The benefits of using ferrochrome slag as waste aggregate in South Africa

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Declaration

I, Elzanne Moodie, declare that the dissertation, which I hereby submit for the degree MSc Environmental Sciences at the North-West University, is my own work and that the sources I have used or quoted for this purpose have been acknowledged in the bibliography and references herein.

05/05/2016.

Signature

Date

Abstract

This research study aims to promote and optimise the reuse of ferrochrome slag in South Africa. In support thereof, the objectives of this research study are to: identify and describe the environmental benefits of using ferrochrome slag as aggregate; to investigate the probable financial benefits of replacing natural aggregates with ferrochrome slag; and to describe methods of facilitating the reuse of ferrochrome slag as aggregate in South Africa. The research study collected data by the qualitative assessment of a systematic literature review from which a comparative analysis is drawn to achieve the aim and objectives of the study.

Ferrochrome slag is generated from the production of ferrochrome and due to its physical and mechanical properties, it is a potentially suitable alternative to natural aggregate used in the construction of roads and infrastructure. South African environmental legislation classified ferrochrome slag as hazardous waste and therefore, the majority of ferrochrome slag has been disposed of onto slag dumps in South Africa. Due to the leaching potential of ferrochrome slag dumps, this has the potential to cause environmental degradation in the event that these disposal facilities are not correctly engineered and operated. The research study confirms that ferrochrome slag does not classify as hazardous when assessed against relevant human health or aquatic ecosystem hazard categories and that there are no physical hazards associated with the reuse of ferrochrome slag under normal conditions.

Moreover, land degradation caused by aggregate mining may result in potentially negative environmental impacts and therefore suitable alternatives to natural aggregate should be considered by the construction industry. A key learning from this study indicates that ferrochrome slag is a potentially suitable alternative to natural aggregate for road construction and concrete in South Africa, and it has become a preferred alternative to natural aggregate in many other countries. The benefit of recycling waste such as ferrochrome slag can be summarised as reducing the reliance on natural material, reducing transport or production energy and reducing waste that has to be disposed of onto slag dumps.

The study shows that reusing ferrochrome slag as aggregate is a financially viable and environmentally sustainable solution to ferrochrome slag waste management in South

Africa. Recent developments toward implementing this solution suggest that the reuse of ferrochrome slag on large scale may realise in the near future; and the researcher acknowledges the effort towards achieving this goal.

Key Words: ferrochrome slag; reuse; waste aggregate; South Africa; benefits.

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I acknowledge the work done by the South African Regulator, as well as the South African Ferrochrome Industry by the Ferro Alloys Producers Association towards the reuse of ferrochrome slag as aggregate in South Africa, and I encourage the completion thereof.

I am privileged to live in such a bio diverse country as South Africa at a time when we are still capable of instilling change towards sustainable environmental solutions. History will judge us harshly if we do not accomplish this responsibility.

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CHAPTER 1: INTRODUCTION

1.1 Background information on chromium

Chromium is a hard, brittle, silver metal with a very high melting point of 1857˚C. It provides vivid colours, strengthens material and provides resistance to corrosion, decay, temperature and wear, making it a metal that ensures permanence (Guertin, Jacobs & Avakian, 2005:2-14). It is also used in the culinary and medical fields to provide hygienic properties to surfaces, utensils and instruments (International Chromium Development Association, 2015).

Chromium was discovered by Nicolas-Louis Vauquelin in the late 1700s when it was identified as a metallic element in the crocoite mineral found in the Siberian Mountains (Weeks, 1968: 271-281). The discovery of crocoite originated from the Siberian Beresof gold mine that was located in the Siberian Ural Mountains, where Johann Gottlob Lehmann found lead chromite in 1761 that became known as Siberian red lead (Guertin, Jacobs & Avakian, 2005:7). The crocoite mineral was difficult to obtain at this time, due to mining conditions, but in 1797 a sample of the mineral was sent to a chemistry professor, Nicolas-Louis Vauquelin, in the Paris School of Mines (Guertin, Jacobs & Avakian, 2005:8).

In 1797 Nicolas-Louis Vauquelin analysed the crocoite mineral and obtained colourful solutions by his experiments. He was also able to isolate the new metal from chromium trioxide, which he obtained by treating the crocoite mineral with hydrochloric acid. Chromium trioxide was then heated intensely in a crucible to produce the new metal that looked like metallic needles (Weeks, 1968: 271-281).

Due to its colouring properties it became known as chromium, named after the Greek word for colour, khrõma, and it found its first use as paint pigment, producing vivid yellow, red and green colours (Weeks, 1968: 271-281). Typically, chromium does not occur in its free metal form under atmospheric conditions due to its reaction with oxygen. This reaction is rapid and results in a strong thin oxide film forming on the surface of the metal which prevents any further reaction (Guertin, Jacobs & Avakian, 2005:4). Chromium is considered a strategic material due to its many uses, but the main commercial use for chromium arises from its passive or alloying properties (Guertin, Jacobs & Avakian, 2005:2). The use of chromium in alloys is due to its oxidation that forms a thin surface layer or film which makes it resistant to corrosion (Guertin, Jacobs & Avakian, 2005:4).

Since its discovery and until the early 1900s chromium had been mainly used as a colour pigment in paint. The demand for the product increased over time and chromium reserves were discovered in other parts of the world besides Siberia, resulting in increased studies into the characteristics of the mineral (Guertin, Jacobs & Avakian, 2005:11-13). In the early 1900s electric arc furnaces were developed and it became possible to smelt chromite into ferrochrome in order to produce chromium metal. After stainless steel was developed in 1913; ferrochrome became extremely useful to provide alloying properties to steel, making it stainless (Guertin, Jacobs & Avakian, 2005:13). Chromium also found other uses such as chromium electroplating, application in refractory bricks and foundry sand (International Chromium Development Association, 2015).

Ferrochrome is produced from chromite, reductants and fluxing agents that are smelted in a ferrochrome furnace and ferrochrome slag is the waste product that is generated from this production process (Biermann, Cromarty & Dawson, 2012:302). Ferrochrome slag can be reused as a building aggregate, but in South Africa the majority of ferrochrome slag is disposed of onto slag dumps. Prior to recent changes in legislation, ferrochrome slag was classified as hazardous waste by South African environmental legislation due to the presence of manganese, iron and hexavalent chromium (Biermann, Cromarty & Dawson, 2012:302).

This classification hindered the reuse of ferrochrome slag for suitable purposes such as aggregate, and therefore contributed to large pieces of land being utilised for the disposal of ferrochrome slag while natural aggregate is extracted from undisturbed land. The legal framework, classification process and reuse challenges are more fully described in the literature review of this report.

1.2 Rationale of the study

South Africa is one of the world's largest producers of ferrochrome and therefore of ferrochrome slag (Chromium: Global Industry Markets and Outlook 12^{th} edition, 2014:200). The reuse of slag, however, has become a highly contentious topic due to restrictions by environmental legislation that hinders the beneficial reuse of ferrochrome slag for suitable applications, such as aggregate (Reuter, Xiao & Boin, 2004:35). This is clearly seen in research conducted by Godfrey *et al.* (2007); Oelofse, Adlem and Hattingh (2007); Oelofse (2009) and Nkosi *et al.* (2013).

Ferrochrome slag is classified as hazardous waste in South Africa and the reuse thereof requires environmental authorisations or exemptions for each reuse facility; which are costly and time consuming. This deters the construction industry from making use of ferrochrome slag as aggregate, due to the amount of time and money required to apply for environmental authorisations or exemptions, resulting in the exploitation of virgin soil for building aggregate (Oelofse, Adlem & Hattingh, 2007:614). This practice results in environmental risk relating to land degradation (Environmental Commissioner of Ontario, 2003:30) and the disposal of ferrochrome slag onto landfill sites also results in environmental risk, such as soil contamination, as well as surface and groundwater pollution (Petersen & Petrie, 2000:356). The literature review of this study elaborates on this critical issue in much more detail.

According to Godfrey *et al.* (2007:3) there are five opportunities that promote the reuse of mineral wastes such as ferrochrome slag. They are: material suitability, technology advancements, supporting legislation, economic viability and environmental benefits. Due to the use of ferrochrome slag as aggregate in Europe, the literature review of this study shows that research has been conducted into the material suitability and technology advancements relating to the reuse of ferrochrome slag as aggregate, as seen in the works of Emery (1982), Barišić, Dimter and Netinger (2010); Gencel *et al.* (2011) and Prusinki, Marceau and Van Geem (2004).

With the recent promulgation of additional supporting legislation to enable the reuse of waste, such as ferrochrome slag, and on the grounds of research conducted by Godfrey *et al.* (2007:3) there is a requirement to research the economic viability and environmental benefits thereof in order to promote reuse in South Africa (Godfrey *et al.*, 2007:2-3).

The benefits of using ferrochrome slag instead of natural materials has not yet been extensively researched in South Africa and the rationale of this study is to address this research requirement to an extent.

1.3 Problem statement

A literature review of international studies showed that there had been extensive research conducted into the suitability of slag, as a replacement for aggregate, as indicated by the works of Barišić, Dimter and Netinger (2010); Gencel *et al.* (2011) and Prusinki, Marceau and Van Geem (2004). The key findings of these sources indicate that ferrochrome slag is not only a suitable alternative to aggregate for use in road construction and concrete, but has become a preferred alternative to natural aggregate in many European countries.

The benefit of recycling ferrochrome slag in this manner is also actively researched, as seen in studies conducted by Nicholls, Clark and Samuel (2004); Hiltunen and Hiltunen (2004); Pekka and Kauppi (2007); Zelic (2004) and Reuter, Xiao and Boin (2004). In essence, the benefits include a reduction in the total amount of aggregate required when comparing the use of ferrochrome slag as aggregate with that of natural aggregate. This benefit results in a reduction of energy consumption, reduced carbon emissions and reduced transport costs, as well as faster construction times and less manpower required. The literature review is discussed in Chapter 3 of this study.

Ferrochrome slag is classified as a hazardous waste in South Africa, resulting in the reuse thereof not being optimised and the potential benefits relating to this reuse not realising (Oelofse, Adlem & Hattingh, 2007:614). There has recently, however, been a change in legislation, making it possible for the reuse of ferrochrome slag to be listed as an activity that does not require a waste management license (Department of Water and Environmental Affairs [DWEA] 2013: 3-21). In order for such a listing to be effective for a material type across an industry, such an industry has to make a joint application in this regard, and this process may result in further delays.

In response to this change in legislation the Ferro Alloys Producers Association (FAPA) has drafted a motivational document on the beneficial use of ferrochrome slag as aggregate material, for submission to the Minister of Environmental Affairs to consider the listing thereof as an activity that does not require a waste management license. It is, therefore, probable that the South African legislative obstacles to the reuse of ferrochrome slag as aggregate may be overcome by this process.

The two remaining opportunities for promoting reuse of ferrochrome slag in South Africa are economic viability and environmental benefits. This gives rise to the research requirement described in section 1.2 above; to investigate and describe the benefits of using ferrochrome slag instead of natural materials as aggregate.

1.4 Aim and objectives of the study

This research study is aimed at promoting and optimising the reuse of ferrochrome slag in South Africa. This will be done by investigating the benefits of replacing natural aggregates (which are extracted from undisturbed land and used for the construction of roads, infrastructure or housing development) with ferrochrome slag, which is currently disposed of on slag dumps.

In support of the aim of the study, the objectives of this research study are:

1. To identify and describe the environmental benefits of using ferrochrome slag as aggregate
2. To investigate the probable financial benefits of replacing natural aggregates with ferrochrome slag
3. To describe methods of facilitating the reuse of ferrochrome slag as aggregate in South Africa

Each research objective is set out below in order to describe how each objective will support the aim of the study.

1.4.1 Objective 1: Identifying and describing the environmental benefits of using ferrochrome slag as aggregate

A study conducted by Hattingh and Friend (2003) considered the disposal practices of ferrochrome slag in South Africa, which included an assessment of the legislative framework and its implications on a disposal site for ferrochrome slag. The study found that a significant amount of money was required to dispose of ferrochrome slag onto a waste site and that the only other viable alternative for managing the ferrochrome slag waste stream was to reuse the slag. The study was able to identify suitable reuse options but concluded that there was limited information available, describing the environmental impact of reusing ferrochrome slag in South Africa (Hattingh & Friend, 2003:23-29).

Objective 1 of this research study is to describe the environmental impact and associated benefits of reusing ferrochrome slag as aggregate in South Africa by a systematic review of available national and international literature and an analysis of the motivational document and related test work prepared by the Ferro Alloys Producers Association on the beneficial use of ferrochrome slag as aggregate material.

1.4.2 Objective 2: Investigating the probable financial benefits of replacing natural aggregates with ferrochrome slag

According to Godfrey *et al.* (2007:13-15) the failure to reuse mineral waste such as ferrochrome slag can be seen as a market failure, where the mining and extraction costs of virgin materials do not reflect the full social cost of failing to reuse mineral waste, such as aggregate, instead of the use of natural aggregate (Godfrey *et al.*, 2007:13-15). Social costs include private costs and external costs; whereas private costs are the direct costs of goods or services paid for by the producer and consumer. (Federal Reserve Bank of San Francisco, 2002). External costs, on the other hand, are those costs that are imposed on society as a result of the product or service, and are not accounted for by the producer or consumer (Eeckhoudt, Schieber & Schneider, 2000).

The extraction costs of natural aggregate do not include the cost of environmental impacts to society, and in the absence of intervention, also do not account for remediation and rehabilitation costs of not using available alternatives, such as ferrochrome slag (Godfrey *et al.*, 2007:14). Environmental costs frequently become externalities and are often not taken into account by a business during decision making processes, such as choosing appropriate raw materials for a project. The benefit of reusing ferrochrome slag as aggregate instead of natural aggregate would for instance not be reflected in prices. The full social cost of such a market failure is unfortunately not felt by the business taking the decision, but in the absence of intervention, rather becomes a social burden (Godfrey *et al.*, 2007:13-15).

According to Godfrey *et al.* (2007:13-15), the environmental benefits of business decisions are not entirely considered in terms of cost; and the overall market failure (referred to above) may be due to a command and control regulatory environment applied in the South African market. Reference is made to regulations that aim to determine behaviour of businesses by command and control restrictions in environmental policy instead of mechanisms such as market-based instruments to either incentivise positive environmental decisions or discourage negative environmental decisions. Examples of such market-based instruments are a reduction in cost of mineral waste (that may be used as aggregate) or the implementation of environmental tax for extracting virgin material (Godfrey *et al.*, 2007:13-15).

Objective 2 of the research study is therefore, to investigate the probable financial benefits of replacing natural aggregates with ferrochrome slag in order to describe the benefits to the ferrochrome industry, construction industry, as well as the social benefits related to the beneficial reuse of ferrochrome slag as aggregate.

1.4.3 Objective 3: Describing methods of facilitating the reuse of ferrochrome slag as aggregate in South Africa

Significant amounts of mineral waste such as ferrochrome slag are produced in South Africa annually, but large scale reuse of ferrochrome slag is not yet taking place optimally (Godfrey *et al.*, 2007:1). Instead large amounts of ferrochrome slag has been disposed of onto slag dumps while natural aggregate is extracted from undisturbed pieces of land, resulting in external cost being incurred due to the resultant social impacts of this market failure. The large scale reuse of mineral waste may become possible, in terms of Section 9(1) of GN R 634 in GG 36784 of 23 August 2013; by the submission of a motivation to the Minister requesting that certain waste management activities be listed as activities that do not require a waste management license (Department of Water and Environmental Affairs [DWEA], 2013:3-21).

According to Section 9(2) of GN R 634 in GG 36784 of 23 August 2013, such a motivation is however substantive in that it will be required to demonstrate that the reuse of ferrochrome slag as waste aggregate can be implemented and conducted consistently and repeatedly in a controlled manner without unacceptable impact on, or risk to, the environment or health. This requirement is also equally relevant to the associated storage and handling of the reuse of ferrochrome slag as aggregate (DWEA, 2013:3-21).

Due to the possibility of the large scale reuse of ferrochrome slag being authorised, it has therefore become prudent to consider methods to optimise its reuse. The report written by Godfrey *et al.* (2007:23) recommends an assessment of the quantity of mineral waste available for reuse in South Africa, consideration of market based instruments to optimise reuse and a cost comparison of the reuse of mineral waste instead of virgin material. Considering these recommendations by objectives one and two, the final objective of the research study is to describe methods of reuse that may be applied in South Africa, by making reference to projects in which such reuse has recently been implemented in South Africa.

1.5 Conceptual framework of the study

The research framework of a study sets out the plan or method that the researcher follows to conduct the study, and each step of the research framework employs a research methodology in accordance with the research design of the study (Leedy & Omrod, 2005: 85). Quantitative data usually refers to numerical data that can be analysed in a statistical manner, while qualitative data usually refers to data, such as literature, that is descriptive and may also include data such as photos or sounds. When conducting qualitative research, data is examined or interpreted to find meaning or to describe the field of study (Struwig & Stead, 2001:243).

This research study follows an exploratory mixed method design by first following a qualitative research method into the data, obtained by a literature review into the topic, after which the researcher tests the qualitative data quantitatively by a comparative analysis thereof as suggested by De Vos *et al.* (2011:441).

