AN INVESTIGATION INTO THE FEASIBLE TRANSPORT DISTANCE FOR REPURPOSING CONSTRUCTION RUBBLE IN JOHANNESBURG, SOUTH AFRICA

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering – Civil.

Johannesburg, 2024

DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

……

(Signature of Candidate)

…12th.. day of ……May….., ….2025…

ABSTRACT

The increasing demand for construction materials, fueled by population growth and infrastructure development, presents significant environmental concerns due to the energy-intensive and carbon-intensive processes involved in manufacturing aggregates. The study investigated the viability of recycled aggregates as a mitigation strategy, focusing on the proximal distance for repurposing demolition rubble in the Gauteng region, Johannesburg in particular, to minimize environmental impacts. A mixed-methods approach combining surveys and interviews with demolition contractors, recyclers, and quarries was employed to conduct a comparative material analysis. The results indicated that recycled aggregates incur higher energy costs, carbon dioxide emissions, and manufacturing costs compared to natural aggregates. Subsequently, the study revealed that there is no feasible transport distance for repurposing rubble in the Johannesburg region due to these increased costs. However, the research also discusses unquantified costs associated with quarrying, such as unreclaimable land degradation and ecosystem disruption, which significantly contribute to the overall environmental impact of natural aggregates. This study contributes to the understanding of construction and demolition waste material recycling, emphasizing the importance of considering both economic and environmental factors. The findings will help in informing policymakers, construction industry stakeholders, and environmental managers on the potential benefits and limitations of recycled aggregates in reducing the ecological footprint of construction materials. The research highlighted the necessity of integrating life-cycle assessment and environmental costing into aggregate production encouraging policy incentives for sustainable construction practices.

DEDICATION

This project is dedicated to myself, my family and friends, whose unwavering support and encouragement have been my constant source of strength and inspiration. This research is a testament to your belief in me and the enduring power of perseverance and resilience.

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LIST OF SYMBOLS

Al_2O_3	Aluminium Oxide
C&D	Construction and Demolition
$CaCO_3$	Calcium Oxide
CaO	Calcium Oxide
CO_2	Carbondioxide
D	Transport Distance
Fe_2O_3	Iron Oxide
GHG	Green House Gases
Kg	Kilogram
kg•CO_2	kilogram of Carbondioxide
Km	Kilometre
m^3	Cubic Metre
MJ	Megajoules
N	Sample size
P	p – value
SiO_2	Silicon Oxide
SDG	Sustainable Development Goals
TJ	Terajoules

NOMACLATURE

(Non-standard – For this study, this is how the following terms were used)

Critical Path Method	: A technique used to identify the most efficient transportation route and schedule to minimise costs and environmental impacts.
Limit Transport Distance	: The maximum distance that aggregates can be transported economically and environmentally, beyond which the costs and environmental impacts become high.
Natural Aggregates	: Aggregates extracted from natural sources such as quarries, pits, and rivers.
Recycled Aggregates	: Aggregates derived from the processing of Construction and Demolition (C&D) waste, including concrete and construction rubble.
Recycled Aggregates Concrete	: A type of concrete that uses recycled aggregates (RA) as a partial or complete replacement for natural aggregates (NA).
Rubble Processing Plants	: Facilities that process C&D waste into RA, including crushing, screening, and sorting.
Critical Path	: A transportation route that determines the optimal distance for transporting aggregates.
Feasible Transport Distance	: The maximum distance that recycled aggregates can be transported while remaining economically viable.
Embodied Energy	: The total energy consumed by a material throughout its life cycle (from extraction and processing to transportation and use).

CHAPTER ONE – INTRODUCTION

1.1. Introduction

1.1.1. Background

Infrastructural development is key in accommodating growing populations and ensuring sustainable urbanisation. Investments in infrastructure such as transportation, water supply, building structures and energy systems are essential for improving quality of life and promoting economic growth. Infrastructure that integrates development with sustainability can reduce environmental damage from resource extraction and material transportation while increasing resilience to natural disasters and ensuring long-term material availability. As cities expand, the increased demand for construction materials puts a strain on the resources, exacerbates environmental degradation, and increases waste generated from both construction and demolition projects.

The global population has increased by more than three times since the 20th century, with 9.7 billion people projected in 2050 (de Marsily and Abarca-del-Rio, 2015). Many of the world's poorest countries, predominantly in Sub-Saharan Africa, are experiencing significant population growth (Population Division, 2022). The surge is predominant, particularly in urban areas of these developing countries, where rapid urbanisation is influencing population trends. Urbanisation, the movement of people from rural to urban areas in search of better living opportunities, has led to an increase in the population living in cities. The United Nations (2018) estimates that by 2030, 5 billion people will live in urban areas, with 90% of this growth of 5 billion people occurring in Asia and Africa. The rapid urbanisation puts immense pressure on existing and new urban infrastructure, resources, and services, necessitating sustainable urban planning and development.

South Africa, currently with a population of over 60 million (Maluleke, 2022), experienced significant population growth. Between 2021 and 2026, the Gauteng province in South Africa is expected to have about 1.4 million immigrants, (Maluleke, 2022). It is the smallest province by land area with the highest population density of over 785 people per square kilometre (Alexander, 2017) and a population exceeding 16.1 million, making up 26.6% of the national population (Maluleke, 2022). Both population growth and urbanisation in South Africa have driven the expansion of urban populations and infrastructure development (Luoma, 2016). This includes constructing new buildings and renovating existing structures. Such activities require significant quantities of construction materials like concrete, which is primarily composed of cement, aggregates (both fine and coarse), and water (Ajamu and Ige, 2015). Thus, the demand for these materials continuously rise with population growth and urbanisation (Marinković et al., 2010).

1.1.2. Demand of Construction Material for Infrastructural Development and their Impacts

Concrete is the most commonly used building material in the construction industry due to its versatility, durability, and cost-effectiveness when compared to steel and timber (Vagtholm et al., 2023). It can be moulded into various shapes and sizes, making it suitable for a wide range of construction projects (Van Damme and Houben, 2018). Concrete is also highly durable, withstanding harsh weather conditions, fire, and corrosion, which ensures the longevity of structures (Janev et al., 2023; Adesina and Zhang, 2024). This makes concrete the favourable choice for most infrastructure projects and everyday construction needs.

Concrete constitutes of cement, aggregates (fine and coarse), and water, all mixed together. With an increase in the manufacture and use of concrete, which is driven by both population expansion and urbanisation, the use and consumption of natural aggregates in concrete production

as a constituent is continuously and rapidly rising (Marinković et al., 2010). This predicament raises concerns regarding the future availability of natural aggregate for concrete production as they are non-renewable resources.

The processes involved in the extraction and manufacturing of natural aggregates include mining, drilling, and blasting, which often require the use of explosives (Bascompta, 2022). The ongoing use of natural aggregates has several harmful effects on the environment. Geological erosion, pollution of the air and water, changes in the landscape, noise, and vibration are just a few of the detrimental impacts of resource extraction on the environment (Harte, 2007). In addition, the process of manufacturing natural aggregates affects water and air quality, generates noise and vibrations, and disrupts the landscape (Drew et al., 2002; Careddu and Siotto, 2011; Kuter, 2013).

In addition, due to the continued consumption of natural materials, there is a forecast of material and resource shortages for use by future generations (Harte, 2007). Aggregate quarries are not infinite, mining from this quarries cannot be continued forever, and thus, we consider mining the aggregates from a site further away from the city. The natural aggregates' extraction and processing result in emissions of carbon dioxide (CO_2) (Meddah, 2017), which have an adverse effect on the environment. Given the rising demand for concrete as a construction material, the environmental impact of CO_2 emissions from natural aggregate manufacturing processes poses a growing concern for the construction industry.

Moreover, to supply and manufacture virgin aggregates, transportation of aggregates from one process stage to the next is necessary, as is the transportation of the aggregates to the concrete plants and construction sites. Over long distances of aggregates delivery, the relative contribution of transport to the total carbon emissions rises, increasing the environmental impact and financial costs (Sabâu et al., 2021). The life cycle analysis of natural aggregates carried out by Meddah

(2017), which included their production, transportation, use, and disposal, highlights their overall environmental impacts, as shown in Table 1.1.

