1 Information on basic physical and chemical properties	
Appearance	Solid, crushed stone
Odour	None
Odour threshold	Not applicable
pH	Not applicable
Melting point	Not applicable
Boiling point	Not applicable
Flash point	Not applicable
Evaporation rate	Not applicable
Flammability	Not applicable
Upper/lower flammability or explosive limits	Not applicable
Vapour pressure	Not applicable
Vapour density	Not applicable

Relative density	Not applicable
Solubility	Not soluble in water
Partition coefficient: n-octanol/water	Not applicable
Auto-ignition temperature	Not applicable
Decomposition temperature	Not applicable
Viscosity;	Not applicable
Explosive properties;	Not applicable
Oxidising properties	Not applicable

SECTION 10: STABILITY AND REACTIVITY

10.1 Reactivity	The product does not contain reactive functionalities.
10.2 Chemical stability	The product is chemically stable under normal ambient and anticipated storage and handling conditions of temperature and pressure.
10.3 Possible hazardous reactions	None known
10.4 Conditions to avoid	None known
10.5 Incompatible materials	None known
10.6 Hazardous decomposition products	None

SECTION 11: TOXICOLOGICAL INFORMATION

11.1 Information on toxicological effects	
(a) acute toxicity;	None
(b) skin corrosion/irritation;	None
(c) serious eye damage/irritation;	Causes eye irritation
(d) respiratory or skin sensitization;	None
(e) germ cell mutagenicity;	None
(f) carcinogenicity;	None

(g) reproductive toxicity;	None
(h) STOT-single exposure;	None
(i) STOT-repeated exposure;	None
(j) aspiration hazard.	None

SECTION 12: ECOLOGICAL INFORMATION

12.1 Toxicity	Not toxic
12.2 Persistence and degradability	Not relevant
12.3 Bioaccumulative potential	None
12.4 Mobility in soil	Insignificant solubility in water, immobile
12.5 Other adverse effects	None identified

SECTION 13: DISPOSAL CONSIDERATIONS

13.1 Waste treatment methods	Large volumes of this material should not be disposed of outside the intended area of use. Empty containers may be disposed of in non-hazardous waste sites. Disposal of waste should be undertaken by a licensed waste contractor in accordance with the National Environmental Management: Waste act 59 of 2008, its amendments, relevant regulations and norms and standards.

SECTION 14: TRANSPORTATION INFORMATION

14.1. UN number	The material is not classified as hazardous for transport
14.2. UN proper shipping name	The material is not classified as hazardous for transport
14.3. Transport hazard class(es)	The material is not classified as hazardous for transport
14.4. Packing group	The material is not classified as hazardous for transport
14.5. Environmental hazards / Marine pollutant (Yes/No)	No
14.6. Special precautions for user	Transport in the original container. Large volumes not packaged in containers should be transported under a tarpaulin.

SECTION 15: REGULATORY INFORMATION

15.1. Safety, health and environmental regulations/legislation specific for the substance or mixture	No labeling is required. Consult the SANS10228, 2003: The Identification and Classification of Dangerous Goods for Transport; as amended. Consult the National Environmental Management: Waste act 59 of 2008, its amendments, relevant regulations and norms and standards.

SECTION 16: OTHER INFORMATION

PRECAUTIONARY NOTES: The slag which is taken for use may only be used for the beneficial uses listed above and no other uses.