1.6 Possible contributions of the study

The research may contribute to promoting and optimising the beneficial reuse of ferrochrome slag as aggregate in South Africa by describing environmental and financial benefits, as well as reuse methods. Optimised reuse of ferrochrome slag as aggregate, instead of using natural aggregate, may reduce the associated external costs of ferrochrome slag disposal and natural aggregate mining as referred to in the literature review and data analysis portion of this study. Moreover, the optimised reuse may also provide a benefit to society in that the construction and ferrochrome industries may be able to internalise those costs that are currently externalised through the implementation of the waste management hierarchy.

1.7 Chapter summary

The introduction to this research study includes a brief background to the field of study and provides the reader with a clear description of the rationale, aim and objectives of this study. This chapter intends to set the framework of the study in order to guide the literature review, data analysis and conclusion in a structured manner.

CHAPTER 2: RESEARCH DESIGN AND METHODOLOGY

2.1 Introduction

This chapter will describe the research design of this study by elaborating on the research methodology employed during this research study. Moreover, the researcher describes the process followed to consider different research designs, and motivates the choice of research methodology used for this study, based on the assessment conducted (Leedy & Omrod, 2005:85).

2.2 Research paradigm

According to Struwig & Stead (2001:242) a research paradigm is “a selection of mutually accepted modes of scientific practice” (Struwig & Stead, 2001:242). It refers to the view that scientists take of the field of their study, based on their scientific knowledge (De Vos *et al.*, 2011:40-41).

Research is conducted on a subject or phenomenon, in order to investigate a research objective or hypotheses by the systematic collection and controlled interpretation of data or theory (De Vos *et al.*, 2011:42). Research must be objective and a researcher must not influence the research to such an extent that the outcome of the research becomes unreliable (Leedy & Omrod, 2005:92-94). The researcher must therefore have complete confidence in the outcome of the research. A research question or belief must be tested in an objective manner, independent of the researcher, in order to measure it against reality (De Vos *et al.*, 2011:42).

A researcher should therefore be extremely critical when choosing a research design, and the instruments used for the study must be scientifically recognised, valid and reliable in order to reach the aim of the study (Leedy & Omrod, 2005:92). The research design of this study is therefore carefully considered in its ability to aid the researcher to reach the objectives of this study. The research design or methodology is the manner in which the researcher constructs the research study, based on his/her theoretical knowledge, and the research method is the manner in which the researcher obtained and analysed the data (Morris-Saunders, 2012).

According to Mackenzie and Knipe (2006:193-205), “pragmatism is seen as the paradigm that provides the underlying philosophical framework for mixed method research”. This research study follows a pragmatic approach by focusing on the objectives of the research study while collecting and analysing data. Therefore, the researcher does not only make use of a single research method, but rather uses a mixed method design to conduct a systematic literature review of the research objectives. By this approach qualitative data (obtained by the literature review) is quantitatively analysed (Mackenzie & Knipe, 2006:193-205).

2.3 Research design and methodology

Leedy and Omrod suggests that each research design employs different research methodologies that are appropriate to the nature of the research problem and dependent on the type of data obtained during the research study (2005:87). This research study is constructed by the use of both qualitative and quantitative data that is analysed in a mixed method approach where the quantitative data analysis is dependent on the qualitative data analysis of the literature review. The mixed method approach is therefore sequential in that the quantitative assessment is dependent on the qualitative assessment as proposed by De Vos *et al.* (2011:439).

The literature review of this study is predominantly qualitative in its assessment of international and South African publications by descriptive research, whereby findings from international studies are described and compared to South African literature and interpreted by deductive reasoning in order to consider the research objectives (Struwig & Stead, 2001:4-8). The data analysis phase takes a mixed method approach by the qualitative assessment of findings, related to the aim and objectives of the study, as well as the quantitative assessment of the qualitative data (where appropriate) to verify and support these findings (De Vos *et al.*, 2011:439).

The research study makes use of a triangulation strategy by collecting multiple sources of data. The literature was obtained by an internet search engine and librarian; and primary and secondary data was obtained from business entities and industry experts. This type of strategy is common in mixed method research designs that make use of qualitative and quantitative data and therefore it was determined to be the appropriate strategy for this study (Leedy & Omrod, 2005:99,136).

The mixed method research strategy utilised for this study entails an embedded design, whereby quantitative and qualitative data are gathered simultaneously in order to support one another's findings. This is made possible by the use of quantitative data being predominantly secondary data, obtained from industry associations (Caruth, 2013:114), and quantitatively testing qualitative findings predominantly identified by the literature review of this study (Wheeldon & Ahlberg, 2012:118-119).

2.4 Limitations of the study

The validity and reliability of a research project have to be considered, irrespective of the methodology used. According to Leedy and Omrod (2005:97) validity is "the accuracy, meaningfulness, and credibility of a research project as a whole", and according to De Vos *et al.* (2011:117), "reliability occurs when an instrument measures the same thing more than once and results in the same conclusion". In order to ensure the researcher remains objective in her approach, the following research guidelines were considered during the research design as advised by Leedy and Omrod (2005:88):

- Universality: the research design must enable any competent person to come to the same conclusion as this study when considering the same aim and objectives (Leedy & Omrod, 2005:88). Recognised scientific methods are therefore utilised to conduct this study and the research process is properly documented to enable thorough reporting thereof. The literature and data review will therefore be described in detail (Struwig & Stead, 2001:144).

- Replication: the research results should be such that any other competent researcher would be able to obtain comparable results, when considering the research problem, by collecting data under the same circumstances and parameters as the researcher (Leedy & Omrod, 2005:88). The sources of literature obtained by the researcher will be compared with a list of sources obtained by the North-West University Librarian on the same research topic in order to ensure that the literature review (on the benefits of using ferrochrome slag) is valid and reliable by a triangulation approach (Struwig & Stead, 2001:145).

- Control: factors that are central to the research problem must be identified and controlled to enable an objective conclusion of the research study (Leedy & Omrod, 2005:88). This study makes use of literature based on real world research, as well as secondary data, obtained from laboratory analysis, and each study must be critically assessed during the literature review to ensure validity thereof (Leedy & Omrod, 2005:92).

- Measurement: data should be measurable, in order to enable the researcher to interpret the results from the data in a qualitative or quantitative assessment (Leedy & Omrod, 2005:88). Qualitative data was mapped out in a table to demonstrate the data analysis thereof, in order to enable the re-test of the data as required (De Vos *et al.*, 2011:254-256).

This study aims to promote and optimise the reuse of ferrochrome slag as aggregate in South Africa, which may pose the risk that a purely advocative approach is taken. According to Hakim (2000:8) advocacy research "consists of collating available evidence or producing new information to support a pre-determined policy position". These types of research often have pre-determined conclusions and may exclude evidence that does not promote that conclusion (Hakim, 2000:8). This risk was considered when planning the research design and methodology of the study.

The aim of this research study was considered when the research methodology was decided on, and the researcher reflected on the benefits and risks that each method might pose. The pragmatic mixed method approach was considered the most valid and reliable method for this study and the approach described above was therefore followed (Leedy & Omrod, 2005:88).

The research was also limited by ethical considerations that required unpublished data used or represented in this report to remain private and not presented in a manner that it might be traced back to any specific operation or construction company, at the risk of posing a liability to that operation (Leedy & Omrod, 2005:101).

2.5 Research methods

2.5.1 Literature review as a research method

The research study made use of an initial rapid review of the literature obtained by a systematic search in order to determine the knowledge base of the subject matter to set out the aim and objectives of the study in order to address research gaps identified during the review. The rapid review further directed the researcher to obtain the required data, for the quantitative assessment, that would inform findings on research objectives identified during the qualitative review of literature by a systematic literature review method (Grant & Booth, 2009:91-108).

The literature review method of the research study is a significant component of the mixed method research strategy and the type of literature review that was conducted for this purpose was therefore carefully considered. Grant and Booth (2009:91-108) describe fourteen types of literature reviews, of which the systematic review method is usually employed in a mixed method research strategy. This type of review systematically searches for literature relevant to the subject in order to obtain comprehensive research on the subject matter. The literature is then assessed in order to determine if it should be included or excluded from the study and the researcher may then present the data in a chronological or narrative manner in order to determine research gaps (Grant & Booth, 2009:91-108).

A systematic literature review of predominantly qualitative data enables the researcher to identify research gaps that may be addressed by the analysis of quantitative data, as described in the design and methodology of this research study by the use of a mixed method design (De Vos *et al.*, 2011:441).

The research framework set out in Table 2-1 below provides a broad understanding of the methodology used for each step in the research design, as described in detail in sections 2.1 to 2.5 above (Leedy & Omrod, 2005:86).

Table 2-1: Research Framework (adapted from Leedy & Omrod, 2005:86)

Step	Research step	Research methodology and paradigm
1	Identify a need in the industry	Rapid literature review
2	Identify research objectives	Systematic literature review
3	Identify opportunity to address the research objectives	Exploratory mixed method design
4	Obtain data relevant to the research study	Triangulation approach
5	Analyse the data	Exploratory mixed method design: quantitatively testing qualitative findings predominantly identified by the literature review of this study
6	Report the findings and conclusion of the study	Scientific report

2.5.2 Data collection and analysis methods for achieving Objective 1

Objective 1 of this study is to identify and describe the environmental benefits of using ferrochrome slag as aggregate in South Africa. In order to reach this objective a systematic literature review was conducted (on an international and national scale) into the benefits of reusing ferrochrome slag as aggregate in South Africa. The outcomes of the qualitative research study of the literature review was supported by a quantitative assessment of secondary data, obtained to bridge any gaps identified during the research study, in order to come to a conclusion on the research topic (Wheeldon & Ahlberg, 2012:114-119).

In order to assess the validity of the aim of this study the literature review starts with a review of the need for an alternative to natural aggregates in South Arica, as well as a need to recycle ferrochrome slag in South Africa. The literature review continues to identify possible challenges that may prevent this need from being met in South Africa in particular, as well as the possible applications of ferrochrome slag in the South African construction industry in terms of product requirements and specification (Mouton, 2001:53, 164). The research study continues to focus on the probable environmental and financial benefits related to the reuse of ferrochrome slag as aggregate in the South African setting and methods to facilitate reuse.

The probable environmental benefit of recycling ferrochrome slag was identified and described by a further literature review of the positive and negative impacts relating to the use of ferrochrome slag as aggregate. Literature was obtained from Google scholar, Science Direct and the NWU library. In order to support findings of the literature reviewed the impact related to the beneficial reuse of ferrochrome slag as aggregate in South Africa (as well as the impact of the disposal of ferrochrome slag onto slag dumps) was sourced from Project data obtained from the Ferro Alloy Producers Association. This report was used to compare findings obtained from the literature review with real world project data.

The total amount of ferrochrome slag that could be recycled was determined from the data sourced on the amount of ferrochrome slag produced by the South African ferrochrome industry annually. The total amount of residual ferrochrome slag stored on slag dumps was also sourced from the Ferro Alloy Producers Association and utilised to identify and confirm the probable environmental benefit described in the study.

2.5.3 Data collection and analysis methods for achieving Objective 2

Objective 2 of this research study is to investigate the probable financial benefits in replacing natural aggregates with ferrochrome slag. The probable financial benefits were investigated in the same manner as the environmental benefits, starting with a systematic literature review and continuing to data analysis, where required.

This objective required a literature review of South African literature and legal publications, which deal with waste management in South Africa. The literature review set out to investigate the scale of the waste challenge in South Africa, as well as some of the legal hurdles that may prevent effective implementation of the intended reuse. Research articles were obtained from Google scholar, Science Direct, the North-West University (NWU) library and a legal database of current legislation.

In order to support the literature review secondary data was obtained on the material suitability of ferrochrome slag as aggregate in South Africa. Aggregate specifications were compared to ferrochrome slag specifications, sourced from the Ferro Alloy Producers Association. This review describes whether additional screening or production costs have to be incurred by the ferrochrome producers in order to make the appropriate ferrochrome slag products available to the market. Additional costs were investigated by identifying the main cost component of aggregates and describing the financial viability of replacing natural aggregates with ferrochrome slag. For the purpose of this investigation ferrochrome slag sale prices and transport costs were sourced from a ferrochrome smelter while aggregate mining costs were sourced from a construction entity.

In addition to the literature study the probable financial benefit related to the recycling of ferrochrome slag was quantified using the main cost component of aggregate and it was investigated whether it would be financially viable to replace natural aggregates with ferrochrome slag in South Africa. The information was sourced from the Ferro Alloys Producers Association and a construction entity.

2.5.4 Data collection and analysis methods for achieving Objective 3

Objective 3 of this research study is to describe methods of facilitating the reuse of ferrochrome slag as aggregate in South Africa. This research objective was also reached by a systematic literature review to enable the researcher to describe research findings (from international and national case studies) on some of the methods to promote the reuse of ferrochrome slag as aggregate in South Africa. The researcher describes the process and progress towards the Ferro Alloys Producers Association application of listing this use as an activity that does not require a waste management license in South Africa. The Ferro Alloys Producers Association's motivational document was reviewed for this purpose and this project report also provided South African case study information on projects where successful reuse took place.

2.6 Complying with ethical principles

Certain fields of study make use of human subjects in the research study, such as social science, medicine and education, and close attention has to be paid to the ethical implications of these studies. Although no direct experiments were conducted on human subjects during this research study, various sources of information were obtained from corporate entities or persons and therefore ethical considerations were involved in this research design. According to Leedy and Omrod (2005), most ethical implications fall within four categories and these categories were adhered to in this study as follows (Leedy & Omrod, 2005:101-102):

- The researcher did not expose research participants to any undue harm; no reference was made to any particular person or company, other than those already identified in published works (Leedy & Omrod, 2005:101-102).

- The researcher obtained permission from the relevant persons, associations and companies to make use of data obtained during the research study for the purpose of fulfilling the aim and objectives of this study without revealing the identity of any particular person or company to which any of the data relate (Leedy & Omrod, 2005:101-102).

- The representation of data in this research study was not made in a manner that any one person or company could be associated with the data or interpretation thereof (Leedy & Omrod, 2005:101-102).

- The researcher did not misrepresent any of the findings made during the research study and the researcher gave full acknowledgment to the other persons' work, ideas, words and data by the bibliography and references of this research study (Leedy & Omrod, 2005:101-102). The limitations of this study was addressed in section 2.4 above.

2.7 Chapter summary

The research design of this study was carefully considered to enable the researcher to follow a structured and scientific approach, while fulfilling the pragmatic aim of the research study, thereby addressing any limitations or ethical concerns that might have been raised. The mixed method strategy utilised for this purpose made use of qualitative and quantitative data in order to address research gaps identified during the systematic literature review. Moreover, the predominant use of secondary data for the quantitative analysis enabled the researcher to follow this approach without time delays (Wheeldon & Ahlberg, 2012:114-119).

CHAPTER 3: LITERATURE REVIEW

3.1 Introduction

Literature was obtained by a systematic collection method, used with a triangulated approach, in order to determine research objectives related to the aim and objectives of this study. Based on the mixed method design of the study, a systematic literature review was conducted on predominantly qualitative literature; however, quantitative information was reviewed (where obtained in the literature in order to address research objectives). The collection process of this literature review was focused around the aim and objectives of the study and a pragmatic approach was therefore followed for this study.

3.2 Legal and other requirements

3.2.1 International sustainability framework requirements

According to Redclift (2005:212) Sustainable Development became a term used "in policy circles after the publication of the Brundtland Commission's report on the global environment and development in 1987" (Redclift, 2005:212). This publication was initiated in December 1983 when the General Assembly of the United Nations tasked the World Commission on Environment and Development to formulate a global agenda for change (Brundtland, *et al.*, 1987:11). Brudtland, *et al.* (1987:24) defined sustainable development as a way to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, *et al.*, 1987:24).

This notion of sustainable development limits progression to an extent that would enable the earth to cope with the effects of such development. This called for improvements in technology, as well as social organisation, and it idealised the basic needs of all humans being met by an equal allocation of resources (Brundtland, *et al.*, 1987:24-25). The commission recognised the dynamics of development; that sustainable development was not a static concept, and that the implementation thereof would be highly dependent on society's resolve (Brundtland, *et al.*, 1987:25). Included in the actions that this report calls for, is a reform of environmental legislation and policies (at all levels of governance) in order to deal with these issues swiftly (Brundtland, *et al.*, 1987:108)

Governments and Industries should consider the efficient use of resources during decision making processes and they should aim to reduce waste consumption and increase reuse practices. Government should establish laws and regulations for this purpose and should also consider positive governance, such as incentives. Industry on the other hand should not only measure its compliance against laws, but it should also act responsibly and ensure good environmental practices at all levels (Brundtland, *et al.*, 1987:219-222).

The United Nations continued to build on the Brundtland report during the 1992 Earth Summit, and the declaration on environment and development was adopted during the United Nations Conference on Environment & Development (UNCED) in Rio de Janeiro in June 1992. Sustainable development was included in the Rio declaration as Principle 3 of 27 and its definition is aligned with the Brundtland report referred to above (United Nations, 1992:1-6). Principle 3 of the Rio declaration states that "the right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations", according to the United Nations (1992:1).

Another output from UNCED is a global plan of action, named Agenda 21, which is aligned with the Rio declaration. It addresses various challenges faced during the implementation of environmental resolutions, such as the Rio declaration, and outlines specific actions to overcome those challenges. It also emphasises the importance of national laws, regulations and other requirements (such as policies and strategies) in executing these actions (United Nations, UNCED, 1992).

Agenda 21 contains programmes relevant to the construction sector and includes the creation of local job opportunities, reducing the cost of building material and improving resource efficiency (United Nations, UNCED, 1992:7.69). It also includes activities that should be undertaken by governments to provide incentives for reusing recyclable waste or preventing recycled materials from being discredited for reuse, by amending product specifications or standards to accommodate such reuse (United Nations, UNCED, 1992:20.13).