Table 1.1: *CO_2 emissions per ton of natural aggregates produced (Meddah, 2017)*

Activity	**Energy source**	**Energy (MJ/ton)**	**Kg•CO_2 e / MJ**	**Kg•CO_2 e / ton**
Quarrying	Fuel oil (NH_4NO_3)	0.05	0.04	0.002
On-site transportation	Diesel	26.41	0.07	1.93
Crushing, sieving and sorting	Electricity	28.80	0.12	3.43
Transportation to the site (50km)	Diesel	38.00	0.07	2.77
TOTAL		93.26	0.31	8.13

Table 1.1 highlights the various activities required to extract natural aggregates and the embodied CO_2 emissions per ton of natural aggregate produced. The use of various none green energy sources such as diesel, fuel oil and electricity power these activities, contributing to the carbon footprint of natural aggregates. The total CO_2 emissions per ton of aggregate production was estimated at 8.1 kilograms. The table also shows the environmental impact of natural aggregates production and highlights the need for sustainable practices to mitigate carbon dioxide emissions, such as using green energy sources, improving energy efficiency and promoting the use of recycled aggregates.

1.1.3. Sustainable measures towards mitigating the negative impacts that arise from the use of construction materials

To mitigate the negative effects that arise from the use of natural aggregates in concrete, sustainable construction materials such as the use of recycled aggregates (RA) have been introduced into concrete production (Chen et al., 2019). Recycled aggregates are produced by recycling concrete waste materials (Visintin et al., 2020). One of the many waste products that can be recycled is waste generated from the demolition of buildings (construction rubble) that have been deserted or have reached their end-of-life. Furthermore, the concrete waste produced during construction of new buildings can also be recycled to produce recycled aggregates (Visintin et al., 2020). Waste from buildings and demolition is increasing globally, thus, the recycling and reuse of construction and demolition waste materials can be an effective waste management strategy (Mistri et al., 2020).

The common technique used to manage construction and demolition (C&D) waste is disposal in landfills. This approach has resulted in tons of C&D waste materials that end up in landfills and occupy significant volume of landfill airspaces (Marinković et al., 2010). Recycling C&D waste is an alternative approach to landfill disposal which can reduce the quantity of C&D waste sent for disposal in landfills and conserve natural resources. This practice of repurposing C&D waste will also relieve pressure on the landfills that are rapidly reaching maximum capacity.

Repurposing C&D waste can also address the future material shortage required for construction materials. This practice is an example of a circular economy. Waste is produced throughout the building and demolition operations. The concept of a circular economy can be combined with that of waste management, resulting in boosting the economy and creating jobs (Sharma et al., 2021).

It is well understood that recycling preserves resources. However, it is debatable whether recycling processes and newer strategies does indeed save energy and financial costs. The production of crushed stone aggregates and the recycling process both require energy. Therefore, it is important to account for this embodied energy when assessing the use of materials for both recycled and natural aggregates. Hence, the question is whether the use of recycled aggregates can reduce both energy use and costs while reducing the negative environmental impact of concrete production.

1.2. Problem Statement

Previous studies have demonstrated the potential benefits of using recycled aggregates in construction, including reduced environmental impacts and cost savings (Ohemeng and Ekolu, 2020). However, the industry's adoption of recycled aggregates remains limited due to concerns regarding their feasibility and sustainability (Zuo et al., 2018). This limitation is particularly concerning given the rapid growth of the construction industry in South Africa, which has led to increased environmental degradation, resource depletion, and substantial greenhouse gas emissions, particularly CO_2, as a result of the extensive use of concrete (Simpeh and Smallwood, 2018). Recent research has highlighted the importance of considering embodied energy, financial costs, and transport logistics when evaluating the use of recycled aggregates (Hameed and Chini, 2010). The geographical distance between demolition sites, recycling plants, and construction sites can significantly impact the cost-effectiveness of recycled aggregates, making them more expensive than natural aggregates in some cases. Furthermore, the environmental benefits of recycled aggregates may be offset by the energy required for transportation and processing. Given the need for sustainable construction practices, it is essential to investigate the environmental,

financial, and logistical aspects of using recycled aggregates in the South African context, Johannesburg. Therefore, this study aims to evaluate the feasibility and sustainability of using recycled aggregates in Johannesburg, with a focus on reducing the industry's carbon footprint and promoting environmentally friendly construction practices.

1.3. Research Significance

The construction industry plays a vital role in the growth and development of South Africa's infrastructure and economy. South Africa is currently experiencing an increase in infrastructure demand brought on by economic and population growth. In addition to the growing population, urbanisation has also led to an increase in infrastructural projects such as the construction of buildings, roads and bridges. Thus, the continued demand for concrete as a construction material used in infrastructural projects results in the depletion of natural raw materials (Habert et al., 2010).

In addition to the exhaustion of natural materials, mining of raw materials and their processing emit greenhouse gases such as CO_2 into the atmosphere, polluting the air and contributing to both climate change and global warming (Ngwepe and Aigbavboa, 2015). Therefore, it is essential to minimise the use of natural materials, in particular, natural aggregates, and adopt the alternative sustainable construction materials, such as recycled aggregates.

The challenge lies in the significant environmental impact of using natural materials for infrastructural developments, which not only depletes these resources but also exacerbates climate change through greenhouse gas emissions. To solve this problem and alleviate the pressure that results from rapid infrastructural developments, principles of the circular economy have been

adopted in place of a linear economy (Godfrey et al., 2021). Concrete waste is recycled and repurposed into concrete aggregates instead of being disposed of in landfills (Batayneh et al., 2007). A study has been conducted on the use of these recycled aggregates in concrete (Hameed and Chini, 2010), where it was concluded that recycling concrete on-site to produce recycled concrete aggregate (RCA) is the most cost-effective and energy-efficient method. Another study compared the costs and benefits of both natural and recycled aggregates. A study conducted in the Gauteng Province by Ohemeng and Ekolu (2020) concluded that recycled aggregates are less costly to produce than natural aggregates; incorporating recycled aggregates (RA) has demonstrated comparable mechanical and durability properties to that made with natural aggregates (NA).

Although the production of recycled aggregates has been found to be less costly than the use of natural aggregates in concrete (Ohemeng and Ekolu, 2020), the distance travelled in transporting construction rubble between demolition sites, landfills, recycling plants, construction sites, and concrete plants is a geographical factor that can make recycled aggregates more costly to use than natural aggregates (Hameed and Chini, 2010). In addition to the issue of financial costs, there are energy costs incurred during the manufacturing and processing stages of both natural and recycled aggregates. Therefore, these aspects need to be investigated to provide a broader understanding of the sustainability and feasibility of using recycled aggregates.

Furthermore, determining the limit transport distance, which can be described as the minimum transport distance for supplying recycled aggregates to construction sites and concrete plants (Marinković et al., 2010), helps in determining the economic distribution of rubble processing units needed within the city. This distribution of processing units can create

opportunities for small, medium, and micro enterprises since there may be a need for more rubble processing units to be established in order to minimise the transport distance and logistics issues associated with transporting recycled aggregates in the city.

In an ideal scenario, where concrete waste is processed on or close to the demolition site, the rubble becomes a suitable supply of recycled aggregates. The closer the processing of waste is to the worksite (concrete plants and construction sites), the less expensive it is, and the less time is required for loading and transportation to and from the site, as well as unloading which not only raises costs but also results in increased CO_2 emissions.

1.4. Scope of the Study

The scope of this study focused on the manufacturing processes of recycled aggregates compared to natural aggregates used in the production of concrete. The financial and environmental costs associated with the extraction, manufacturing, and processing of these aggregates were compared and analysed. Recycling construction and demolition waste is an important component of sustainable waste management, and transportation of waste plays an important role in this process (Ulubeyli et al., 2017). The study was conducted in Gauteng, Johannesburg, using the two aggregate production and supply models (shown in Figure 1.1).