The implementation of Agenda 21 was reviewed in New York in 1992 (United Nations, 1992:1-3) and progress was reviewed in Johannesburg in 2002 (United Nations, 2002:1-2). Both these reviews showed progress towards the implementation of Agenda 21, but continued to raise the concern that unsustainable resource consumption was taking place and that the earth was not capable of coping with the current rate of consumption or development. Progress was therefore not being made fast enough to counteract environmental degeneration and the issue of sustainable development should therefore remain at the forefront of policy makers' and policy executors' concerns.

The United Nations also adopted the Millennium Declaration in September 2000, reaffirming their commitment to certain fundamental values, which included respect for nature. Herein it was once again required to implement the principle of sustainable development and to change "the current unsustainable patterns of production and consumption" (United Nations, 2000:2).

In line with these developments, the International Council on Mining and Metals (ICMM) provides a sustainability framework against which international Mining and Metal producers can measure their sustainability performance (ICMM, 2003). This framework was drawn up in line with other international standards, to which these producers prescribe, and it includes ten principles that aim to ensure continual improvement on key issues. These principles focuses on continual improvement of environmental performance, which also requires good waste management practices (ICMM, 2003).

3.2.2 Overview of the South African legal framework requirements

According to Ian Farlam (cited by Van der Linde, 2006:1) the Johannesburg Principles were adopted by judges from around the world in August 2002 to reconfirm their commitment to the principles of the Rio Declaration. In December 2003 these judiciaries came together to design workable plans that would enable them to become involved in the drafting, implementation and enforcement of their respective environmental laws (Van der Linde, 2006:1). South Africa's continued commitment to the international sustainable development framework was not only seen by this process, but also by the Johannesburg Declaration of Sustainable Development (United Nations, 2002:1).

Since its promulgation South African environmental legislation has stemmed from the Constitution of the Republic of South Africa (Act 108 of 1996) and it gives every South African the right to an environment that is not harmful to his/her health or wellbeing (Van der Linde, 2006:5). Although South Africa had environmental legislation in place prior to 1996, the Constitution fortified environmental conservation and sustainable development as a basic human right (Van der Linde, 2006:7). Subsequent to the Constitution, the National Environmental Management Act (107 of 1998) is likely the most important environmental law in South Africa and it functions as framework legislation. Specific environmental legislation follows from the National Environmental Management Act (107 of 1998), to deal with issues such as air quality, biodiversity and waste management (Van der Linde, 2006:5, 31). Since the promulgation of the Constitution of the Republic of South Africa (Act 108 of 1996) significant development in environmental law has taken place in order to give effect thereto (Kotze, 2003:81).

Recent amendments included the National Environmental Management: Waste Amendment Act (26 of 2014), which commenced on 2 July 2014 and which amended the National Environmental Management Waste Act (59 of 2008). The National Environmental Management Laws Amendment Act (25 of 2014) was also recently promulgated and commenced on 2 September 2014. Among significant changes are the implementation of "One Environmental System" and a renewed definition of "waste".

The National Environmental Management: Waste Act (59 of 2008) as amended defines "waste" to mean:

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 reused, 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 reuse, recycling or recovery has been approved or, after such approval, once it is, or has been reused, recycled or recovered;
ii. where approval is not required, once a waste is, or has been reused, 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."

Schedule 3 to the National Environmental Management: Waste Act (59 of 2008) as amended categorises waste as either hazardous or general waste and defines "hazardous waste" as "any waste that contains organic or inorganic elements or compounds that may, owing to the inherent physical, chemical or toxicological characteristics of that waste, have a detrimental impact on health and the environment and includes hazardous substances, materials or objects within business waste, residue deposits and residue stockpiles as outlined below". The schedule includes a table of waste that form part in the definition for hazardous waste.

On the other hand, the National Environmental Management: Waste Act (59 of 2008) as amended; defines "General Waste" to include "Waste from thermal processes" including "waste from casting of ferrous pieces not otherwise specified in Category A". On the grounds that Category A as previously referred to does not include waste from chrome thermal metallurgy or wastes from ferrous thermal metallurgy but only "hazardous portion of wastes from casting of ferrous pieces" under the section for "Waste from thermal processing"; one can argue that ferrochrome slag may be classified as general waste. This argument would however require that ferrochrome slag is not a "hazardous portion of waste from casting of ferrous pieces" and a waste classification process may be able to confirm or refute this argument.

However, the National Environmental Management: Waste Act (59 of 2008) as amended includes "residue stockpiles" under the definition of hazardous waste and defines "residue stockpiles" as "any debris, discard, tailings, slimes, screening, slurry, waste rock, foundry sand, mineral processing plant waste, ash or any other product derived from or incidental to a mining operation and which is stockpiled, stored or accumulated within the mining area for potential reuse, or which is disposed of, by the holder of a mining right, mining permit or, production right or an old order right, including historic mines and dumps created before the implementation of this Act".

In the case of ferrochrome manufacturing facilities being directly incidental to mining operations where these operations are situated on mine property these operations would therefore be operating under the Mineral and Petroleum Resources Development Act (28 of 2002) as amended. In line with the revised classification for residue stockpiles and on the grounds that ferrochrome slag dumps may have been managed as residue stockpiles through an approved Environmental Management Programme in line with the requirements the Mineral and Petroleum Resources Development Act (28 of 2002), it may be argued that ferrochrome slag dumps may be defined as a Category A or hazardous waste, in terms of the National Environmental Management: Waste Act (59 of 2008) as amended.

One of the objectives of the National Environmental Management: Waste Act (59 of 2009) is to provide reasonable measures for “reducing, reusing, recycling and recovering waste”. In addition to these requirements, the National Waste Management Strategy (Department of Environmental Affairs [DEA] 2012: 4-12) was established for implementation on 4 May 2012, under section 6 of the National Environmental Management: Waste Act (59 of 2008). The National Waste Management Strategy (DEA 2012: 4-12) aims to achieve the objectives of the National Environmental Management: Waste Act (59 of 2008) and requires generators of waste (including ferrochrome producers) to minimise and recycle waste, in line with the waste management hierarchy, prior to considering the treatment or disposal of waste (DEA 2012: 4-12).

According to the List of Waste Management Activities that have, or are likely to have, a detrimental effect on the Environment (Department of Water and Environmental Affairs [DWEA] 2013: 1-8) the “reuse and recycling of hazardous waste in excess of 1 ton per day” classified as a Category B waste management activity. Ferrochrome slag may be classified as hazardous waste and if the argument cannot be refuted through a classification process, the reuse of ferrochrome slag may therefore require the user to conduct an environmental impact assessment and apply for a Waste Management Licence prior to such reuse. Although this would be a necessary process in the case of hazardous waste being reused, it is understandable that a developer may view this process as an extremely costly and time consuming process compared to obtaining natural aggregate elsewhere.

According to Kotze (2003:82), Section 24 of the Constitution of the Republic of South Africa (Act 108 of 1996) is worded in such a manner that there is a conflicting relationship between environmental conservation contained in Section 24(a) and sustainable development contained in Section 24(b). Section 24 of the Constitution of the Republic of South Africa (Act 108 of 1996) states that:

“Everyone has the right –

a) to an environment that is not harmful to their health or well-being; and
b) to have the environment protected, for the benefit of present and future generations, by reasonable legislative and other measures that –
    i. prevent pollution and ecological degradation;
    ii. promote conservation; and
    iii. secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development”.

Kotze’s statement may be oversimplified, but if the limited reuse of ferrochrome slag is considered it may be argued that the classification thereof as hazardous waste have made the reuse thereof a very cumbersome process (Oelofse, Adlem & Hattingh, 2007:614) and may have contributed to ferrochrome slag being disposed of rather than reused.

Waste classification is based on the risk that each type of waste poses to human health and the environment (Nkosi *et al.,* 2013:303-308). Prior to 2013, the classification of ferrochrome slag as hazardous waste was motivated by the leaching potential of slag when stored in large quantities, coupled with the large amount of ferrochrome slag produced in South Africa (Oelofse, Adlem & Hattingh, 2007:610-616). Although the intention of the legislation was to promote reuse of waste such as ferrochrome slag, the practical implementation of the legislation may have contributed to ferrochrome slag disposal rather than reuse for adequate purposes, such as aggregate. The promulgation of additional supporting legislation may however promote the reuse of ferrochrome slag as aggregate further.

3.2.3 Ferrochrome slag specifications

Ferrochrome slag is a form of waste rock generated from the production of ferrochrome, an essential component of stainless steel (Yilmaz & Kok, 2009:310). Air cooled slag forms a crystalline rock like product similar to basalt and consist of silica (SiO_2), alumina (Al_2O_3), magnesia (MgO) and lime with a small amount of residual metal (chromium, iron and calcium oxides) (Gencel *et al.*, 2011:633-640). The typical composition of ferrochrome slag is 30% SiO_2, 26% Al_2O_3 and 23% MgO with some chromium and iron oxides, as well as 2% CaO (Pekka & Kauppi, 2007:171, 173).

According to Biermann, Cromarty and Dawson (2012:302), the ferrochrome production process utilises raw materials that usually consist of chromite in different size fractions (e.g. lumpy, fines, briquettes or pellets), reductants (anthracite, char, coke and coal), and fluxing agents such as quartzite, dolomite and limestone or burnt lime. Furnace conditions are maintained as optimally as possible in order to control furnace output by ensuring furnace bed permeability and slag properties are optimised (Biermann, Cromarty & Dawson, 2012:302). Ferrochrome slag is therefore inherently controlled in the ferrochrome production process due to controls implemented to ensure ferrochrome product quality (Biermann, Cromarty & Dawson, 2012:302). The product specification of ferrochrome slag can be defined and inherently controlled by the ferrochrome manufacturers (Holappa, L and Xiao, Y. 2004:436) which, if done correctly, will enable these manufacturers to define ferrochrome slag properties in the listing process referred to above.

Air-cooled slag is crushed in order to extract any additional metal remaining in the slag, by a density separation or jigging process. The "waste" product or slag is then stored on slag dumps, requiring large pieces of land, posing a possible ecological risk due to the leaching potential of slag dumps in the event that these facilities are not engineered and operated correctly (Gencel *et al.*, 2011:633-640).

South Africa is one of the largest producers of ferrochrome (and therefore ferrochrome slag) and although this material is an excellent replacement for aggregate in the construction of roads or infrastructure, the majority of ferrochrome slag is disposed of onto large slag dumps due to its classification as waste or hazardous waste, whichever the case may be, in South Africa (Reuter, Xiao & Boin, 2004:35). There has been research conducted on the use of ferrochrome slag as aggregate, which has resulted in the optimised utilisation thereof, especially in European countries. Due to the restrictions placed on the reuse thereof by South African environmental legislation, this has become a highly debated topic (Reuter, Xiao & Boin, 2004:35).

3.2.4 Environmental benefits

According to Petersen and Petrie (2000:356) a simple description of leachate generation is a "dissolution of soluble substances contained in the solid waste material into rain or process water percolating through the deposit". Leachate potential is, however, somewhat complicated by bulk transport, diffusion effects and chemical reactions. Bulk transport refers to the variability of flow rates throughout the deposit as rainfall events or dry seasons occur and as the deposit compositions differ (Petersen & Petrie, 2000:356).

Diffusion effects may take place in waste deposits where fluid moves slowly, resulting in fluid movement taking place by molecular diffusion within an aqueous phase which may result in the leaching process being retarded. Finally, chemical reaction refers to the release of chemicals into the aqueous medium from solid particles in the deposit (Petersen & Petrie, 2000:356). It can therefore be understood that a large slag dump would continue to be a potential source of leachate until such time that the dump is either reused or lined, capped and closed for final disposal of slag or closure of the waste facility.

In a research study on the reuse of ferrochrome slag from the Outokompu plant in Finland, Pekka and Kauppi (2007:178) conclude that the mineralogy and microstructure of ferrochrome slag is the reason why the slag leaching is significantly lower than expected when slag is recycled. These findings are confirmed by Ananthi and Karthikeyan (2015:75-76) and Panda, *et al.* (2013: 263) stating that chromium in ferrochrome slag exists in a highly stable spinal phase which inhibits the release thereof under ambient conditions (Ananthi & Karthikeyan, 2015:75-76).

The Outokumpu plant has been producing ferrochrome and ferrochrome slag since 1968, adding up to six million odd tonnes of ferrochrome slag that have been utilised for various applications since the early seventies. The case study could not show any environmental disadvantages related to the use of ferrochrome slag as aggregate. In addition to this, extensive medical research has shown that there are also no health risks relating to the long term use of ferrochrome slag products (Pekka & Kauppi, 2007:171-179). Although the climate in Finland is vastly different to that in South Africa, the study provides an assessment of the long term reuse of ferrochrome slag in large quantities, unlike any other studies obtained, and is therefore taken into account for the purpose of this research study.

According to Gericke (1995), ferrochrome slag could safely be consigned to a landfill site for non-hazardous substances but there were some concerns regarding the possibility of Cr(III) oxidising to its hexavalent state, Cr(VI), resulting in hexavalent chromium leaching from slag dumps. According to Gericke (1995), none of the published work available at the time related specifically to ferrochrome slag dumps, but rather to results from tests conducted under laboratory conditions. Further tests had been conducted in this study to simulate ferrochrome slag dump conditions in South Africa and at the time of presenting the report at the 1995 Infacon the results from the study showed no hazards associated with hexavalent chromium leaching from a slag dump (Gericke, 1995:132-133). A recent case study provides further insight into the leaching potential of ferrochrome slag dumps and is discussed under Section 3.3.3 of this report.

A study was conducted by Nicholls, Clark and Samuel (2004:11-12) on an area where ferrochrome slag had been used for the construction of roads. The study conducted test work on soil, ground water and plants to determine if ferrochrome slag posed a risk in terms of its leaching potential in real world conditions, where it would be influenced by conditions such as biological activities or acid rain. The study showed that ferrochrome slag had a low leaching potential and low fine particle migration to soil when used as aggregate in the construction of roads. There was, however, a significant uptake of chromium by the plants in the surrounding area (Nicholls, Clark & Samuel, 2004:11-12).

Although available case studies on the reuse of ferrochrome slag, from Finland in particular, raised no environmental concerns related to the long term reuse of ferrochrome slag; no South African case studies could be obtained by the researcher that assessed the long term reuse of ferrochrome slag in large quantities in a water scarce climate. It may therefore be required that the finding made by Nichols, Clark and Samuel are assessed through biological monitoring in an area where long term reuse of ferrochrome slag would take place in South Africa.

An overview of the findings from the Ferro Alloys Producers Association's motivational document, regarding the leaching potential of ferrochrome slag, is described in subsequent sections of the literature review in order to address this research objective to some extent. According to Prusinki, Marceau and Van Geem (2004:1) there is a significant environmental benefit when using blast furnace slag from iron making operations to produce cement which can be used as a partial replacement (35-50%) for

Portland cement in concrete. Prusinki, Marceau and Van Geem (2004:1-14) indicate an energy saving of around 35%, a reduction in CO_2 emissions of around 38% and a reduction in the use of natural aggregates of around 9% when compared to Portland cement mixtures. These results were calculated from the energy input of the cement manufacturing production process, coal powered electricity utilised by this process, as well as transport benefits from the reduced reliance on natural aggregate (Prusinki, Marceau & Van Geem, 2004:11-14). It is likely that further savings can be realised when using ferrochrome slag to replace natural aggregate in the concrete mixture.

3.2.5 Negative impacts relating to the extraction of natural aggregate

The exploitation of natural resources for aggregate entails the quarrying of large areas of land requiring the removal of vegetation, topsoil and subsoil and only after these layers have been removed, can the desired aggregate be accessed. During this process, habitat and watercourse destruction takes place (Environmental Commissioner of Ontario, 2003:30). Although quarried land can be rehabilitated, permanent changes to soil grade patterns cannot be avoided. Natural aggregate seams are reservoirs for underground water resources, but the water storage capacity is diminished when these aggregate seams are removed and the grade patterns changed even after being rehabilitated to productive land uses (Environmental Commissioner of Ontario, 2003:30).

Watercourses can be negatively affected by quarrying activities notwithstanding the excavation depth remaining shallower than the water table due to the base flow of natural streams that can be diminished. Aggregate resources and base flow are particularly important to maintain flow in streams where the groundwater volume makes up the largest quantity of the stream, especially during dry periods (Environmental Commissioner of Ontario, 2003:30).

According to the Ontario Environmental Commissioner (2003:31) land degradation is occurring at a faster pace than rehabilitation efforts due to aggregate demand for road and infrastructure development. Each kilometre of highway can require up to 15,000 tonnes of aggregate for a two lane roadway and up to 48,000 tonnes for a 6 lane roadway. An important opportunity for reducing reliance on aggregate is the use of waste aggregate, but this is not optimised due to a lack of incentive or monitoring of how much recycled aggregate is used during construction (Environmental Commissioner of Ontario, 2003:31-32).

The Mineral and Petroleum Resources Development Act (28 of 2002) requires a mining right or a mining permit, whichever the case may be, for aggregate mining in South Africa along with the development and implementation of an Environmental Management Programme. Substantive requirements are also in place for the rehabilitation and closure of mining operations. Based on the study from the Environmental Commissioner of Ontario, the overall rehabilitation pace of aggregate mining operations may have to be considered compared to the aggregate demand in order to control the risk of environmental degradation. The risk of watercourses being negatively affected would be amplified in South Africa due to water scarcity and the reliance on groundwater as a water source.

According to Godfrey *et al.* (2007:13-15) it is common practice in South Africa that consecutive mining takes place on the same site in order to effectively exploit the mineral deposit and in the process creates job opportunities (Godfrey *et al.*, 2007:15). According to Godfrey *et al.* (2007:13-15) in these cases a large company would typically exploit high value ores at production rates of about 15kg/t after which a second company would continue with production until production rates decline to about 5-10kg/t. Finally a smaller company would mine the marginal mineral deposits that may not be as attractive to the larger groups (Godfrey *et al.*, 2007:15). It is understood that aggregate mining may form part of these marginal mineral deposits.

This common practice may create the risk that the cumulative environmental impact becomes the responsibility of the small company that remains on the mining site. Smaller companies may not possess adequate funding to rehabilitate the cumulative environmental liability through closure provision. According to Godfrey *et al.* (2007:13-15), this often results in these companies being liquidated which requires remediation to be funded by government (Godfrey *et al.*, 2007:15).

3.2.6 Positive impacts relating to the reuse of ferrochrome slag as aggregate

Road construction requires large amounts of natural materials for the six layered structure. The United Kingdom has estimated the total amount of aggregates, required for the construction of 1 km of road, to be between 12 500 and 37 500 tonnes. Physical tests show that ferrochrome slag is “highly suitable” for aggregate replacement in road construction (Nicholls, Clark & Samuel, 2004:4, 11). According to De Beer, Maina and Netterberg (2012:49), South African pavements are similarly designed in a six layered structure consisting of a 15mm surfacing layer, a 125mm cemented base layer, a 200mm cemented subbase layer, a 150mm selected layer and an in situ subgrade layer (De Beer, Maina & Netterberg, 2012: 49). Similar large amounts of aggregate would therefore be required for pavements in South Africa.

Research conducted by Emery (1982:95-118) confirms that ferrochrome slag is considered to be a very good alternative to the large quantity of natural materials required in the granular layers, capping and subbase layers of road structures (Emery, 1982:95-118). Slag has been used in the construction of roads since the Roman era when crude iron was processed and the first modern road construction with slag was recorded in England in 1813. Asphalt mixtures where slag was used as aggregate, were first tested in Toronto in 1969, providing positive results in terms of bearing capacity, impact resistance and durability (Barišić, Dimter & Netinger, 2010:523-528).

Ferrochrome slag positively affects the mechanical properties of a hot bituminous mix when used as aggregate. It can also be utilised in the granular layer during road construction, yielding good results in terms of physical and mechanical properties (Yilmaz & Kok, 2009:310). Yilmaz and Kok conducted a study that determined that ferrochrome slag mainly differs from the usual limestone aggregate in its texture. It is coarser and more porous which improves its adhesion ability to the asphalt binder (Yilmaz & Kok, 2009:315).

The use of ferrochrome slag as course aggregate yielded optimum results in terms of water resistance, indirect tensile stiffness modulus (ITSM), tensile strength ratio and Marshal stability value (Yilmaz & Kok, 2009:316-317). It should, however, be noted that ferrochrome slag is not suitable as a replacement for total aggregate; it does not yield the same positive results when compared with the control aggregate in terms of water resistance and strength tests. Nevertheless, ferrochrome slag used as total aggregate yielded positive results in terms of moisture damage and can be used as a replacement for total aggregate in applications where low traffic volumes and high exposure to water take place, such as in pavements (Yilmaz & Kok, 2009:316-317).

Ananthi and Karthikeyan (2015:76) agree that ferrochrome slag is a suitable replacement for course aggregate in concrete. The use thereof yields positive results by improving the compressive strength, splitting tensile strength, wear resistance and freeze thaw resistance of concrete. It also increases the unit weight of concrete when natural aggregate is replaced with ferrochrome slag (Ananthi & Karthikeyan, 2015:76). Ferrochrome slag is also a suitable replacement for natural aggregate in high strength concrete applications due to its excellent mechanical properties, providing improved compressive strength in concrete. Ferrochrome slag can be made available in different sizes to enable use in these applications (Panda, *et al.* 2013:262).

3.2.7 Ferrochrome slag as a suitable alternative to natural aggregate

According to The South African National Roads Agency (2011:11) aggregate is a solid material usually derived from crushing a form of hard rock. Ferrochrome slag is referenced in this manual as being one of the possible aggregates along with slag from steel or ferromanganese manufacturers. Aggregate is used in various construction applications (South African Pavement Engineering Manual, 2011:11). In order to meet demands for aggregate required in applications such as road and other constructions, natural mountainous areas are exploited to obtain this building material, causing destruction to the natural environment. The use of ferrochrome slag or other waste products for this application is an opportunity to reduce environmental impact on natural resources (Yilmaz & Kok, 2009:310).

The increased focus on waste reduction and recycling in South Africa has led to new strategies being developed in order to reduce waste disposal and reliance on natural materials (Nkosi *et al.*, 2013:303-308). The recycling of ferrochrome slag by using it as aggregate is a very practical solution to this challenge. Ferrochrome slag is not only a possible option to use as an alternative to natural aggregate, but it is a better alternative. The benefit of recycling waste such as ferrochrome slag can be summarised as a reduction in the reliance on natural material, a reduction of transport or production energy and a reduction of waste that has to be disposed of onto landfill sites (Gencel *et al.*, 2011:633-640).

3.2.8 South African restrictions and limitations of reuse

A site where ferrochrome slag is reused, requires a waste management licence, and prior to 2013 required a waste permit or an exemption in terms of Section 20 of the Environmental Conservation Act (73 of 1989) as amended (Oelofse, Adlem & Hattingh, 2007:610-616). The requirement to go through this process for each and every reuse may be viewed as costly and time consuming by industry, due in part to inefficiencies in the cooperative authorisation process (Oelofse, Adlem & Hattingh, 2007:610-616). Although the study conducted by Oelofse, Adlem and Hattingh (2007:614) makes a broad statement regarding the cooperative authorisation process it also makes reference to a case study. In this case a motivation for the reuse of ferrochrome slag as aggregate was submitted to government for evaluation and due to a delay in response from government for a period of seven months, the manufacturer reverted back to using natural aggregate (2007:614).

There are also no specific legal requirements to reuse the slag, which may be seen as reason for the high amounts of slag disposed rather than reused in South Africa (Oelofse, Adlem & Hattingh, 2007:610-616). This indicates a lack in economic incentive to implement the nationally accepted waste management hierarchy of reusing ferrochrome slag rather than disposing of it onto slag dumps (Nkosi *et al.*, 2013:303-308). Although there are no specific legal requirements in place, the South African legislation does require waste generators to manage their waste streams responsibly and therefore treatment, reuse and recycling of waste should be considered prior to final disposal.

The ferrochrome industry of today is undergoing challenging times and this is not only due to volatile market prices and increased electricity costs but according to Biermann, Cromarty and Dawson (2012:302) this is now also due to the pressure to minimise the production of waste and other factors such as pressures to improve working conditions.

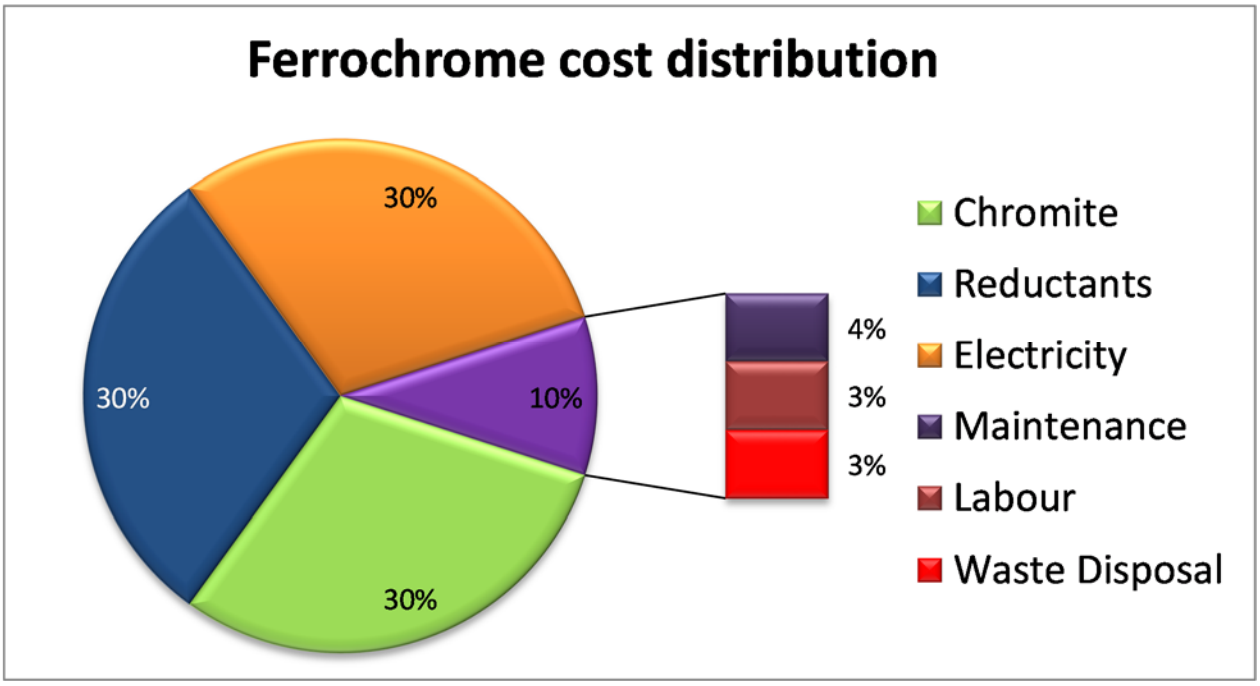

Figure 3-1: Typical ferrochrome cost distribution (Biermann, Cromarty & Dawson, 2012:302)

While input costs such as chromite ore, reductants and electricity each accounts for around 30% of the ferrochrome production costs, these inputs are fairly constant; the remaining 10% can fluctuate depending on optimisation of waste disposal, maintenance and labour costs (Biermann, Cromarty & Dawson, 2012:302). Effective recycling initiatives such as the utilisation of ferrochrome slag as building aggregate are therefore becoming more and more significant. The cost of licencing, engineering and operating a ferrochrome slag disposal facility should therefore be a strong consideration to motivate the reuse of ferrochrome slag to the extent required to optimise such reuse.

3.2.9 South African supporting legislation

The National Environmental Management Waste Act (59 of 2008) Section 69(a), (b), (g), (h), and (m) makes provision for the Minister of Water and Environmental Affairs to make regulations on the identification, classification, utilisation (by way of recovery, reuse and recycling) and management of waste. The Minister has exercised this right and the Waste classification and management regulation (DWEA, 2013:3-21) was promulgated on the

23rd of August 2013. Chapter 4 of the regulation is of specific importance to the utilisation of ferrochrome slag as aggregate in South Africa. This regulation allows the submission of a motivation to the Minister to apply for certain waste management activities to be listed as activities that do not require a waste management licence (DWEA, 2013:3-21).

According to Section 9(2) of GN R 634 in GG 36784 of 23 August 2013, such a motivation is substantive in that it will be required to demonstrate that the reuse of ferrochrome slag as waste aggregate can be implemented and conducted consistently and repeatedly in a controlled manner without unacceptable impact on, or risk to, the environment or health. This requirement is also equally relevant to the associated storage and handling of the reuse of ferrochrome slag as aggregate (DWEA, 2013:3-21). Section 5 of the regulation complicates an application from any single operation in industry as indicated below. Section 5 of the Waste classification and management regulation (DWEA, 2013:3-21) states that:

"A motivation in terms of Regulation 9(1) which is substantially similar to a previous motivation that had been rejected in terms of sub regulation (2)(c), may only be resubmitted if –

a) The application contains new and material information not previously submitted to the Minister; or
b) A period of three (3) years has elapsed since the application was lodged".

The ferrochrome industry makes use of very similar raw material inputs and production processes, which result in ferrochrome slag not being materially different from one ferrochrome smelter to another. An application of this nature would therefore have to be submitted jointly by the industry rather than by a single operation; else the industry runs the risk of triggering Section 5 of the Waste classification and management regulation (DWEA, 2013:3-21) that would cause further delays and deter the reuse of ferrochrome slag in South Africa.

The Ferro Alloy Producers Association (FAPA) is an industry association of ferrochrome producers. They have launched a project to submit a motivation to the Minister of Water and Environmental Affairs regarding the beneficial use of ferrochrome slag as aggregate. This project was initiated in line with the published regulations for Waste Classification and Management (DWEA, 2013:3-21) which makes allowance for the submission of such a motivation for a listed waste management activity that would promote or support waste minimisation or beneficial reuse. Favourable consideration of such a motivation by the Minister may result in the beneficial use of ferrochrome slag as aggregate being listed as a waste management activity which does not require a waste management licence (JMA Consulting (Pty) Ltd., 2013:3).

To this end, FAPA requested JMA Consulting (Pty) Ltd. to assist in drafting a motivational document. Infotox Pty Ltd. (Infotox) was requested to perform technical work in order to determine the classification of ferrochrome slag and to evaluate physical, health and environmental risk related to the reuse of ferrochrome slag as aggregate (JMA Consulting (Pty) Ltd., 2013:3). Based on a study by Hattingh and Friend (2003:23-29) there is limited information available, describing the environmental impact of reusing ferrochrome slag in South Africa that may aid in identifying suitable reuse options (Hattingh & Friend, 2003:23-29). The literature review will therefore include a description of some of the project data from the FAPA motivation report and its technical work conducted by Infotox in order to address this research opportunity to some extent.

Infotox has completed various technical assessments for the purpose of the FAPA motivational document and compiled the following reports in support thereof:

- Globally Harmonised System (GHS) Classification of Ferrochrome Slag (Van Niekerk and Fourie, 2011)
- Generic Assessment of Exposure to Dust from Ferrochrome Slag (Van Niekerk, Sep, 2011)
- pH Dependence of Leaching Characteristics of Ferrochrome Slag (Van Niekerk, Oct, 2011)
- Ageing Characteristics of Ferrochrome Slag (Van Niekerk, 18 Nov, 2011)
- Assessment of Ferrochrome Slag for Landfill Disposal (Van Niekerk, 14 Nov, 2011)
- Criteria Document for the Classification of Ferrochrome Slag in Accordance with SANS 10234: 2008 Ed 1.1 (Van Niekerk, 6 Nov, 2011).

3.3 Environmental impact

3.3.1 Classification of ferrochrome slag in terms of the Globally Harmonised System of classification and labelling of chemicals

The Waste classification and management regulation (DWEA, 2013:3-21) requires all waste generators to classify their waste streams in accordance with SANS 10234 (South African National Standards, 2008) for the Globally Harmonized System of classification and labelling of chemicals (GHS). The GHS aims to establish harmonised criteria against which hazardous substances such as waste will be classified worldwide. The classification of waste is done according to their health, environmental and physical hazards upon which the labelling and safety data sheets are drawn up in order to communicate any hazards identified during the classification process (Van Niekerk & Fourie, 2011).

In accordance with SANS 10234 waste should be assessed on physical hazards, health hazards and hazards to the aquatic environment (SANS, 2008). According to Van Niekerk and Fourie (2011) a series of hazard codes have been developed to assist with the classification of each of the hazards. These hazard codes define limiting concentrations for hazardous constituents above which it would classify as hazardous and below which as non-hazardous (Van Niekerk & Fourie, 2011). Annexure B of SANS 10234 sets out the hazard statements for these codes by assigning a unique alphanumerical code as follows. The letter "H" indicates that it is a hazard statement, followed by three numbers of which the first indicates whether it is a physical hazard (number 2), health hazard (number 3) or environmental hazard (number 4). The following two numbers are included for sequential numbering; examples of these codes are: H200 for unstable explosives or H300 indicating fatal if swallowed (SANS, 2008).

According to Infotox, the test work on the ferrochrome slag sample assessed did not exceed any of the limiting concentrations and therefore did not classify as hazardous under any of the relevant human health or aquatic ecosystem hazard categories. The assessment also indicates that there are no physical hazards associated with ferrochrome slag (Van Niekerk & Fourie, 2011). In order to provide further information on the assessment, a description of the Infotox project test work follows.

The Infotox GHS study into the classification of ferrochrome slag material, which can also be described as “preparations”, could not follow the default classification method. This is based on the total concentration of a substance, expressed as a percentage. According to Van Niekerk and Fourie, in the case of preparations such as metallurgical slag, the physical, chemical and toxicological / eco-toxicological properties of the preparations are distinct from those of their elemental constituents. The approach followed by Infotox, in accordance with the GHS, was to conduct a default assessment of hazards to human health and also where concentrations of elements exceeded the limit and therefore indicated hazards to human health. Bio-elution testing was conducted on those elements. In such cases, the classification was based on the bio-elusion test results, which represented the physiological bio-accessibility of the relevant elements (Van Niekerk & Fourie, 2011:1-2).

Bio-elusion tests are conducted assuming constituents are bio-accessible and bio-available in order to measure the degree to which a substance is dissolved in artificial biological fluids. According to Van Niekerk “bio-accessibility refers to the amount of a chemical that is available to interact with an organism’s contact surfaces, and is therefore potentially available for absorption”, and “bio-availability refers to the extent to which a substance can be absorbed by a living organism and reach the systemic circulation” (Van Niekerk, Sep, 2011:1). Artificial biological fluids have been developed for saliva, sweat, gastric, intestinal and alveolar systems and depending on the type of hazard, the relevant artificial fluid is used (Van Niekerk & Fourie, 2011:2).