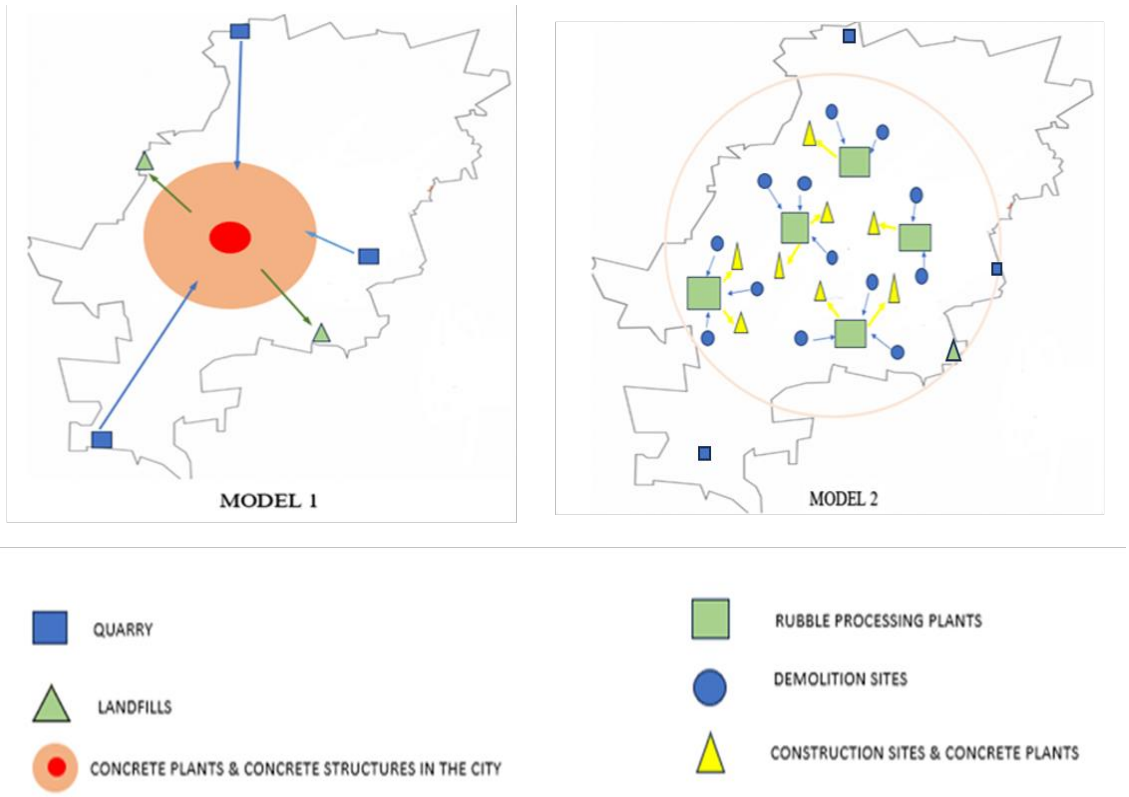


Figure 1.1: *A schematic representation of the Johannesburg map in Gauteng, South Africa, demonstrating the two aggregates supply models of aggregates: Model 1 demonstrates a conventional, linear supply and disposal of aggregates, while Model 2 demonstrates a supply and repurposing of waste.*

Johannesburg is an expanding metropolitan area with a mix of high-rise buildings, industrial areas, and residential areas. The layout and development history of the city play an important role in understanding the transport distance and demand for aggregates. The city's development has been shaped by its history as a mining town, with quarry sites and industrial areas located on the outskirts of the city.

Model 1 shown in Figure 1.1 represents the linear economy of construction materials, where raw materials are extracted, used to manufacture natural aggregates, and get disposed at the

end of their life cycle. In this model, the quarry sites are situated on the outskirts, distant from the major population centers included in the geographical sampling of the study - Johannesburg, a city in Gauteng province, South Africa. The quarry sites extract and produce the natural aggregates (NA), which are then transported to the concrete plants for concrete production and construction sites for concrete use. The model additionally shows the location of the landfill sites, which are also located on the outskirts of the city. These sites receive the construction rubble that gets disposed of from the demolition sites and new construction sites.

Model 2 in Figure 1.1 represents a circular economy model in which materials are repurposed at the end of their life cycle. In Model 2, there are distributed recycling sites that process construction rubble into recycled aggregates. The recycling sites receive rubble from demolition sites or new construction sites in the city. The recycled aggregates are then supplied within the city at an economically feasible distance, as demonstrated in Model 2 in comparison to the distance in Model 1. Both quarry sites and landfills still exist, although smaller volumes both leave the quarry sites and arrive in landfills.

While recycled concrete aggregates offer potential environmental and economic benefits, both of which are explored in this study, their use must be carefully managed to address the associated constraints and challenges. The challenges associated with the use of recycled aggregates in Model 2, which can affect their use in comparison to natural aggregates, are highlighted below:

1. **Environmental Concerns**: Recycled aggregates (RA) reduce natural resource demands and free up landfill space, but their transportation and processing may result in negative

environmental impacts. Thus, the carbon footprints of RA production and transportation should be considered in sustainability assessments.

2. **Economic Considerations**: Recycled concrete aggregates may offer cost saving benefits. However, costs may vary based on market demand and the location of demolition sites, rubble processing units, construction sites, and concrete plants, which also determine the distance required to transport recycled aggregates.

Moreover, the perspective and scope of recycling concrete and demolition waste include environmental evaluation and economic evaluation. As transport is a variable parameter in sustainable waste management, it can significantly impact the economic and environmental viability of recycling construction rubble (Chen et al., 2019). Hence, bi-criteria evaluation, taking into consideration both environmental and economic concerns were conducted in this study.

Transport distances are a key factor in evaluating the economic implications of aggregate supply and use within the construction industry. This study places particular emphasis on transport distance, as it significantly influences both the environmental and economic costs associated with aggregate production. The 20 km limit transport distance (defined as the maximum distance materials can be transported before the costs and environmental impacts outweigh the benefits), identified by Marinković et al. (2010) in their study conducted in Serbia, was adopted as a benchmark for this investigation. While the context of Johannesburg in South Africa differs from Serbia, the principle of minimising transport distance to reduce environmental impact remains relevant. In Johannesburg, the recycling sites (rubble processing units) are distributed as seen in Model 2 and they can supply recycled aggregates within the city at an economically viable

distance. This reduces the need for long-distance transportation and associated environmental costs.

The link between distance and demand is important in understanding the feasibility of recycled aggregates. As demand for aggregates increases, the need for longer transport distances also rises, particularly when construction occurs on the outskirts of the city, leading to increased environmental impact. This study aims to determine the viability of using recycled aggregates to reduce costs and meet demand by limiting transport distances. Considering Johannesburg's urban layout, the study further seeks to provide insights into the potential of recycled aggregates to minimize environmental impact while addressing the needs of a rapidly growing city.

Several paths exist when considering the feasibility of the construction rubble from demolition sites, processing the rubble into recycled aggregates, manufacturing recycled aggregates concrete, and finally using recycled aggregates concrete in infrastructure projects on construction sites (as seen in Figure 1.2). In this study, we employed the critical path method to determine the minimum transport distance for using recycled aggregates. This method was adapted from a previous studies by Tsakiroglou (2002), Ganesh et al. (2021) and Bi et al. (2022), which provided a framework for optimizing transport logistics. Figure 1.2 was created to illustrate this method. The figure, Figure 1.2 is broken down into routes 1- 4 to demonstrate the different possible paths.

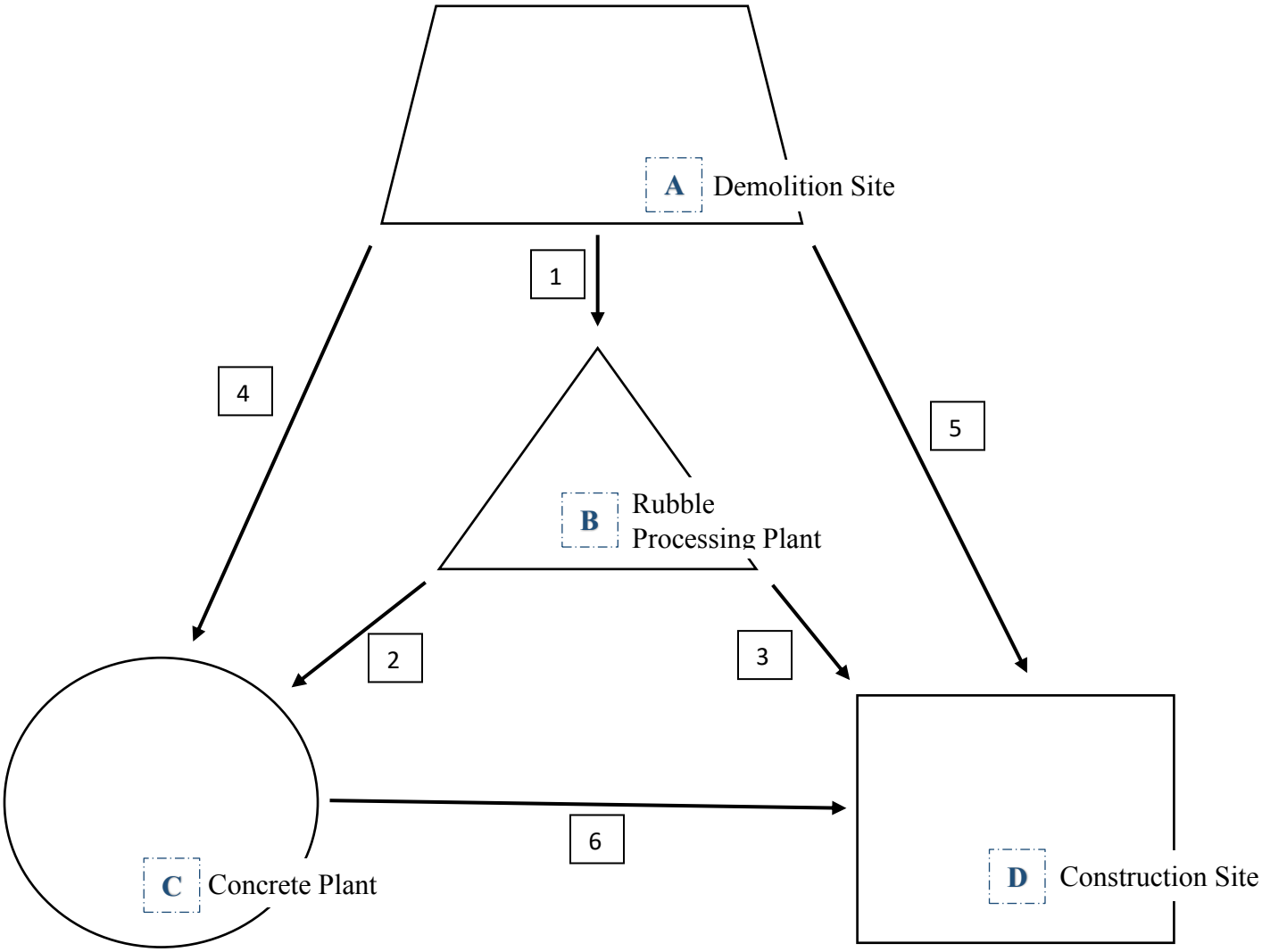


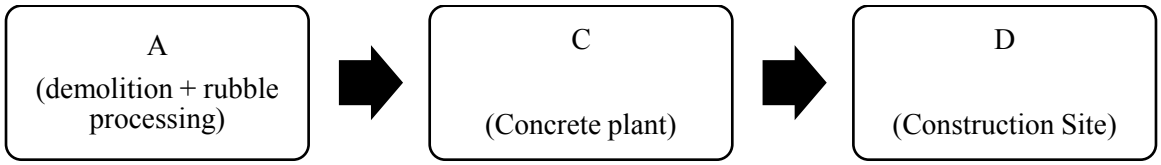
Figure 1.2: *A model illustrating the different distance scenarios that can exist for the supply of RA; from demolition of a building structure to use of demolition waste on a construction site.*

In the context of aggregate transportation, the critical path refers to the transportation routes that determine the minimum costs required to transport recycled aggregates from the demolition

sites to the construction site. The critical path is important in determining the limit transport distance of aggregates, as it takes into account costs (economic and environmental) associated with each transportation route (Ganesh et al., 2021). Hameed and Chini (2010) concluded that the most favourable path is one where demolition, rubble processing, concrete manufacturing, and building construction all take place on one site. This results in minimal transportation of aggregates. The critical path method was used to determine the various alternative routes that can result with respect to determining the feasible transport distance for using recycled aggregates.

Route1

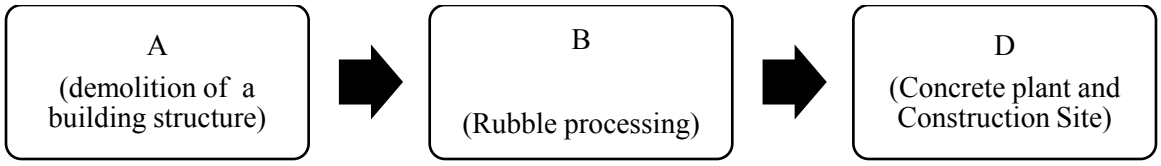
Path (1 – 4 – 6)



- In this route, the building is demolished at the demolition site (**A)**.
- The rubble processing unit is still located at the demolition site **(A)**.
- Upon the processing of rubble into recycled aggregates, the aggregates are then transported to a concrete plant (**C**) located outside the construction site, **(D)** for concrete manufacturing.
- From the concrete plant, the recycled aggregates concrete is transported for use on the construction site.

Route 2

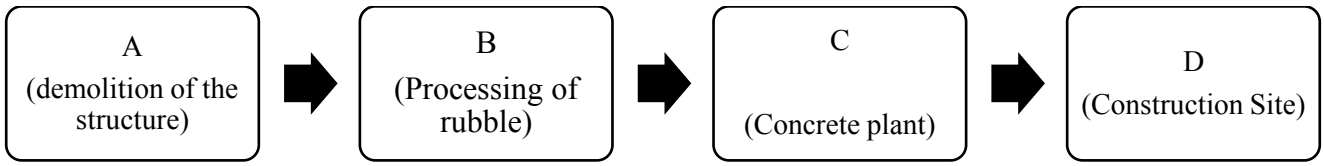
Path (1 – 3)



- In this route, the rubble is not recycled on the demolition site.
- The construction rubble from the demolition site (**A**) is transported to the rubble processing unit at site (**B)** for recycling.
- From the processing unit (**B**) the recycled aggregates are transported to the concrete plant, situated at the construction site in (**D)**.
- The manufactured concrete is then used on the same site in **D**.

Route 3

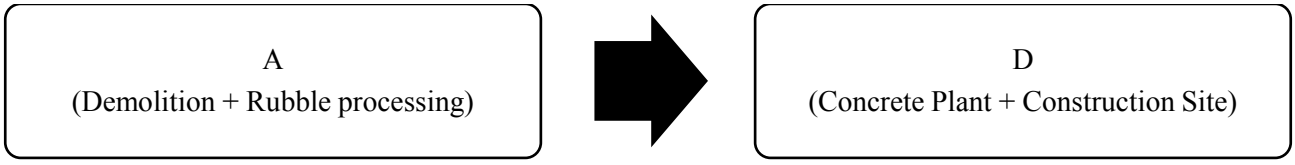
Path (1 – 2 – 6)



- After the demolition of the building, rubble is transported from the demolition site (**A)** to the processing unit in site (**B)**.
- From the processing unit, the recycled aggregates are transported to the concrete plant in (**C)** for concrete manufacturing.
- The concrete from (**C)** is then transported to the construction site in (**D)**.