The aquatic toxicity assessment was based on the guidance provided by the GHS for preparations containing poorly soluble elements, indicating that a dissolution screening test is required. According to Van Niekerk and Fourie, such a test assesses the proportion of a metal, expressed as mass percentage in the material, which would be available to exert its toxic effects on aquatic organisms (Van Niekerk & Fourie, 2011:2). According to Van Niekerk and Fourie, the following table indicates a summary of the hazard classification of ferrochrome slag according to aquatic toxicity and human health hazards.

Table 3-1: Hazard classification summary of ferrochrome slag (aquatic toxicity and human health hazards) (Van Niekerk & Fourie, 2011:27).

Hazard class	Classification	Overall hazard classification of the slag
Human health		
Acute toxicity: Oral	Not classified	Not hazardous with regard to human health – not classified under any human health hazard category applicable to SANS 10234:2008.
Acute toxicity: Inhalation	Not classified	
Acute toxicity: Dermal	Indications of toxicity not found: not classified as hazardous	
Skin corrosive or skin irritant	Not classified	
Respiratory sensitisation and skin sensitisation	Not classified	
Germ cell mutagenicity	Not classified	
Carcinogenicity	Not classified	
Reproductive toxicity	Not classified	
Specific target organ toxicity – single exposure	Not classified	
Specific target organ toxicity – repeated exposure	Not classified	
Aquatic ecosystems		
Acute hazards	Not classified	Not hazardous to the aquatic environment – not classified under any environmental hazard category applicable to SANS 10234:2008.
Chronic hazards	Not classified	

The dissolution test method referred to by Van Niekerk and Fourie (2011:2) was identified in Annexure G and Annexure H of SANS 10234 which describes test methods for poorly soluble compounds such as metals for the purpose of classification (SANS, 2008). The reasons for not following default test methods as described by Van Niekerk and Fourie could be confirmed in these annexures due to the insolubility of metal compounds such as ferrochrome slag.

3.3.2 Assessing potential risk associated with the beneficial reuse of ferrochrome slag

Upon completing the GHS classification assessment, Infotox continued to assess potential risks associated with the beneficial reuse of ferrochrome slag in line with the Waste classification and management regulation (DWEA, 2013:3-21). These assessments considered risks relating to exposure to dust from ferrochrome slag, leaching and ageing characteristics, as well as the effects of landfill disposal (JMA Consulting (Pty) Ltd., 2013). The assessment process followed by Infotox for the purpose of assessing potential risks associated with the reuse of ferrochrome slag is described in order to express some of the requirements that a motivation in terms of the Waste classification and management regulation (DWEA, 2013:3-21) would need.

Infotox's assessment of exposure to dust from ferrochrome slag was based on a conservative hypothetical exposure scenario, considering associated exposure to members of the public and employees in occupational scenarios. The exposure scenario is based on the National Ambient Air Quality Standards (Department of Water and Environmental Affairs [DWEA], 2009:6-9) that limits particulate matter (PM10) as follows:

Table 3-2: National Ambient Air Quality Standards for Particulate Matter (PM10) (DWEA, 2009:6-9).

Average Period	Concentration	Frequency of Exceedance	Compliance Date
24 hours	120 µg/m^3	4	Immediate – 31 December 2014
24 hours	75 µg/m^3	4	1 January 2015
1 year	50 µg/m^3	0	Immediate – 31 December 2014
1 year	40 µg/m^3	0	1 January 2015
The reference method for the determination of the particulate matter fraction of suspended particulate matter shall be EN 12341			

According to Van Niekerk (2011) the assessment was done on the assumption that dust levels have to be controlled within this limit, irrespective of type or condition. An elemental analysis of the ferrochrome slag sample was then conducted and maximum constituent concentrations were related to maximum airborne dust concentrations. Ferrochrome slag airborne concentrations were calculated at the limiting PM10 concentrations and those constituents exceeding the hazardous exposure limit were further assessed by bio-elusion tests for alveolar fluid (Van Niekerk, Sep, 2011). According to Van Niekerk, the conclusion from the assessment is represented in Table 2 below.

Table 3-3: Airborne concentrations of elements from slags at the occupational exposure limit for dust (Van Niekerk, Sep, 2011:6).

Element	Concentration	OEL	Comments
	mg/m3		
Ag	0.0007	0.01	-
Al	0.0150	2	Soluble compounds
B	0.0011	3	10 as B_2O_3
Ba	0.0016	0.5	Soluble compounds
Ca	0.0171	1.4	2 as CaO
Co	0.0001	0.1	Cobalt metal – dust and fumes Co
Cr	0.0038	0.5	Cr(III) compounds
Fe	0.0303	1	Soluble salts
K	0.0019	-	Toxicity depends on anion
Mg	0.0238	6	10 as MgO, respirable dust
Mn	0.0007	5	Dust and compounds
Na	0.0063	-	Toxicity depends on anion
Ni	0.0003	0.1	Soluble compounds
Ti	0.0007	3	5 as TiO_2, respirable dust
Zn	0.0011	8	10 as ZnO fumes

According to Van Niekerk “all of the estimated concentrations of airborne pollutants indicated in Table 2 above are well below the occupational exposure limit set by the South African Department of Labour and US NIOSH in the case of lead” (Van Niekerk, Sep, 2011:6). The interpretation of the results are, however, cautioned on the conservative assumptions made in that dust should be controlled according to the limit set for Particulate Matter (PM10) by the National Ambient Air Quality Standards (DWEA, 2009:6-9) and the occupational exposure limit for respirable dust (Van Niekerk, Sep, 2011:7).

Based on the understanding that external stressors such as low pH conditions of surrounding materials may increase the leaching potential of many inorganic species by influencing solubility, a pH dependence leach test assessment was conducted by Infotox Pty Ltd. The assessment was conducted to determine whether the beneficial reuse of ferrochrome slag as aggregate in environments with varied pH levels might have a serious leaching potential which might be detrimental to human health and the environment. According to Van Niekerk “the study represented a close approximation of soil pore water concentrations in equilibrium with slag at a liquid-to-solid ratio of 10:1” (10 ml extractant / g dry sample). The conservative screening assessment aims to estimate potential risk by using contaminant concentrations against a risk-based guideline. It would not be able to directly represent drinking water conditions in the event of slag affecting water bodies (Van Niekerk, Oct, 2011:1).

Results from the pH dependence leach test were compared to conservative drinking water guidelines based on regular drinking of water as a sole drinking water source and according to Van Niekerk (2011:10-11), “thus serves as a very conservative screening guideline” (Van Niekerk, Oct, 2011:10-11). The assessment concluded that changes in pH might affect leaching potential in that low pH levels might result in leaching of cobalt, manganese and lead to be more pronounced. The study therefore cautioned ferrochrome slag use under low pH conditions but did find that beneficial reuse of ferrochrome slag as aggregate under natural pH or higher would be safe in terms of leaching potential (Van Niekerk, Oct, 2011:10-11).

These findings are aligned with a study conducted by Panda, *et al.* (2012:272) into the leaching potential of chromium from ferrochrome slag. They concluded that the chromium leaching potential from ferrochrome slag was low and was determined to fall within allowable regulatory limits under normal environmental conditions. The leaching potential was, however, influenced by factors such as pH or sizing and the study confirmed that significant leaching of chromium takes place at very low pH levels.

Weathering or ageing characteristics of ferrochrome slag were assessed by humidity cell tests which were conducted on a fresh ferrochrome slag sample. According to Van Niekerk weathering potential is determined by hydration, carbonation and oxidation and due to the potential for oxidation of chromium to its hexavalent state; the possibility of hazards to human health or the environment may increase, making this assessment necessary for the motivational document (Van Niekerk, 18 Nov, 2011:1).

In the case of ferrochrome slag, 15 test cycles were performed on a 1 kg, <6mm particle size slag sample lightly pressed into position in a column. Each cycle consisted of 7 days where 3 days employed dry air, 3 days water-saturated air and one water leach day. The test method required at least 10 cycles in order to observe trends, in the case of ferrochrome slag, Infotox conducted 15 cycles in order to observe better clarification of trends over time. According to Van Niekerk ageing test results indicated very low leaching of hazardous elements. Although chromium leach trends indicated a slight increase over time, it was concluded that it was very unlikely that chromium concentrations would ever reach levels of concern in the environment (Van Niekerk, 18 Nov, 2011:11).

3.3.3 Assessing ferrochrome slag for landfill disposal

According to JMA Consulting (Pty) Ltd. it was considered appropriate that ferrochrome slag be assessed for landfill disposal following the GHS classification process, seeing that the beneficial reuse of ferrochrome slag as aggregate would require ferrochrome slag to be stored on slag heaps. Such an assessment is a further requirement of the Waste classification and management regulation (DWEA, 2013:3-21). In the FAPA motivational document, the landfill disposal assessment aimed to determine if ferrochrome slag could be defined as an inert waste, in which case it would be required to meet the following criteria according to the National Environmental Management Waste Act (59 of 2008) as ammended:

- “does not undergo any significant physical, chemical or biological transformation after disposal;
- does not burn, react physically or chemically biodegrade or otherwise adversely affect any other matter or environment with which it may come into contact; and
- does not impact negatively on the environment, because of its pollutant content and because the toxicity of its leachate is insignificant”.

The assessment succeeded in classifying ferrochrome slag as "inert material" based on the findings from the Infotox Pty Ltd assessment that there are insignificant amounts of toxic constituents derived from the ferrochrome slag for the sample assessed. An appropriate leach test (Water Leach Test ASTM D3987 – 6) was applied in order to assess leaching characteristics of the ferrochrome slag sample.

According to Van Niekerk, the results indicated in Table 3 below demonstrate that the toxicity of leachate from ferrochrome slag is insignificant and serves to classify ferrochrome slag as inert (Van Niekerk, 14 Nov, 2011:3).

Table 3-4: Screening assessment for the classification of ferrochrome slag for landfill disposal (Van Niekerk, 14 Nov, 2011:2-3).

Constituents in slag	Concentration	LCTi	Guideline	Reference
	Mg/l			
Elements				
Ag	0.007	No value	0.18	USEPA 2011
Al	0.314	No value	37	USEPA 2011
Arsenic	0.004	0.01	0.01	WHO 2011
Boron	0.022	0.5	7.3	USEPA 2011
Barium	0.003	0.7	7.3	USEPA 2011
Beryllium	<0.001	No value	0.073	USEPA 2011
Bismuth	0.004	No value	120	INFOTOX, based on NAP 2005
Cadmium	<0.001	0.005	0.018	USEPA 2011
Cobalt	<0.001	0.5	0.011	USEPA 2011
Chromium (total)	0.022	0.1	0.05	WHO 2011
Chromium (VI)	<0.01	0.05	0.05	WHO 2011
Copper	<0.001	1.0	1.5	USEPA 2011
Iron	0.488	No value	26	USEPA 2011
Mercury	<0.001	0.001	0.011	USEPA 2011
Manganese	0.069	0.4	0.4	WHO 2011
Molybdenum	0.009	0.07	0.18	USEPA 2011
Nickel	<0.001	0.07	0.73	USEPA 2011

Lead	0.019	0.01	0.01	WHO 2011
Antimony	0.004	0.01	0.02	WHO 2011
Selenium	0.000	0.01	0.18	USEPA 2011
Silicon	1.606	No value	See note below	Centre Européen d'Etude des Silicates 2008
Tin	0.000	No value	22	USEPA 2011
Strontium	0.010	No value	22	USEPA 2011
Titanium	0.007	No value	9.3	INFOTOX, based on NSF International 2005
Vanadium	<0.001	0.1	0.18	USEPA 2011
Tungsten	0.001	No value	0.06	USEPA 2006
Zinc	0.004	3.0	7	INFOTOX, based on Baars, *et al.*, 2001
Zirconium	<0.001	No value	17.5	INFOTOX, based on Harrison, *et al.*, 1951
Inorganic anions				
Chloride	<5	100	250 (t)	USEPA 2006
Sulphate	<5	200	250 (t)	USEPA 2006
No3 as N, Nitrate –N	<0.2	6.0	6.0	DWAF 1996
F, Fluoride	<0.2	1.0	1.0	DWAF 1996
Alkali and alkaline earth metals				
Sodium	0.364	No value	200	WHO 2011
Potassium	0.194	No value	100	DWAF 1996
Calcium	2.985	No value	100	WHO 2011
Magnesium	1.021	No value	100	WHO 2011

According to JMA Consulting (2013:63) the overall conclusion of the technical work was that "the ferrochrome slag investigated in the reported study poses no risk to human health and ecosystems under non-aggressive conditions" (JMA Consulting (Pty) Ltd., 2013:63). The technical work performed for the report was conducted by independent scientists as indicated in a declaration of independence of each of the technical reports. And both the technical work and motivational report were peer reviewed by suitably qualified professionals to verify the conclusions and technical work to be free from errors. The peer review found the report to be valid (JMA Consulting (Pty) Ltd., 2013: App VII).

Based on the outcome of the classification process described above and on the grounds of the argument posed in section 3.2.2 above; that ferrochrome slag may be defined as general waste, ferrochrome slag may very well be classified as general waste if this argument is accepted by the regulator. In this case, a waste management licence may however still be required to reuse ferrochrome slag as aggregate depending on the amount of waste reused per day. The submission of a motivation to request that the reuse of ferrochrome slag as aggregate should be listed as an activity that does not require a waste management licence would therefore still be prudent.

3.4 Financial benefits

3.4.1 Ferrochrome slag disposal costs

According to Booysen (2009:11) the typical slag to metal ratio of ferrochrome is 1.1 – 1.9 tonnes of slag for every ton of ferrochrome and a typical ferrochrome furnace can produce around 330 to 380 tons of ferrochrome slag per day (Booysen, 2009:11). This places the disposal costs of ferrochrome slag into context and emphasises the cost saving benefits related to the effective recycling of ferrochrome slag by reuse opportunities such as building aggregate (Biermann, Cromarty & Dawson, 2012:303).

According to Hattingh and Friend (2003) the disposal cost of permitting and constructing a hazardous waste disposal facility for a ferrochrome plant operating for 55 years was conservatively estimated between 6.2 and 12 million rand in 2003. Disposal to an offsite hazardous disposal landfill site was estimated at around 5.9 billion rand (Hattingh & Friend, 2003:23). These amounts have increased significantly since 2003 due to inflation. If an average inflation rate of 4% is used between 2003 and 2016, a hazardous waste disposal site would amount to around 10.3 to 20 million rand and offsite hazardous waste disposal would amount to around 9.86 billion rand.

3.4.2 Quantities of ferrochrome slag that can be utilised as building aggregate in South Africa

Ferrochrome slag would only be a sustainable alternative to natural aggregate if the supply of ferrochrome slag to the construction industry is enough to sustain construction at the quantities required by the construction industry to satisfy its demand for years to come. According to JMA Consulting (Pty) Ltd the total amount of residual ferrochrome slag in South Africa totals 62 424 631 tonnes of slag; and each year the South African ferrochrome industry produces around 4 859 025 tonnes of slag at a slag to metal ratio of around 1.1 – 1.9 (JMA Consulting (Pty) Ltd., 2013:9-10).

The majority chromite reserves are located in South Africa and therefore the majority of the global stainless steel demand for ferrochrome originates from South Africa. According to JMA Consulting (Pty) Ltd. the South African chromite reserves amount to 75% of the global chromite reserves and 85% of the ferrochrome used for stainless steel manufacturing worldwide is South African ferrochrome (JMA Consulting (Pty) Ltd., 2013:1). According to the International Chromium Development Association (ICDA) South Africa's chromite reserves total around 8.6 billion tonnes of which 3.1 billion tonnes are proven in-situ reserves and 5.5 billion tonnes are estimated additional reserves (International Chromium Development Association, 2015).

3.4.3 Sustainability of ferrochrome slag supply in South Africa

The global stainless steel demand is likely to increase by around 5% year on year. This growth rate can be directly correlated with the expected growth rate of the global ferrochrome industry (JMA Consulting (Pty) Ltd., 2013:1). Although recent ferrochrome market trends indicate higher growth rates in China compared to South Africa due to the export of South African chromite ore to China; South African ferrochrome production continues to compete in the global market, indicating positive projections of a sustained supply of ferrochrome and ferrochrome slag in South Africa (Chromium: Global Industry Markets and Outlook 12th edition, 2014:200).

According to the International Chromium Development Association's market overview for 2014 global ferrochrome production reached a new record high despite various challenges in the international ferrochrome community. Ferrochrome production ended off at 11.8 Mt for 2014 and although China produced the majority of ferrochrome at 4.2 Mt, South Africa remains a major competitor, reaching around 4 Mt despite major challenges relating to a 5 month strike in the Platinum sector impacting UG2 output (International Chromium Development Association, 2015). Due to the export of un-beneficiated chrome ore to China and escalating electricity prices in South Africa, South Africa has been replaced as the top producer of ferrochrome by China who owns only 1% of the world's chrome reserves. South Africa supplied over half of China's chrome ore in 2012 despite causing an ailing ferrochrome industry in South Africa (Dhawan, 2013).

According to the International Chromium Development Association (2015) the illustration below indicates this trend, yet a fairly constant supply from Africa is also evident (International Chromium Development Association, 2015).