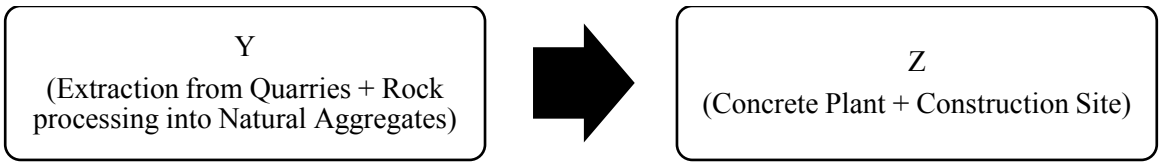
Route 4

Path (5)



- The building is demolished at the demolition site in (**A)**.
- The rubble processing plant is located at the demolition site in (**A),** which eliminates the distance of transporting the construction rubble to a processing plant in (**B)** outside the demolition site.
- Once the construction rubble has been processed into recycled aggregates, they are then transported to the concrete plant, which is situated on the construction site in (**D)**.
- Incorporating a concrete plant on the construction site eliminates the distance of first transporting the recycled aggregates to the concrete plant in (**C)** outside the construction site (**D**) for concrete manufacturing to be used on the construction site.

Multiple transportation routes exist within a city. These routes are influenced by factors such as geographical location and can result in significant difference in the outcomes of feasible transport distances. For the purpose of this study, the focus is on one path, Route 4 of Figure 1.2, which is the transportation of recycled aggregates from the recycling facility, situated at the demolition sites to the concrete plants situated on construction sites. This is the preferred path in this study as it allows for an unbiased comparison between the manufacturing processes of recycled aggregates and natural aggregates, (from site Y to site Z) due to its similarities as indicated below.



By focusing on one specific path, this study may provide a detailed analysis of the critical path and its implications for the limit transport distance of recycled aggregates. This contributes

to the development of more efficient and sustainable aggregate transportation systems, which is critical for the construction industry's transition towards a more circular economy (Yu et al., 2022).

1.5. Aim

This study aims to compare the two aggregate supply models for natural aggregates and recycled aggregates to determine the proximity within which it is feasible to use construction rubble in terms of the associated embodied energy and financial costs in Gauteng, Johannesburg.

1.6. Objectives

In order to achieve the aims, the objectives of the study were to:

- Review the processes involved in both the extraction and processing of raw materials used in the manufacturing of natural aggregates as well as the processes involved in the manufacturing of recycled aggregates.
- Determine both the relative environmental and financial costs for Johannesburg associated with the manufacturing processes of the two models of the aggregates production for both natural and recycled aggregates.
- Determine the amount of energy required to extract natural resources, process, and manufacture both natural and recycled aggregates.
- Determine the costs that are associated with the transportation of both aggregate categories to construction sites and concrete sites.
- Determine the economic distribution of recycling sites in Johannesburg with respect to distance.

1.7. Hypothesis

The sustainable aggregate production supply approach is the one presented in Model 2 of Figure 1.1. In Johannesburg, it is feasible to demolition rubble, recycle it into aggregates on the demolition site and supply it to construction sites and concrete plants within a 20 km radius of recycling sites.

1.8. Research Questions

1. What are the processes involved in the manufacturing of conventional aggregates and the repurposing of construction waste as aggregates in Johannesburg?
2. What are the costs associated with the use of each material category, natural and recycled aggregates, in Johannesburg, Gauteng?
3. What is the distance at which the costs of repurposing construction rubble exceed the costs of extracting and using natural materials in Johannesburg, Gauteng?
4. What substances get emitted into the atmosphere during the aggregates production processes, and in what quantities in Johannesburg, Gauteng?
5. What is the economic distribution of recycling sites that make it feasible transport distance for repurposing construction rubble in Johannesburg?

1.9. Outline of the Report

Chapter One – introduces the research study by highlighting the critical need for sustainability in infrastructural development in Southern Africa in particular, South Africa. With global population growth and urbanisation driving increased demand for infrastructure, the chapter explores the environmental impacts and the use of recycled aggregates as mitigation strategies. It also discusses the research's significance, scope, aim, objectives, hypotheses, questions, and limitations.

Chapter Two – The chapter reviews traditional construction materials and the standard manufacturing process of concrete. One of the constituents of concrete, natural aggregates, that are used in the manufacturing of concrete are reviewed as well as how they are manufactured and the environmental impacts. The chapter goes on to review circular economy and waste management in the construction industry. The construction and demolition potential of concrete waste to be reused and processed into recycled aggregates is reviewed, this covered both the processes and costs involved.

Chapter Three – The chapter details the methodology employed in the study. It describes the approach used to collect data using questionnaires, including the tools and methods utilised. The chapter describes the types of the participants involved in the research, detailing their demographics and geographic origins. Lastly, it provides a clear overview of how the study was conducted, including ethical concerns of the research process.

Chapter Four – This chapter presents the results and findings of the study. It begins by outlining the manufacturing processes involved in manufacturing natural and recycled aggregates. The chapter illustrates the embodied energy of two aggregate types, which covers energy consumption and emissions throughout production stages. It also analyses the financial costs associated with manufacturing both natural and recycled aggregates, offering insights into economic implications. Moreover, the chapter includes an analysis of the transport distances required for supplying these aggregates.

Chapter Five – In this chapter, the objectives of the study are reviewed together with hypothesis. Additionally, implications of the study have been outlined. The limitations of the study

have been acknowledged, providing recommendations for further research and improvement.

CHAPTER TWO – LITERATURE REVIEW

2.1. Overview

The construction industry plays an important role in shaping the built environment, influencing economic development, and contributing to the overall well-being of a nation (Khan and McNally, 2023). This literature review explores four key themes: conventional construction practices, sustainability, the circular economy, and waste management of construction materials. A review of these themes served as a foundation for this research project.

The chapter covers the following:

- The conventional construction Industry in South Africa
- Sustainability in the South African Construction Industry: Navigating Challenges for a Greener Future
- Circular Economy in South Africa
- Waste Management in South Africa

2.2. Conventional Construction of Buildings

2.2.1. Overview

Traditional construction methods and materials have influenced the development of building structures throughout history, and some of these methods are still in use today (Muazu and Alibaba, 2017). Regardless of their continued use, there is pressure for continued research on new methods and materials due to challenges experienced with current technologies. The continued research uncovers new developments for innovative and sustainable design (Sierra-Perez et al., 2016). To appreciate the developments in today's construction industry, an understanding of how traditional building techniques have evolved is essential. Masonry techniques are one of the oldest building techniques and are widely used in modern industries due

to its simplicity (Lourenço, 2014). It involves laying stone, bricks, or blocks on top of each other, a technique that has been successfully used since ancient times (Almusaed and Almssad, 2018).

Both ancient and modern societies have used stone, a widely abundant raw material, for building construction, particularly in stone masonry (Ngowi, 1999). In recent times, there has been a shift towards brick masonry, where concrete and cement bricks are now commonly used. These bricks are produced using concrete and cement, and rely on limestone as a primary raw material of cement manufacturing (Marinković et al., 2010). On the other hand, clay, another building material was often used for brick manufacturing, especially when stone was scarce. This stone scarcity prompted the development of brick moulding techniques, which resemble the modern practice of casting concrete into brick moulds for construction purposes (Li et al., 2022). However, there was a decline in masonry as a structural material, which began in the 20th century with the introduction of concrete structures (Lourenço, 2014).

2.2.2. How Concrete Is Traditionally Manufactured

Concrete is the most commonly used construction material worldwide due to its affordability, durability and ease of use (Marinković, 2010). Concrete, composed of water, coarse aggregates such as stone, fine aggregates such as sand, and cement, has various applications (Mundra et al., 2021). It can be seen in walls, roofing, floor plans, foundations, and various other structural components of construction projects (Krishna et al., 2016). Concrete's main constituent, cement, is crucial because it acts as the primary binder, giving concrete its strength, durability, and ability to set and harden over time (Khalaf et al., 2019).

Cement is a fine powdered material with adhesive properties that acts as the binder in concrete. In 1824, one of the types of cement, Portland Cement (PC), received a patent in England and has been used since 1892 in South Africa. Cement is primarily made from lime (CaO), which is derived from the decomposition of limestone ($CaCO_3$). In addition to lime, other key components such as aluminum oxide (Al_2O_3), silica (SiO_2), and iron oxide (Fe_2O_3), are also essential in the manufacturing process (Owens, 2013). The manufacturing processes of cement as seen in Figure 2.1 below and the traditional materials used in the process (coal, for example, used as fuel) emit large quantities of carbon dioxide and increase the carbon footprint, negatively impacting the environment (Mohamad et al., 2022).

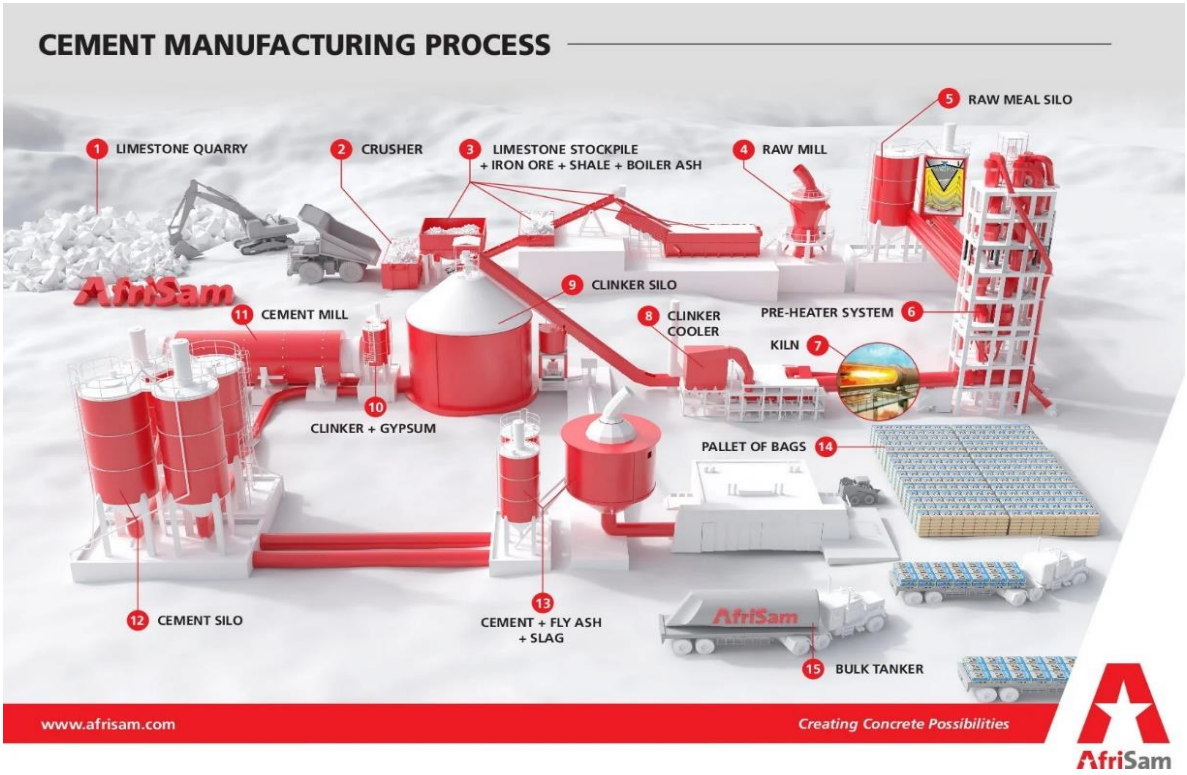


Figure 2.1: *The process of manufacturing cement (https://www.afrisam.co.za/manufacturing-process/).*

In addition to cement, aggregates such as sand, gravel, and crushed stones play a crucial role in concrete production. Aggregates can be grouped into two types, as fine aggregates (sand) and coarse aggregates (gravel or crushed stone). Fine aggregates fill the gaps between the larger particles, reducing the cement requirement, while coarse aggregates provide the concrete with its strength and durability. The Department of Mineral Resources (2014) emphasised the need for aggregates to be of good quality, consistent, cost-effective, and to ensure long-term supply assurance for the construction sector.

2.2.3. Natural Aggregates and their Manufacturing Processes

Aggregates have traditionally been widely used in concrete due to their strength, ease to process, and cost, which lead to an intense demand for aggregates, thus putting pressure on the resources for construction materials. Aggregates are manufactured by first extracting the raw materials as seen in Figure 2.2 below. The extraction processes involve drilling, blasting, and mining bedrock from an open-pit quarry in the South African context (Gbeve, 2013). Drilling explores the surface rock formations, while blasting breaks the rock into pieces suitable for crushing. The blasted material can be extracted using conventional earth-moving equipment and then processed into natural aggregates by crushing and screening (see Figure 2.2).

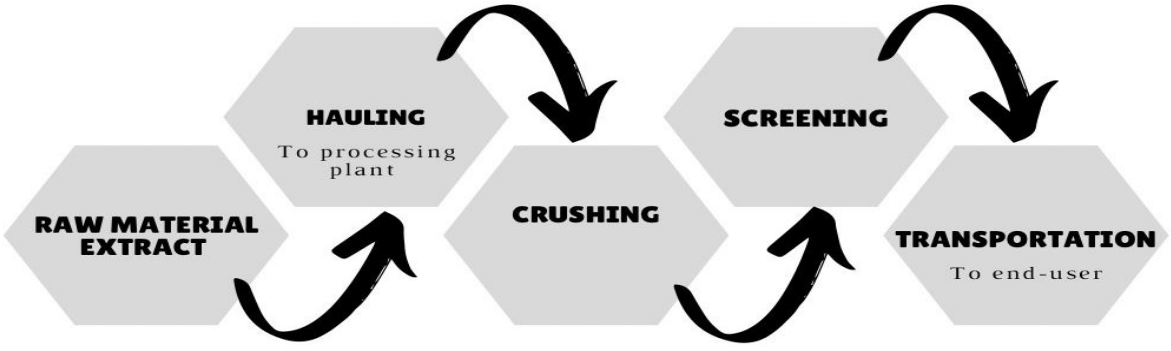


Figure 2.2: *The process of manufacturing natural aggregates.*

The mining of resources involves large pits and quarries, which are often in operation for about 50 years. Coarse aggregates and fine aggregates are manufactured from rocks such as granite, basalt, sand and dust. In the context of South Africa, coarse aggregates are mined from open pit quarries. Coarse aggregates are then further crushed and screened to produce fine aggregates as shown in Figure 2.2. The intense demand for aggregates has led to the depletion of locally accessible resources from quarries that are situated on the outskirts of cities and towns, necessitating the exploration of new sources and quarries farther away, resulting in increased transportation costs to supply the aggregates (Department of Mineral Resources, 2014).

Drilling and blasting are used during the initial quarry process, and the mined rock is then removed by the use of earthmoving equipment such as bulldozers. Mined rock is then sent to a processing plant, where it undergoes several crushing and sizing phases which breaks large rocks into different aggregate sizes (Guimaraes et al., 2007). To ensure that concrete with required fresh and hardened properties is attained, aggregates must be durable, hard, chemically inert, and clean (Muhit et al., 2013).

Fine aggregates, on the other hand, can be found naturally and can also be manufactured (Abu Seif, 2014; Premanand et al., 2023). Natural sand is composed of grains that form as a result of the chemical and/or physical weathering of rocks (Hack, 2020). Alluvial, wind-blown, and beach sands are examples of natural sands. Rocks and gravel are mechanically crushed to produce manufactured sand (Wembe, 2023). Natural sand is often extracted using earthmoving machinery, and the amount of processing required typically depends on the grade of sand and its intended application.

Due to engineering activities involved in the aggregate extraction and manufacturing, it can be seen that quarrying causes severe environmental damage. The most visible effects are a conversion in land use and a shift in geomorphology, together with corresponding changes in the surrounding environment. Other effects, as previously noted, include habitat loss, erosion, dust, vibration, noise, and abandonment of the mined site (Willis and Garrod, 1999).

2.2.4. Environmental Impacts of the Natural Aggregates Manufacturing Processes

The process of manufacturing natural aggregates is energy-intensive, it relies on fuel sources like diesel and electricity (Ozcelik, 2018; Igogo et al., 2021). Diesel engines power heavy machinery used in extracting, processing, and transporting natural aggregates, while electricity is used to operate crushers, screens, and conveyors in aggregate processing plants (Klanfar et al., 2016).