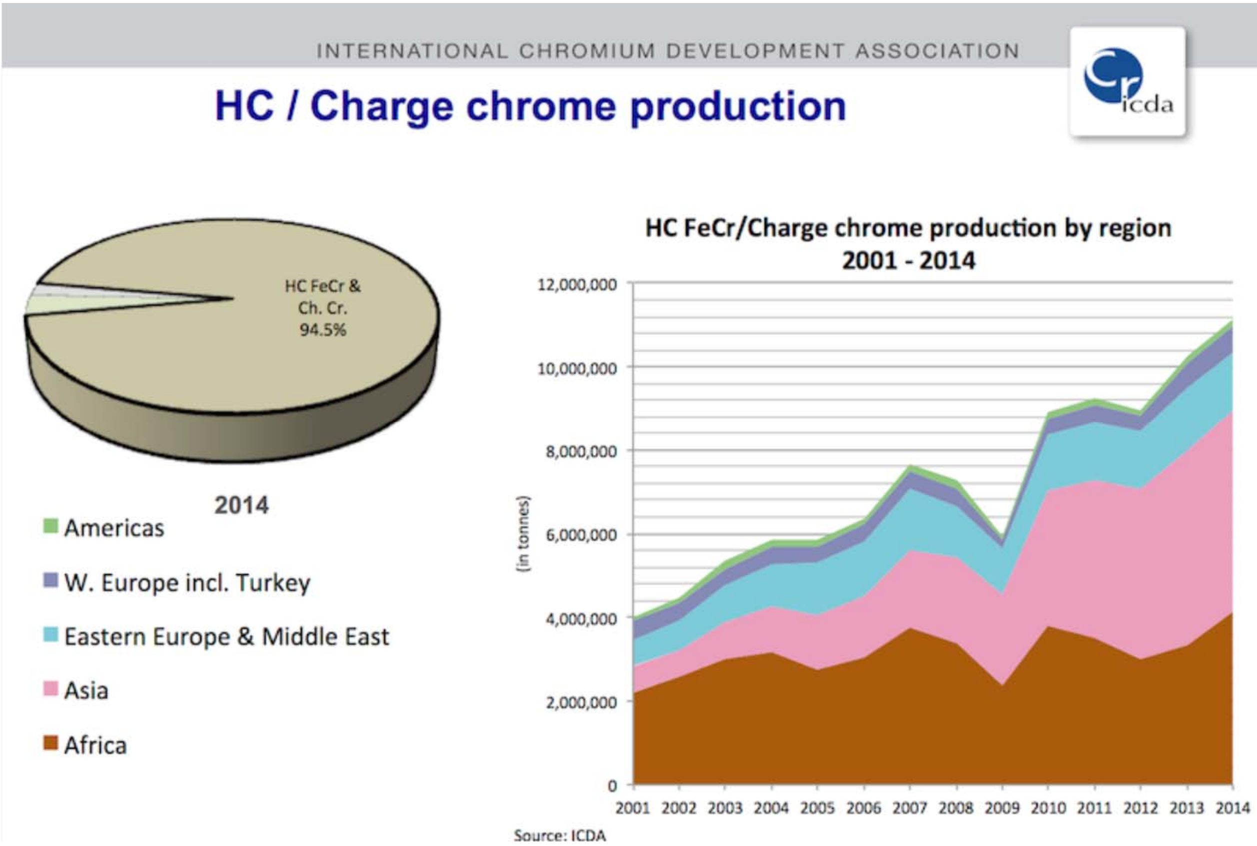

Figure 3-2: Ferrochrome production by region for the period 2001 to 2014 (International Chromium Development Association, 2015). http://www.icdacr.com

Despite market changes regarding the export of chrome ore to China, the ICDA report continues to speak to the long term outlook that the South African ferrochrome industry will be sustained for years to come. Therefore, the utilisation of ferrochrome slag is viewed as a long term sustainable alternative to natural aggregate in South Africa, especially taking into account the large amount (62 million tonnes) of residual slag stored on slag heaps.

3.4.4 Aggregate demand in South Africa

According to JMA Consulting (Pty) Ltd. (2013:2) "the most mined material in the world" is aggregate and the large scale aggregate mining in South African is indicative of the approximate 502 registered operational quarries in the country (JMA Consulting (Pty) Ltd., 2013:2-5). Aggregate demand is determined by the growth of the construction industry at a consumption rate of around 2 000 kg per capita in South Africa, which accounts for approximately 1 million jobs (JMA Consulting (Pty) Ltd., 2013:5, 35). Aggregate is used in all roads and concrete-containing structures such as buildings or sidewalks and make up the majority of the volume off these structures, at around 75 percent for concrete and 95 percent for asphalt mixtures (JMA Consulting (Pty) Ltd., 2013:35).

Aggregate is usually extracted near the locations of end use due to the largest portion of aggregate cost being contained in transport fees. According to JMA Consulting (Pty) Ltd. (2013:35) "aggregate weight is high but the value of the material is low" and therefore the cost of aggregate is mostly influenced by the cost of transport and therefore the distance of the aggregate quarry or supply from the end use location (JMA Consulting (Pty) Ltd., 2013:35). It is therefore necessary to take this factor into account when considering the financial benefits of using ferrochrome slag as aggregate.

3.4.5 Financial viability of the replacement of natural aggregate with ferrochrome slag in South Africa

Consideration should also be given to the amount of natural aggregate required compared to the amount of ferrochrome slag aggregate required. Research indicate a benefit regarding the use of ferrochrome slag as opposed to natural aggregate in road construction in that 30 to 50 percent less aggregate is required during construction, which provides an added benefit of speeding up the construction process and therefore a reduction in the number of man hours required for the construction project (JMA Consulting (Pty) Ltd., 2013:37).

Upon determining the main cost elements related to aggregate extraction, the availability of alternative aggregate in the form of ferrochrome slag can be investigated. In addition to this, the limiting factor regarding transport costs of aggregate will be assessed, based on the location of ferrochrome smelters in South Africa. The financial benefits relating to reuse can be investigated by this assessment. The literature will focus on determining the locations of the various ferrochrome slag producers in South Africa. Then a financially viable transport radius can be considered during the data analysis of the study to provide information for the consideration of ferrochrome slag as a viable alternative to natural aggregate from a financial perspective.

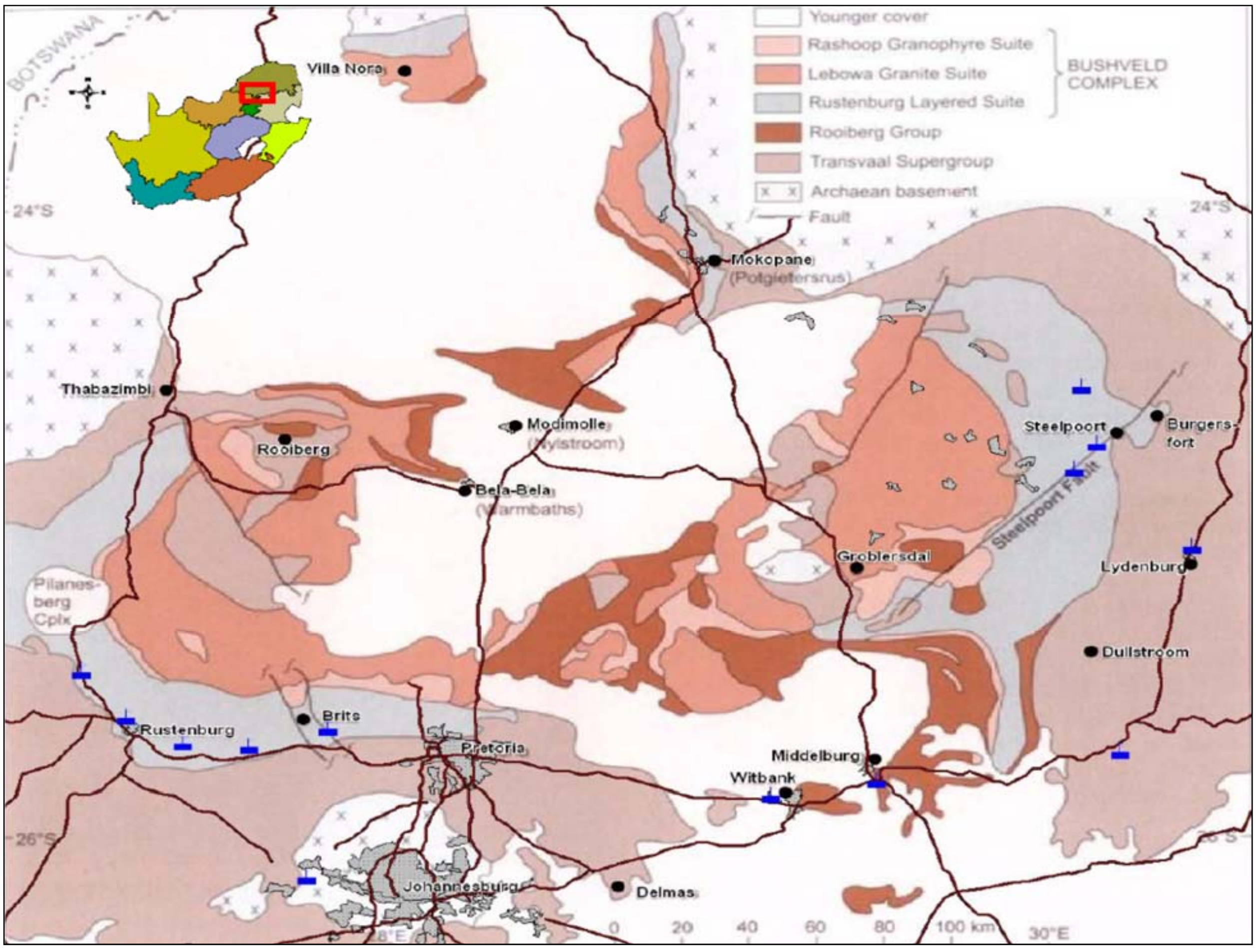

Figure 3-3: Generalised geological map of the Bushveld Complex with the Ferrochrome Smelter locations indicated on the map (JMA Consulting (Pty) Ltd., 2013:7).

According to JMA Consulting (Pty) Ltd. South African chromite reserves are located within the Bushveld Igneous Complex (BIC) and most of the country's ferrochrome smelters are located on the brim of the Bushveld Complex, with the exclusion of one smelter in Kwa-Zulu Natal (JMA Consulting (Pty) Ltd., 2013:6-7).

3.4.6 Financial benefits related to road construction

According to Hiltunen and Hiltunen (2002:359) slag properties include a higher bearing capacity and insulation capability of slag compared to natural material. The use of ferrochrome slag as aggregate also speeds up the construction process due to a smaller amount of aggregate being required, providing the added benefit of reduced transport costs making it the more economic option (Pekka & Kauppi, 2007:171-179). In the concrete industry these savings go hand in hand with environmental benefits. Similar savings are realised in terms of a reduced reliance on natural materials, and a reduction in CO_2 that would have been emitted if those natural materials were extracted from the natural environment (Hiltunen & Hiltunen, 2002:359).

3.4.7 Financial benefits related to concrete

The high compressive strength of concrete, which is made with unscreened ferrochrome slag, is said to be due to the high intrinsic strength of the slag particles, combined with the uneven surfaces of the slag grain that improve the binding effect between slag grains and cement paste (Zelic, 2004:2340-2349). Due to these properties, the quality of concrete made with ferrochrome slag is good in terms of volume mass, water permeability, abrasion, wear and frost resistance. These properties make it suitable for applications requiring high performance concrete, such as concrete in hydraulic engineering applications that are subjected to highly abrasive or corrosive environments. This type of concrete requires stone of igneous origin that is expensive and has to be transported over large distances to the point of use. In these applications, the economic benefits of utilising slag instead of natural aggregates are emphasized (Zelic, 2004:2340-2349).

3.5 Methods to facilitate reuse

3.5.1 International cases

Ferrochrome slag has been recycled successfully in some European countries for more than a century. According to Hiltunen and Hiltunen (2004:357) more recently 350 000 t of ferrochrome slag was recycled in Finland during 2002; and during 2000 Europe utilised 45.5 million tons of different slag products (Hiltunen & Hiltunen, 2004:357). The utilisation of ferrochrome slag in Finland has been optimised to the extent that various products are produced from ferrochrome slag. These products are seen as part of the production process and none of the product is abandoned. This classification of ferrochrome slag as product instead of waste did not come about easily in Finland. It was only after court proceedings that the classification was changed and the utilisation of ferrochrome slag was optimised (Pekka & Kauppi, 2007:171-179).

The European countries that have been successfully using slag as aggregate has also had to overcome legal hurdles of their own, similar to those that we now have to overcome in South Africa. Finland was one of the leaders in addressing those hurdles between ferrochrome producers and the authorities. They have come to the conclusion that ferrochrome slag should be controlled as a by-product in the industry and that the required production process of ferrochrome intrinsically sets and controls the quality requirements of ferrochrome slag (Hiltunen & Hiltunen, 2004:357). Moreover, the classification of ferrochrome slag as a waste product made the utilisation of slag as aggregate cumbersome and costly, a definition that has since been revised in Finland (Pekka & Kauppi, 2007;171-179). According to the National Environmental Management: Waste Amendment Act (26 of 2014), the definition of the by-product has recently be deleted from the National Environmental Management Waste Act (59 of 2008). A similar process to classify ferrochrome slag as a by-product in South Africa may therefore not likely be achieved in the near future.

Finland's Outokumpu plant produces three different ferrochrome slag products with different aggregate sizes and size distribution: 11-22 mm, 4-11 mm and 0-4 mm and complies with the relevant EN Standard (EN 13285). This process enhancement has achieved ferrochrome slag the status as preferred aggregate in road construction (Pekka & Kauppi, 2007:171-179). The benefits of utilising slag as aggregate have been seen to reduce the reliance on natural material by almost double the amount required annually due to the properties of slag (Hiltunen & Hiltunen, 2004:359).

FAPA's approach to submit a motivational document for the beneficial reuse of ferrochrome slag is a method to facilitate reuse on a large scale in South Africa. Should the motivation for beneficial reuse of ferrochrome slag succeed and this activity be listed as a waste management activity not requiring a waste management licence, the ferrochrome industry should prepare itself to make ferrochrome slag available as an aggregate product on large scale in order to facilitate reuse. To this end, reference is made to the process followed by the Outokumpu Tornio Works that makes use of a European Standard, EN 13242 and EN 13043 to provide assurance in terms of product quality of their ferrochrome slag products based on aggregate requirements. These requirements are mainly size distribution and intrinsic properties such as resistance to fragmentation and durability (JMA Consulting (Pty) Ltd., 2013:37).

South African ferrochrome producers are capable of supplying similar ferrochrome slag products as the Outokumpu example (11-22 mm, 4-11 mm, 0-4 mm) by implementing minor modifications by the installation of additional screens or conveyances where required and certifying ferrochrome slag product according to South African quality standards for aggregate.

3.5.2 South African methods of facilitating reuse

According to Godfrey *et al.* (2007:13-15) a cooperative governance process is required to overcome the limitations of reusing mineral wastes, such as ferrochrome slag in South Africa; therefore both government and industry have a role to play in this process. The change in legislation allowing a waste management activity to be listed as an activity that does not require a waste management licence and the response from the Ferro Alloys Producers Association to develop a motivational document for the beneficial reuse of ferrochrome slag are strong indications that both government and industry are working towards this goal. Moreover, the report written by Godfrey *et al.* (2007:4-15) refers to market based instruments rather than command and control regulations as methods to optimise reuse of mineral waste such as ferrochrome slag in South Africa.

Command and control regulations such as those currently applied by South African legislation succeed in directly regulating behaviour and can be seen as treating the symptoms of the market failing to take the social cost, as well as direct cost of their decision into account when considering reuse of mineral waste such as ferrochrome slag rather than using natural aggregate (Godfrey *et al.*, 2007:15). Market based instruments may, however, be more effective in addressing the cause of such market failures by the implementation of incentives for reusing mineral waste such as ferrochrome slag rather than extracting natural aggregate. Reference is made to market based incentives such as subsidies for reusing mineral wastes such as ferrochrome slag and imposing an environmental related tax on the extraction of natural aggregate which would further assist in making the reuse of ferrochrome slag more cost effective than extracting natural aggregate (Godfrey *et al.*, 2007:15).

Although South African examples of successful reuse are not well publicized, there are examples of pilot projects, as well as large scale road construction projects in which ferrochrome slag was successfully used as a replacement for natural aggregate. The FAPA motivational document makes reference to pilot projects where ferrochrome slag was successfully used as concrete aggregate in RDP housing and in the manufacturing of cement bricks, as well as a large scale road construction project (JMA Consulting (Pty) Ltd., 2013:39).

Ferrochrome slag replaced natural aggregate in various applications in the construction, extension and refurbishment of the N4 Toll Road. Ferrochrome slag was used as a multipurpose aggregate during this project and reference can be made to this successful construction project in cases where South African examples have to be sited to motivate reuse of ferrochrome slag as aggregate (JMA Consulting (Pty) Ltd., 2013:39). According to JMA Consulting (Pty) Ltd ferrochrome slag can either be crushed to the required specification during the metal extraction process of a ferrochrome smelter or crushed slag can be screened into the required fraction sizes required for each specific application (JMA Consulting (Pty) Ltd., 2013:39).