The machines used in the manufacturing processes of aggregates consume large amounts of energy. In addition, the combustion of diesel and electricity generation releases carbon dioxide (CO_2) emissions and other greenhouse gases into the atmosphere, exacerbating climate change (Eldesouki et al., 2023). Although diesel consumption has been linked to environmental issues, including greenhouse gases and nitrogen oxides, contributing to air pollution and climate change (Perera, 2017), it is an essential fossil fuel in the aggregate industry as it enables a smooth operation of various activities such as transportation of aggregates in quarries. Transportation of aggregate to consumers can increase the negative impacts associated with the supply of aggregates, as most trucks use diesel. (Bortoli, 2023).

Additionally, electric-powered equipment like crushers, screens, and conveyors are becoming more common due to technological advancements and environmental concerns. Research shows the potential benefits of electrification, produced from clean sources such as uranium, include lower greenhouse gas emissions, reduced operational costs, and increased energy efficiency (Schoeneberger et al., 2022). However, the challenge lies in finding a solution that meets the increasing demand for aggregates while minimising the environmental impact of the aggregate production process.

In an attempt to address the negative environmental impact, method used to assess and quantify the environmental impacts of aggregates production is the life cycle assessment (LCA). The impact assessment methods consider different environmental impact assessment elements such greenhouse gas emissions, global warming potential, pollution and air quality to name a few. The most important aspects that are related to the carbon footprint and embodied energy are the energy use and greenhouse gas emissions. The life cycle assessment has been investigated in some studies to measure the impact of aggregates on the environment. This can be seen in study of Dias et al. (2022) where the environmental impacts of various types of aggregates was compared to understand the relationship between Global Warming Potential (GWP) and energy use. Another study by Braga et al. (2017) conducted an LCA of aggregates in Portuguese to compare the environmental and economic impacts of natural and recycled aggregates. In this study inputs and outputs values of the life cycle phases for coarse aggregates were collected as seen in the Figure 2.3.

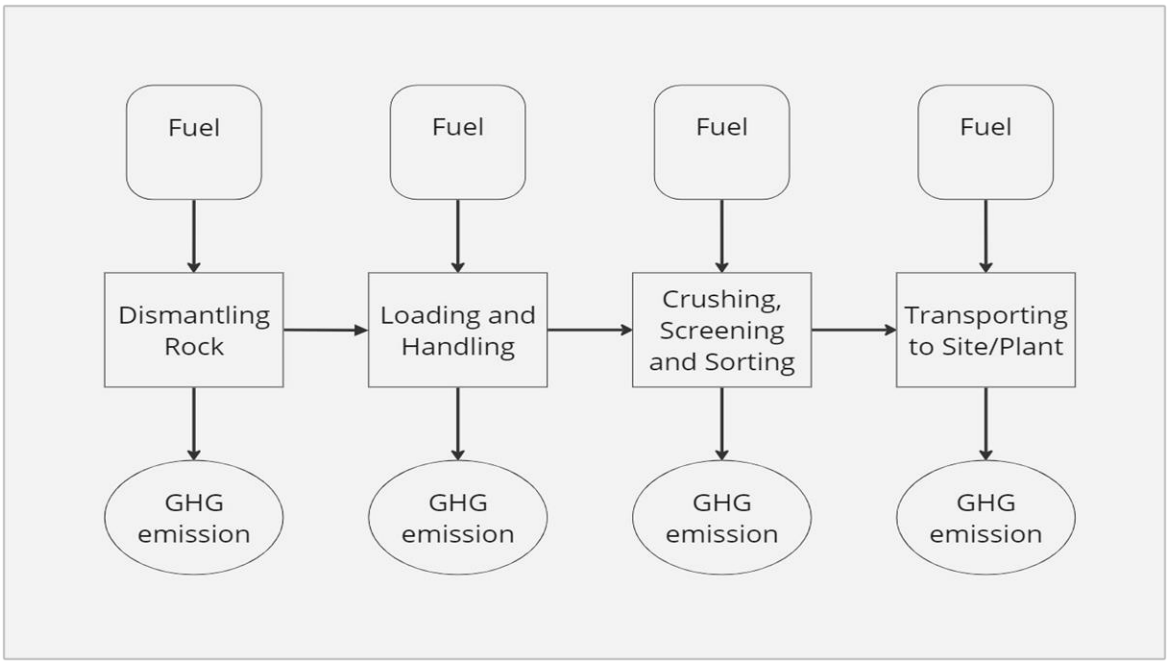


Figure 2.3: *The Life Cycle Assessment of Natural Aggregates, a method used to assess the environmental impact of manufacturing natural aggregates (Braga et al., 2017).*

When comparing the overall inputs (fuel consumption) and outputs (greenhouse gas emissions) of manufacturing natural aggregates against processing recycled aggregates, the study by Braga et al. (2017) concluded that the environmental impact of natural aggregates is greater than the environmental impact of recycled aggregates.

2.3. Sustainability

2.3.1. Sustainable Construction Materials

Sustainable development has been defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Verma, 2019). The definition of sustainable development was revised in 2006, highlighting “a long-term vision for sustainability in which economic growth, social cohesion, and environmental protection

are mutually supportive" (Mavi et al., 2021). The construction industry needs to take measures to enhance the social, economic, and environmental sustainability. By using life cycle assessment (LCA), it is possible to quantify and maximise the three aspects (social, economic and environmental) (Ortiz et al., 2009). Sustainability serves as an effective instrument for economic and activity decision-making since it has an ability to integrate social and environmental factors.

The goal of sustainability is to achieve an equilibrium where environmental benefits for the public are promoted while competitive advantages and financial gains for construction enterprises are pursued (Hossain et al., 2020). The economic pillar of sustainability encompasses short-term costs and construction time as well as the long-term financial viability of the project (Mavi et al., 2021). It is important to consider the overall impact on the economy and ensure that resources are being used efficiently. Addressing sustainability issues requires considering all three pillars: environmental, economic, and social factors. Implementing sustainable construction concepts leads to high-performance green buildings, promoting sustainable built environments.

Furthermore, construction projects are increasingly prioritising environmental-friendly techniques through the adoption of sustainable building practices and materials (Florez et al., 2013). The choice of construction materials significantly contribute to the carbon footprint of the construction industry, with the production, transportation, and disposal of these materials leading to emissions, energy consumption, habitat destruction, and resource depletion (Serdar and Bjegovic, 2019). Thus, it is evident that the selection and reuse of materials plays a crucial role in meeting sustainability goals.

A sustainable material is generally one that minimises the negative environmental impact throughout its lifecycle while being both cost efficient and cost efficient (Ljungberg, 2007). In

their study, Damman and Elle (2006) defined sustainable materials as materials that are simple to construct with and use fewer resources during production, delivery, and erection. On the other hand, Glavic and Lukman (2007) defined them as materials produced using non-polluting processes and systems that conserve energy and natural resources in ways that are commercially feasible, safe, and healthy for consumers.

The triple bottom line and life-cycle assessment are used to assess the performance of sustainable materials, which are expected to be economically, environmentally, and socially beneficial (Abeysundara et al., 2009; Ljungberg, 2007). As the construction industry has come to understand, sustainable buildings have the potential to reduce environmental impact and provide substantial social and environmental benefits (Florez et al., 2013). However, in order to realise these benefits, it is necessary to choose construction materials that adhere to sustainability principles.

The most sustainable building materials are those that are cost-efficient and have less embodied energy. These materials are good for the economy since they reduce expenses associated with operations, consumption, and maintenance (Ghisellini et al., 2018). An example of a construction material that can be made more sustainable is concrete. This can be achieved by substituting constituents of concrete. Therefore, factors such as quantity of the substitute material, production processes, final product performance, and their impacts on the environment, economy, and people determine the sustainability of concrete (Nilimaa, 2023).

Several studies support this claim; a study on the reuse of glass and clay brick waste as a substitute for natural aggregate in green concrete found that incorporating recycled waste materials

led to reduced energy consumption. This approach aids in environmental preservation and the conservation of natural resources by reducing the need for virgin materials (Olofinnade et al., 2019).The strength of the paving bricks improved with the addition of waste glass sand, meeting the requirements for compressive strength. These bricks demonstrated that recycled glass can perform comparably to, or even better than, natural aggregates in certain applications.