According to JMA Consulting (Pty) Ltd., (2013:39-41) Ferrochrome slag was used for the following purpose during the N4 Toll Road construction project:

- Drainage aggregate: Ferrochrome slag was screened to comply with the required drainage aggregate specification and according to JMA Consulting (Pty) Ltd.

substantial amounts (around 7 000 t) of ferrochrome slag was successfully used as drainage aggregate along the N4 between Witbank and Middelburg and between Wonderfontein and Belfast (JMA Consulting (Pty) Ltd., 2013:39).

- Layer work material: Although ferrochrome slag cannot be used as a complete aggregate replacement for this purpose, it has been successfully blended with other natural aggregates to enhance the properties of the total aggregate mix. A small section of the N4 between Belfast and Machadodorp was rehabilitated with such an aggregate mix, although it took some time to correct the grading by the correct blend. According to JMA Consulting (Pty) Ltd, around 10 000 t have been used for road shoulder rehabilitation in an in-situ gravel mix, and around 20 000 t have been used in sub-base construction in a borrow-pit material mix (JMA Consulting (Pty) Ltd., 2013:39-40).
- Asphalt: An asphalt plant near Witbank has been making use of ferrochrome slag in pit sand mix for many years and upgrades to the N4 of as far back as 1999 are documented in the FAPA motivational report. An amount totalling around 175 030 t of ferrochrome slag has been used in asphalt surfacing on the N4 highway with great success. According to JMA Consulting (Pty) Ltd of this 14 580 t was used for continuous medium grade asphalt in the Witbank N4/3 contract; 74 650 t in the N4/6-7X Eland Valley contract; 59 900 t in the N4/5 Widening and rehabilitation contracts; and 25 900 t in the N4/3 UTFC contract (JMA Consulting (Pty) Ltd., 2013:40).
- Seal work: Ferrochrome slag is ideally suited for seal work and relatively small scale use on the N4 indicated that standard seal design procedures can be used and that the ferrochrome slag specification complies with the grading requirement. According to JMA Consulting (Pty) Ltd the required grade was met in these cases with the grading, ALD, Flakiness index and ACV (Dry) complying with the COLTO specification. It was, however, noted that it is somewhat difficult to broom loose aggregate from the rough surface due to the mechanical properties of ferrochrome slag as opposed to smoother surface aggregates. A total usage of 15 030 t was reported, of which 7 830 t in the N4/3 (16mm) and 7 200 t in the N4/6-7X (13.2mm) (JMA Consulting (Pty) Ltd., 2013:41).

3.6 Chapter summary

The literature review shows that the South African legislative framework is aligned with the international sustainable development framework in accordance with the Brundlandt report and subsequent United Nations publications. The review identified that there has to be a balance between environmental conservation and sustainable development, not only in the legislative framework, but also in the real world example of ferrochrome slag reuse.

The systematic review of literature related to the subject was able to reach the objectives of this chapter by describing the environmental benefits, investigating the financial benefits and describing methods to facilitate the reuse of ferrochrome slag as aggregate in South Africa.

CHAPTER 4: DATA ANALYSIS

4.1 Introduction

The systematic literature review of international, national and project literature successfully provided qualitative data on each objective of the study. The qualitative data was assessed by a quantitative comparative assessment of the literature. The research objectives was investigated by this approach in order to reach the aim of the study.

4.2 Data collection

The literature review of this study was utilised as the source of data for the purpose of this assessment. In order to aid in the data collection, a list of the bibliography of the research study was sorted by type and location. Each source was numbered in alphabetical order and sorted chronologically in order to determine if there were any significant indications as to how these studies had developed over time. Thereafter, an assessment of the literature yielded key statements that would aid the researcher in assessing each of the objectives of the study.

Objective 1 of the study is to identify and describe the environmental benefits of using ferrochrome slag as aggregate. Key statements relevant to this objective include the properties of ferrochrome slag that improve construction material, as well as the environmental benefits that these properties yield. Objective 2 of the study is to investigate the probable financial benefits of replacing natural aggregates with ferrochrome slag. The key statements assessed for this objective relate to the properties of ferrochrome slag that give rise to a cost reduction in the construction project as well as a reduction of social costs related to the reuse of ferrochrome slag as aggregate. Objective 3 of the study is to describe methods of facilitating the reuse of ferrochrome slag as aggregate in South Africa. Key statements relating to this objective include requirements from the construction industry, as well as learnings from the studies from the literature review that would optimise reuse opportunities in South Africa.

The literature sources that did not yield any key statements were removed from the data collection bibliography list and a final list was compiled as indicated in Figure 4-1 below.

Bibliography					
No	Reference	Year	Country	Title	Type
11	Emery, J.J.	1982	United States of America	Slag Utilization in Pavement Construction.	Article
14	Gericke, W.A.	1995	Norway	Environmental aspects of ferrochrome production.	Article
12	Environmental Commissioner of Ontario.	2003	Canada	“Aggregate Use in Road Construction.” Thinking Beyond the Near and Now	Article
20	Hattingh, J. and Friend, J.F.C.	2003	South Africa	Environmental and economic implications of slag disposal practices by the ferrochromium industry: A case study.	Article
25	Kotze, L.J.	2003	South Africa	The Constitutional Court’s Contribution to Sustainable Development in South Africa.	Article
21	Hiltunen. R and Hiltunen. A	2004	Finland	Environmental aspects of the utilization of steel industry slag.	Article
22	Holappa, L and Xiao, Y.	2004	South Africa	Slags in ferroalloys production – review of present knowledge.	Article
30	Nicholls, C., Clark, M. and Samuel, P.	2004	United Kingdom	State of the art test methods to detect hazardous components in road materials for recycling	Report
39	Prusinki, J.R., Marceau, M.L. and VanGeem, M.G.	2004	International	Life cycle inventory of slag cement concrete.	Article
41	Reuter, M., Xiao, Y., and Boin, U.	2004	Netherlands	Recycling and environmental issues of metallurgical slags and salt fluxes.	Article
74	Zelic, J.	2004	Croatia	Properties of concrete pavements prepared with ferrochromium slag as concrete aggregate.	Article
40	Redclift, M.	2005	London	Sustainable development (1987–2005): an oxymoron comes of age.	Article
63	Van der linde, M.	2006	South Africa	Compendium of South African Environmental Legislation.	Book
15	Godfrey, L., Oelofse, S., Phiri, A. et al.	2007	South Africa	Mineral waste: the required governance environment to enable re-use.	Report
34	Oelofse, S.H.H., Adlem, C.J.L. and Hattingh, J.	2007	South Africa	Overcoming bureaucratic obstacles to the re-use of metallurgical slag – A South African case study.	Article
37	Pekka, N. and Kauppi, M. (2007).	2007	Finland	Production, characteristics and use of ferrochromium slags.	Article
33	Oelofse, S.	2009	South Africa	Improved waste management services – Will the Act make a difference?	Seminar
73	Yilmaz, M and Kok, B.V.	2009	India and Turkey	Effects of ferrochromium slag with neat and polymer modified binders in hot bituminous mix.	Article
2	Barišić, I., Dimter, S. and Netinger, I.	2010	Croatia	Possibilities of application of slag in road construction.	Article
13	Gencel, O., Koksal, F., Ozel, C. and Brostow, W.	2011	International	Combined effects of fly ash and waste ferrochromium on properties of concrete.	Article
54	South Africa. National Roads Agency.	2011	South Africa	South African Pavement Engineering Manual	Manual
64	Van Niekerk, W.C.A., and Fourie, M.H.	2011	South Africa	Globally Harmonised System Classification of Ferrochrome Slag.	Project Report
65	Van Niekerk, W.C.A., and Fourie, M.H.	2011	South Africa	Generic Assessment of Exposure to Dust from Ferrochrome Slag.	Project Report
66	Van Niekerk, W.C.A., and Fourie, M.H.	2011	South Africa	pH Dependence of Leaching Characteristics of Ferrochrome Slag.	Project Report
67	Van Niekerk, W.C.A., and Fourie, M.H.	2011	South Africa	Criteria Document for the Classification of Ferrrochrome Slag in Accordance with SANS 10234:2008	Project Report
68	Van Niekerk, W.C.A., and Fourie, M.H.	2011	South Africa	Assessment of Ferrochrome Slag for Landfill Disposal.	Project Report
69	Van Niekerk, W.C.A., and Fourie, M.H.	2011	South Africa	Ageing Characteristics of Ferrochrome Slag.	Project Report
3	Biermann, W., Cromarty, R.D. and Dawson, N.E.	2012	South Africa	Economic modelling of a ferrochrome furnace.	Article
36	Panda, C.R., Mishra, K.K., Panda, K.C., Nayak, B.D. Rao, D.S. and Nayak, B.B.	2012	International	Environmental and technical assessment of ferrochrome slag as concrete aggregate material.	Article
24	JMA Consulting (Pty) Ltd.	2013	South Africa	Beneficial use of Ferrochrome Slag as Aggregate Material.	Project Report
31	Nkosi, N., Muzenda, E., Zvimba, J. and Pilusa, J.	2013	South Africa	The current waste generation and management trends in South Africa: A Review.	Article
35	Panda, C.R., Mishra, K.K., Panda, K.C., Nayak, B.D. and Nayak, B.B.	2013	International	Environmental and technical assessment of ferrochrome slag as concrete aggregate material.	Article
8	Roskill	2014	International	Chromium: Global Industry Markets and Outlook	Report
1	Ananthi, A and Karthikeyan, J.	2015	India	A review on the effect of industrial waste in concrete.	Article

Figure 4-1: Bibliography list for the purpose of data collection.

Those sources that were removed from the list included literature sources utilised to inform the research methodology and legal framework review of the study. These sources were seen as secondary sources and were not specifically relevant to the objectives of the study in yielding key statements as described above.

The bibliography list was then grouped into international literature, South African literature or project data and utilised to create a spreadsheet that indicated which of the sources in the literature review supported the respective key statements identified.

4.3 Data analysis

The data collection yielded an information chart as indicated in the figures below that was utilised to conduct a comparative assessment of the literature review in order to describe each of the research objectives.

4.3.1 Data analysis for achieving Objective 1

Objective 1 of this research study is to identify and describe the environmental benefits of using ferrochrome slag as aggregate. A comparative analysis of the literature review was conducted by making use of the information chart indicated in Figure 4-2 and Figure 4-3 below. The comparative analysis confirms that there are very limited sources citing the environmental benefits of reusing ferrochrome slag in South Africa. International literature from a variety of different countries and climates were, however, successful in describing these benefits and also provides reasons for ferrochrome slag being the preferred alternative to natural aggregate. The comparative analysis yielded the following findings.

The reduction in natural aggregate consumption is expected as a direct benefit from reusing ferrochrome slag instead of natural aggregate. International literature confirms that these benefits can be described as a reduced reliance on natural material resulting in less land being degraded by aggregate mining and less land being required for disposing of ferrochrome slag. The benefits resulting from this change are reduced soil grade changes and a reduction in the degradation of water storage capacity from aggregate mining, as well as reduction in the leaching potential from ferrochrome slag dumps. South African literature indicates that these benefits are expected by the reuse of ferrochrome slag instead of natural aggregates in South Africa. The comparative analysis therefore confirms that these benefits are expected in any location where the use of natural aggregate is replaced with ferrochrome slag. In order to confirm that these benefits would realise in South Africa it would however be required that ferrochrome slag be reused as waste aggregate on large scale for an extended duration.

	Benefits	International Literature																
		9	14	12	21	30	39	41	74	40	37	73	2	13	36	35	8	1
Bibliography	Source Identification (Abbreviated by first author & subject where required)	Emery	Gericke	Ontario	Hiltunen	Nicholls	Prusinki	Reuter	Zelic	Redclift	Pekka	Yilmaz	Barišić	Gencel	Panda	Panda	Roskill	Ananthi
	Year	1982	1995	2003	2004	2004	2004	2004	2004	2005	2007	2009	2010	2011	2012	2013	2014	2015
Environmental	Improved physical & mechanical properties				■				■			■	■			■		
	Improved bearing capacity of roads				■								■					
	Improved impact resistance												■					
	Improved durability								■			■	■					
	Courser more porous particle											■						
	Improved adhesive strength								■			■						
	High insulation capacity (water and frost)				■				■			■						■
	High compressive strength								■							■		■
	High volume mass								■									■
	High abrasion resistance								■									
	Reduction in energy consumption				■		■				■			■				
	Reduction in carbon emissions				■		■				■							
	Reduction in land degradation (aggregate mining)			■								■		■				
	Reduction in soil grade changes (aggregate mining)			■														
	Reduction in diminished water capacity (aggregate mining)			■														
	Reduction in leaching potential (ferrochrome slag dumps)										■				■	■		■
	Reduction in land degradation (ferrochrome slag dumps)													■				
	FeCr slag reuse is not hazardous to health or environment					■					■							
	FeCr Slag dumps do not have leaching potential (except at low pH)		■												■			
	Reduction in leaching potential of ferrochrome after recycling					■					■							■

Figure 4-2: Data collection of International literature sources on environmental benefits.

The comparative analysis found that ferrochrome slag is not only seen as an alternative option for aggregate, but rather a better aggregate product than natural aggregate in road and concrete applications. Ferrochrome slag particles are course and porous which results in ferrochrome slag particles binding much better to a medium like cement than natural aggregate would. This improvement in the adhesion strength of ferrochrome slag improves the physical and mechanical properties of the road and concrete construction medium which result in further benefits. These include an improvement in the bearing capacity, impact resistance, durability, compressive strength, volume mass and abrasion resistance. It also provides higher insulation capacity to water and frost.

The physical and mechanical properties of ferrochrome slag aggregate resulting in improved bearing capacity in road infrastructure makes it possible to use less building material for a project when using ferrochrome slag rather than natural aggregate. The construction project is effectively reduced by this benefit and this results in less material being required for a project which means less material has to be produced, transported and handled. Less energy in the form of electricity, fuel and raw materials is therefore required and this results in a reduction in carbon emissions into the atmosphere, making ferrochrome slag a sustainable alternative to natural aggregate.

	Benefits	South African Literature										Project Report						
		20	25	22	63	15	34	33	54	3	31	64	65	66	67	68	69	24
Bibliography	Source Identification (Abbreviated by first author & subject where required)	Hattingh	Kotze	Holappa	Van der Linde	Godfrey	Oelofse	Oelofse	SA: Pavement Eng.	Biermann	Nkosi	Van Niek: GHS	Van Niek: Dust	Van Niek: Leach	Van Niek: SANS	Van Niek: Landfill	Van Niek: Ageing	JMA
	Year	2003	2003	2004	2006	2007	2007	2009	2011	2012	2013	2011	2011	2011	2011	2011	2011	2013
Environmental	Improved physical & mechanical properties																	
	Improved bearing capacity of roads																	
	Improved impact resistance																	
	Improved durability																	
	Courser more porous particle																	
	Improved adhesive strength																	
	High insulation capacity (water and frost)																	
	High compressive strength																	
	High volume mass																	
	High abrasion resistance																	
	Reduction in energy consumption																	
	Reduction in carbon emissions																	
	Reduction in land degradation (aggregate mining)					■	■											
	Reduction in soil grade changes (aggregate mining)																	
	Reduction in diminished water capacity (aggregate mining)																	
	Reduction in leaching potential (ferrochrome slag dumps)						■			■								
	Reduction in land degradation (ferrochrome slag dumps)	■									■							
	FeCr slag reuse is not hazardous to health or environment											■	■	■	■	■	■	■
	FeCr Slag dumps do not have leaching potential (except at low pH)													■				
	Reduction in leaching potential of ferrochrome after recycling																	

Figure 4-3: Data collection of South African literature sources and project reports on environmental benefits.

The FAPA motivational document is advocative in its approach but was found to be a credible source of project data as it was peer reviewed and made use of independent technical work. The literature review made use of these technical reports rather than the motivational document itself where environmental impact of reusing ferrochrome slag in South Africa was described. The technical and motivational report supports the literature review conducted of international reuse of ferrochrome slag, stating that there are no negative environmental or health impacts created by the reuse of ferrochrome slag as aggregate.

This research study therefore describes environmental benefits of reusing ferrochrome slag as aggregate and does not list environmental or health impacts that can be expected from this practice. The comparative analysis was successful in describing the environmental benefits of reusing ferrochrome slag as aggregate that can be expected in South Africa.

4.3.2 Data analysis for achieving Objective 2

Objective 2 of this research study is to investigate the probable financial benefits of replacing natural aggregates with ferrochrome slag. A comparative analysis of the literature review is indicated in Figure 4-4 and Figure 4-5 below.

The comparative analysis indicates that the majority of financial benefits arise from the physical and mechanical properties of ferrochrome slag resulting in less aggregate being required when compared with natural aggregate. This results in faster construction, which requires less manpower than a longer project and a reduction in transport cost due to less construction material required. These benefits were cited by international literature and confirmed by South African project data. Due to the direct replacement of natural aggregate with ferrochrome slag, an expected benefit is a reduction in the disposal cost of ferrochrome slag and a reduction in the mining cost of natural aggregate as well as a reduction in environmental liability on both accounts. Although these benefits are expected, the change may also result in additional costs being created by implementing this practice. It was therefore necessary to assess the literature in order to determine if any additional costs may arise.

Benefits		International Literature																
		9	14	12	21	30	39	41	74	40	37	73	2	13	36	35	8	1
Bibliography	Source Identification (Abbreviated by first author & subject where required)	Emery	Gericke	Ontario	Hiltunen	Nicholls	Prusinki	Reuter	Zelic	Redclift	Pekka	Yilmaz	Barišić	Gencel	Panda	Panda	Roskill	Ananthi
	Year	1982	1995	2003	2004	2004	2004	2004	2004	2005	2007	2009	2010	2011	2012	2013	2014	2015
Finan-cial	Less FeCr slag aggregate than natural aggregate required				■		■				■							
	Faster construction time				■		■				■							
	Reduction in manpower				■		■				■							
	Reduction in transport cost				■		■		■		■			■				
	Reduction in ferrochrome slag disposal costs																	

Figure 4-4: Data collection of International literature sources on financial benefits.

Benefits		South African Literature										Project Report						
		20	25	22	63	15	34	33	54	3	31	64	65	66	67	68	69	24
Bibliography	Source Identification (Abbreviated by first author & subject where required)	Hattingh	Kotze	Holappa	Van der Linde	Godfrey	Oelofse	Oelofse	SA: Pavement Eng.	Biermann	Nkosi	Van Niek: GHS	Van Niek: Dust	Van Niek: Leach	Van Niek: SANS	Van Niek: Landfill	Van Niek: Ageing	JMA
	Year	2003	2003	2004	2006	2007	2007	2009	2011	2012	2013	2011	2011	2011	2011	2011	2011	2013
Finan-cial	Less FeCr slag aggregate than natural aggregate required																	■
	Faster construction time																	■
	Reduction in manpower																	■
	Reduction in transport cost																	■
	Reduction in ferrochrome slag disposal costs	■								■								

Figure 4-5: Data collection of South African literature sources and project reports on financial benefits.

In order to implement the change the ferrochrome industry will need to supply ferrochrome slag at the correct fraction sizes in order for it to be utilised for different applications in the construction of roads or infrastructure. The literature review indicates that this is not a significant or costly challenge. The required size fractions can be supplied by the installation of additional screens at the ferrochrome slag discharge points of these operations. The transport costs of aggregate were, however, raised as the main cost contributor for aggregate by the literature review and it is therefore prudent to consider the transport cost and distance that ferrochrome slag would have to be transported in order to implement the change. According to the Ferro Alloys industry the sales price of ferrochrome slag is around R14 per ton and according to information sourced from a construction entity, the extraction price of aggregate (excluding overhead fees) is around R98 per ton. The average road transport rate was also obtained from a ferrochrome operation at around R2 per ton of slag per kilometre.

When considering the viability of reusing ferrochrome slag as aggregate instead of virgin material, the location of ferrochrome smelters should be taken into account, compared to the location of quarries, in order to determine if the replacement is viable for the specific project. In addition to financial considerations, the total social cost of such a decision should also be taken into account, an example of which is the environmental benefits relating this reuse as explained above or the additional road maintenance that may be required due to increased transport requirements for aggregate.

For the purpose of this study, the financial viability of reusing ferrochrome slag as aggregate is considered for construction projects where aggregate is extracted within a 100 km radius of the project. The cost of aggregate would therefore amount to around R298/t including transport costs. In order to break even in terms of aggregate cost the distance from the closest ferrochrome slag supplier should not exceed a distance of 142 km from the construction project and this would also contain the additional road maintenance cost that may arise from this activity.

4.3.3 Data analysis for achieving Objective 3

Objective 3 of this research study is to describe methods of facilitating the reuse of ferrochrome slag as aggregate in South Africa. The comparative analysis of the literature review is indicated in Figure 4-6 and Figure 4-7 below. The analysis confirms that ferrochrome slag is a suitable material to be used instead of natural aggregate in the construction of roads and infrastructure. Moreover, the ferrochrome slag product is inherently controlled in the ferrochrome production process and product quality of ferrochrome slag is therefore constant. Aggregate sizing fractions can also be supplied by ferrochrome operations at specifications required by the construction industry or certified based on the required South African aggregate standard.

The literature review further indicates that there are significant amounts of ferrochrome slag available for reuse in South Africa and that the ferrochrome industry can be expected to continue producing ferrochrome and ferrochrome slag in South Africa for many years to come. Ferrochrome slag is therefore a consistent quality controlled product that can be supplied to the construction industry as building aggregate on a long term basis in South Africa.

	Benefits	International Literature																
		9	14	12	21	30	39	41	74	40	37	73	2	13	36	35	8	1
Bibliography	Source Identification (Abbreviated by first author & subject where required)	Emery	Gericke	Ontario	Hiltunen	Nicholls	Prusinki	Reuter	Zelic	Redclift	Pekka	Yilmaz	Barišić	Gencel	Panda	Panda	Roskill	Ananthi
	Year	1982	1995	2003	2004	2004	2004	2004	2004	2005	2007	2009	2010	2011	2012	2013	2014	2015
Methods of reuse	Material suitability	■			■	■	■	■				■	■	■		■		■
	Supporting legislation									■								
	Economic viability																	
	Environmental benefits																	
	Market based instruments would promote reuse			■														
	Sustainable quantifies of mineral waste available for reuse																■	
	No requirement to reuse mineral waste for aggregate			■														
	FeCr Slag is inherently controlled in production process				■													
	Implementation of standard sizing specification										■					■		
	Overcome bureaucratic obstacles would promote reuse				■			■			■							

Figure 4-6: Data collection of International literature sources on methods of reuse.

Many sources cited the bureaucratic obstacles that would have to be overcome to enable the reuse of mineral waste in South Africa. However, the literature review confirms that legislation to support sustainable development opportunities is developing quickly in South Africa. The literature review encourages these obstacles to be overcome in order to optimise reuse of ferrochrome slag in South Africa. The chronological assessment of the literature review indicates that the development of the sustainable development legislative and regulatory framework drives research on the utilisation of ferrochrome slag as aggregate. It is therefore necessary to recognise the importance of these instruments in driving sustainable solutions such as the reuse of ferrochrome slag as aggregate.

Benefits		South African Literature										Project Report						
		20	25	22	63	15	34	33	54	3	31	64	65	66	67	68	69	24
Bibliography	Source Identification (Abbreviated by first author & subject where required)	Hattingh	Kotze	Holappa	Van der Linde	Godfrey	Oelofse	Oelofse	SA: Pavement Eng.	Biermann	Nkosi	Van Niek: GHS	Van Niek: Dust	Van Niek: Leach	Van Niek: SANS	Van Niek: Landfill	Van Niek: Ageing	JMA
	Year	2003	2003	2004	2006	2007	2007	2009	2011	2012	2013	2011	2011	2011	2011	2011	2011	2013
Methods of reuse	Material suitability	■					■		■	■								■
	Supporting legislation		■		■	■	■											
	Economic viability					■				■								
	Environmental benefits	■				■												
	Market based instruments would promote reuse					■	■											
	Sustainable quantifies of mineral waste available for reuse					■		■		■								■
	No requirement to reuse mineral waste for aggregate	■				■	■											
	FeCr Slag is inherently controlled in production process			■						■								
	Implementation of standard sizing specification																	■
	Overcome bureaucratic obstacles would promote reuse					■	■				■							

Figure 4-7: Data collection of South African literature sources and project reports on methods of reuse.

Another opportunity to promote sustainable development opportunities, such has the reuse of ferrochrome slag as aggregate, are market based instruments. The literature review encourages the implementation of these types of legal instruments rather than command and control instruments in order to incentivise and measure reuse rather than purely regulating it. These market instrument could include subsidies for using ferrochrome slag as aggregate or environmental tax for the mining of natural aggregate. The external costs of increased road maintenance could for instance be internalised through the application of toll fees on relevant roads in order to utilise toll fees for road maintenance instead of government funds obtained from tax payers.

4.4 Chapter summary

The data analysis of this study was based on a mixed method design which utilised both qualitative and quantitative data in order to address the research objectives raised by the literature review of the study. Moreover, it was successful in promoting the reuse of ferrochrome slag as aggregate in South Africa by describing the environmental benefits, investigating financial benefits and describing methods to facilitate reuse of ferrochrome slag in South Africa. The data analysis shows that reusing ferrochrome slag as aggregate is a viable option in South Africa. This reuse strategy would likely provide benefits to both the ferrochrome and construction industry due to financial benefits related to a reduction in environmental liability, and to society due to environmental benefits relating to the reuse and a subsequent reduction in the externalised costs thereof.

CHAPTER 5: CONCLUSION

5.1 Introduction

The research study was able to meet its objectives. These objectives were based on research objectives and recommendations arising from a systematic literature review which formed part of a mixed method research strategy described in Chapters 1, 2 and 3 of this study.

5.2 Conclusion on literature review

Godfrey *et al.* (2007:2-3) identified five opportunities that promotes reuse of mineral waste such as ferrochrome slag in South Africa. These are material suitability, technology advancements, supporting legislation, economic viability and environmental benefits.

Three of the opportunities were met by international research conducted on the material suitability and technology advancement related to reusing ferrochrome slag as aggregate, as referred to in the literature review of this study. The recent promulgation of additional supporting legislation left only the economic viability and environmental benefits in question. This research study was able to provide insight into the economic viability and environmental benefits related to the beneficial reuse of ferrochrome slag by a systematic literature review, as well as the review of secondary data obtained from the Ferro Alloys Producers Association's motivational document and technical work conducted by Infotox for the purpose of the motivational document. Moreover, the study was able to describe South African and International projects where ferrochrome slag was successfully reused as aggregate in order to describe methods to facilitate reuse.

The study recommends that an organisation should not only base its business decisions on direct costs. An organisation should consider the complete social cost of a decision such as motivating the reuse of mineral waste as aggregate instead of extracting natural material for the same purpose (Godfrey *et al.*, 2007:13-15). The research study was able to provide a reference base for successful South African projects recently completed, as well as environmental and economic benefits that could aid in such a motivation.

The study further recommended that research be conducted to quantify the amount of ferrochrome slag available to the South African market for reuse in order to consider market based instruments to promote reuse and to conduct cost comparisons for reusing ferrochrome slag instead of natural aggregate (Godfrey *et al.*, 2007:23). The literature review was able to address this requirement and according to JMA Consulting (Pty) Ltd. the total amount of residual ferrochrome slag in South Africa totalled 62 424 631 tonnes in 2013 with an additional annual ferrochrome slag production of around 4 859 025 tonnes of slag (JMA Consulting (Pty) Ltd., 2013:9-10).

According to Hattingh and Friend the cost of an H:H slag dump for a ferrochrome plant operating for 55 years was conservatively estimated between 6.2 and 12 million Rand in 2003 and disposal to an offsite H:H landfill site was estimated at around 5.9 billion Rand (Hattingh & Friend, 2003:23). These amounts have increased significantly over the past 13 years due to inflation and if an average inflation rate of 4% is used between 2003 and 2016, the cost of a hazardous waste disposal site would amount to around 10.3 to 20 million rand and offsite hazardous waste disposal would amount to around 9.86 billion rand. Should the argument to define ferrochrome slag as general waste be accepted, the liner requirements of a ferrochrome slag waste facility would not be as stringent as for hazardous waste and the construction cost of such a facility would therefore reduce.

Based on these volumes, it stands to reason that South African ferrochrome producers would be able to commit to a sustained and reliable ferrochrome slag supply to the South African construction industry for years to come. Moreover, the ferrochrome industry would be able to internalise the external costs related to the environmental liability of ferrochrome slag dumps and would also obtain a cost saving due to diminishing disposal cost of one of its main waste streams. The total social cost related to ferrochrome slag disposal and aggregate mining would therefore decrease.

5.3 Conclusion on the data analysis

The research study describe the following benefits of reusing ferrochrome slag instead of mining natural material for aggregate use:

- Due to the properties of ferrochrome slag particles, less than half of the amount of ferrochrome slag aggregate is required during road construction compared to natural aggregate.
- The reduction in mining natural material results in less energy being consumed for aggregate production and therefore less carbon dioxide being released per ton of aggregate used.
- Environmental degradation relating to the mining of natural materials for aggregate use is eliminated. These risks include:
    - Soil grade changes causing diminished water storage capacity and diminished base flow.
    - Land may be disturbed faster than it can be rehabilitated due to aggregate demand.

- The use of ferrochrome slag as aggregate in road construction yields the following benefits when compared to natural aggregate:
    - Improved bearing capacity, impact resistance and durability.
    - Improved mechanical properties of hot bituminous mix when ferrochrome slag is used in granular layers.
    - Due to ferrochrome slag being courser and more porous than natural aggregate particles, the use thereof results in improved adhesion to asphalt binder.
    - Improved water resistance and indirect tensile strength.
    - Although ferrochrome slag cannot be used as a total aggregate replacement for road surfaces with high traffic demand, it can be used for total aggregate replacement in applications with low traffic and high moisture demand such as pavements.
    - High insulation capacity.
    - Faster construction time due to smaller amounts of aggregate required compared to natural aggregate and therefore reduction in transport costs.

- The use of ferrochrome slag as aggregate in concrete yields the following benefits when compared to natural aggregate:
    - High compressive strength
    - High volume mass
    - High water permeability

- o High abrasion resistance
- o High wear and frost resistance
- o Perfect aggregate for high performance concrete such as hydraulic applications in a highly corrosive environment

Although some earlier research conducted by Reuter, Xiao and Boin (2004:35) and Gericke (1995:132-133) raised the possibility that ferrochrome slag may classify as hazardous waste due to the leaching potential of ferrochrome slag dumps, the literature review and data analysis of secondary data, confirm that ferrochrome slag classifies as inert waste and does not leach under non aggressive conditions. A conservative guideline used for a pH dependence leach test did, however, raise some concerns related to the use of ferrochrome slag at very low pH levels and cautioned against such use, but the study found that beneficial reuse of ferrochrome slag at neutral to acidic pH levels would be safe in terms of leaching potential (Van Niekerk, Oct 2011:10-11). The overall conclusion of the literature review and data analysis confirms that there are no physical or health hazards related to the reuse of ferrochrome slag as aggregate and this conclusion is in line with research findings from Pekka and Kauppi (2007), indicating that there are no health hazards related to the prolonged reuse of ferrochrome slag from the Outokumpu operation in Finland.

The main cost component of aggregate was determined to be transport costs. In order to determine if ferrochrome slag is a financially viable alternative to natural aggregate, an assessment was conducted to determine the distance at which ferrochrome slag could be supplied from a ferrochrome slag smelter, while remaining financially viable to a construction company. In order to break even in terms of aggregate cost, it was determined that the distance from the closest ferrochrome slag supplier should not exceed a distance of 142 km from the construction project. The research study therefore concludes that the distance of a construction project to its nearest ferrochrome slag supplier may be a limiting factor in terms of reusing ferrochrome slag as aggregate in South Africa. These challenges can, however, be overcome by securing cheaper transport such as rail transport or by the implementation of market based instruments such as subsidies for using waste aggregate.

5.4 Recommendations

An international study on Finland's Outokumpu plant showed that minor process modifications are capable of earning ferrochrome slag its status of becoming the preferred aggregate in road construction. Slag from a ferrochrome smelter's metal extraction process can be screened into three sizing specifications (11-22 mm; 4-11 mm and 0-4 mm) and made available to the market. The slag product can also be marketed as an aggregate that complies with a product standard such as the European Standard (EN 13285) used by Outokumpu by the implementation of a sampling strategy to confirm product specifications (Pekka & Kauppi, 2007:171-179).

Some South African ferrochrome operations may require minor modifications to accomplish a particular sizing specification and this may be achieved by modifications such as the installation of additional screens or conveyance systems where required to separate ferrochrome slag size fractions as indicated above. If the ferrochrome industry in South Africa succeeds in earning a similar preferred aggregate status for its slag, the financial benefit of not having to construct a waste facility for the disposal of ferrochrome slag would far outweigh the cost of these minor modifications or the resultant external costs related to the environmental liability of such a waste facility. It is recommended that further research be conducted to quantify the probable financial benefits.

According to the Ontario Environmental Commissioner incentives may very well be able to promote reuse of mineral waste such as ferrochrome slag in which case it would be required to monitor the amounts of waste reused in order to control the awarding of incentives (Environmental Commissioner of Ontario, 2003:31-32). An excellent example of such incentives are referred to in the report by Godfrey *et al.* (2007:15) as market based instruments instead of command and control instruments.

5.5 Suggestions for future research

This is a qualitative study into the benefits of reusing ferrochrome slag as aggregate in South Africa. The study recommends that quantitative and pilot research projects be launched at selected sites to substantiate the qualitative findings made by this research study. It is also recommended that research be conducted into the use of market based instruments that would promote and optimise the reuse of mineral waste such as ferrochrome slag as aggregate in South Africa.

Reference is made to incentives that would act as positive drivers for environmentally responsible decisions like using ferrochrome slag as aggregate instead of natural material by subsidising the use of mineral wastes like ferrochrome slag. Deterrents can in turn be implemented to prevent poor environmental decisions such as extracting natural material for use as aggregate in cases where suitable waste aggregate can be used. An example referenced was the implementation of environmental tax on the extraction of natural material (Godfrey *et al.*, 2007:15).

Should the cooperative governance process referred to in this study succeed, it may result in large scale reuse of ferrochrome slag as aggregate in South Africa. The study therefore recommends that the long term effects of reusing ferrochrome slag as aggregate in South Africa be monitored and assessed.

5.6 Concluding statement

The research study promotes the reuse of ferrochrome slag as waste aggregate in South Africa in that it is a financially viable and environmentally sustainable solution to waste management in South Africa. Recent developments from the regulating authority and industry toward implementing this solution suggest that the long awaited opportunity for reuse may very well realise in the near future. The researcher acknowledges the effort of these entities towards achieving this goal by a cooperative governance process and encourages the completion thereof. The research study hopes to support these efforts by providing further research into the benefits of using ferrochrome slag instead of natural materials in South Africa in order to promote the reuse thereof.

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