Another research study investigated the performance of green concrete paving blocks integrated with industrial scrap steel mill scale for sustainable construction. The study highlighted the reduction of energy consumption during production and the eco-friendly nature of using industrial waste materials in concrete (Parvathikumar et al., 2023).

Another study considered the production of concrete shellfish waste powder and rice husk ash as substitute materials for cement and fine aggregate, respectively. This study demonstrated that these materials can be a solution to replace some cement and fine aggregate, leading to the development of environmentally friendly concrete with high strength and workability (Arumningsih et al., 2022). Similarly, in another study, concrete with wheat straw ash and silica fume as cement substitutes was evaluated and it was demonstrated that these materials can lead to the production of high-performance and sustainable concrete with reduced global warming potential (Khan et al., 2022). These studies provide evidence that the incorporation of substitute materials into concrete production can have positive effects on the environment by reducing the carbon emissions, energy consumption, and the depletion of natural resources. These substitute materials contribute to the development of environmentally friendly concrete with a reduced global warming potential (Althoey et al., 2023).

2.3.2. Sustainability in the South African Construction Industry

The construction industry is responsible for severe environmental damage through waste generation, energy and water depletion, and other harmful practices. In response to these issues, experts and environmentalists have called for the adoption of sustainable construction practices (Dosumu and Aigbavboa, 2019). Sustainable construction practices aim to minimise the negative impact on the environment by using renewable materials, reducing waste, and implementing energy-efficient designs. This includes the use of eco-friendly building materials such as recycled aggregates concrete (RAC) and sustainable steel (Wang et al., 2023). By adopting sustainable construction practices, the industry can play a crucial role in mitigating environmental damage and moving towards a more sustainable future (Mfon and Bassey, 2023).

As mentioned before, in South Africa, the construction sector heavily relies on conventional construction materials like cement, steel, and bricks, which not only have high carbon emissions during production but also require extensive extraction of raw materials (van Wyk, 2017; Labaran et al., 2021). Sustainable alternatives, such as recycled aggregates, low-carbon cement, and locally sourced materials, can reduce the environmental impact that is associated with construction activities (Orhon and Altin, 2019). By using recycled aggregates, construction projects can reduce the need for extracting natural resources, thereby minimising habitat destruction and preserving the natural environment (Ogundairo et al., 2019). Low-carbon cement, on the other hand, emits fewer greenhouse gases during production, helping to curb global warming (Barbhuiya et al, 2024). Lastly, sourcing materials locally reduces both energy consumption and transportation emissions, making it a more sustainable option overall. The implementation of these alternatives in the South African construction sector as they have been in

Hong Kong can significantly contribute to reducing its environmental impact and promoting a greener future (Ogundairo et al., 2019).

One of the primary challenges hindering the adoption of sustainable construction practices in South Africa is the perceived additional cost of using sustainable materials (Unni and Anjali, 2022; Sundayi et al., 2015). Conventional construction materials may appear cheaper upfront as their life-cycle costs do not consider the long-term effects of environmental degradation (Kats, 2013). Despite potential higher initial costs, sustainable construction materials can offer cost savings over a building's lifespan. Thus, a comprehensive cost-benefit analysis that incorporates life cycle costs and environmental externalities should be conducted to demonstrate the long-term advantages of adopting the use of sustainable materials (Unni and Anjali, 2022).

By conducting a comprehensive cost-benefit analysis that includes life cycle costs and environmental externalities, decision-makers can make more informed choices about sustainable materials (Kats, 2013; Unni and Anjali, 2022). This analysis will highlight the potential long-term financial advantages of investing in sustainable alternatives (Reddy, 2016). Therefore, it is essential to consider multiple aspects when evaluating the benefits of using sustainable materials (Sundayi et al., 2015).

2.4. Circular Economy in the Construction Industry

2.4.1. Overview

A circular economy is a restorative, closed ring that minimises resource utilisation, emissions, waste, as well as energy loss (Akhimien et al., 2021). The circular economy aims to supersede the conventional "take-make-dispose" linear paradigm with a regenerative strategy that

prioritises resource conservation, waste minimisation, and prolonged material life. Circular economy includes techniques like remanufacturing and repurposing waste material with the goal of building a stronger and resilient economy. The transition away from linear economic models of production, use, and disposal can be made possible through restoration, reprocessing, reusing, and recycling (Neves and Marques, 2022). This shift towards a circular economy is seen as crucial for achieving long-term environmental sustainability and reducing the strain on limited resources (Neves and Marques, 2022). Through sustainable materials, increased recovery of materials, and decreased waste production, the circular economy seeks to increase material efficiency (Hossain et al., 2020).

Furthermore, rethinking a building or infrastructure project's complete life cycle is necessary when implementing circular economy ideas in the construction sector (Gamage et al., 2024). Designing for ease of disassembly and material recovery at end of life is the first step in this process. Recyclability, durability, and reuse potential should be taken into consideration when choosing materials and products (Ogunmakinde et al., 2022; Ogunmakinde et al., 2022). Effective material management, sorting on-site, and appropriate recycling and repurposing methods may ideally contribute to minimising construction waste (Mhlanga et al., 2024).

2.4.2. Circular economy in the South African construction industry

The construction sector in South Africa stands to gain a great deal from the implementation of circular economy principles which can help lessen the extraction of resources, produce less waste, and save costs (Govender et al., 2023). The industry can boost employment growth, open up new commercial prospects, and improve the nation's reputation for sustainability by adopting circularity. The shift to a circular economy coincides with South Africa's National Development Plan and Sustainable Development Goals (SDGs) (Mhlanga et al., 2024).

There are numerous possibilities in South Africa for the building sector to successfully apply circular economy concepts (Hoosain et al., 2023). The country has an abundance of secondary resources that are suitable for use in construction activities. This encompasses the potential of upcycling waste resources, for example, using crushed concrete or crushed bricks to build new roads or turning plastic waste into material for construction (Qian et al., 2024; Ren, et al., 2024). Working together, government agencies, academic institutions, and industry players may help identify and capitalise upon these chances to adopt the circular economy. The South African government has initiated measures to facilitate the shift towards a circular economy. A framework of policies to sustainability is provided by the Integrated Resource Plan and the National Waste Management Strategy (Adeleke et al., 2021; Mhlanga et al., 2024).

The National Waste Management Strategy (NWMS) and the Renewable Energy Independent Power Producer Program (REIPPP) are two examples of government efforts designed to promote sustainable practices in the building sector (Mhlanga et al., 2024). The NWMS and REIPPPP are key initiatives in South Africa that promote sustainable building and construction practices. The NWMS focuses on reducing waste generation and promoting recycling, encouraging the use of recycled materials and green building practices. The REIPPPP encourages the integration of renewable energy sources into building designs, reducing the carbon footprint of construction projects and supporting energy-efficient, green-certified buildings. These programs help reduce the environmental impact of the construction industry, promote sustainable materials, and align South Africa with global sustainability goals. There is still need for initiatives that promote sustainable construction practices. As the construction industry continues to grow, it is

crucial for the country to prioritise sustainability in order to protect natural resources and combat climate change.

2.5. Waste Management in the South African Construction Industry

2.5.1. Overview

Construction materials are one of the significant contributors to the generation of waste in the construction industry (Western Cape Government, 2018; Kohler et al., 2022). Between 5 million and 8 million tonnes of construction waste are produced annually in South Africa, most of which is dumped in landfills, with very little of it being reused or recycled (Fitchett and Rambuwani, 2022). Construction and Demolition (C&D) waste excludes hazardous waste and is produced during the construction activities, refurbishing, and collapse of structures such as buildings, roads, and bridges (Berge and Blottnitz, 2022). Concrete, wood (from buildings), asphalt (from roads and roofing shingles), gypsum (the main component of drywall), metals, bricks, glass, plastics, salvaged building components (doors, windows, and plumbing fixtures), trees, stumps, earth, and rock from clearing sites are examples of C&D waste.

2.5.2. Demolition of Structures – A Source of Construction and Demolition Waste

The demolition of buildings and structures can be approached using two methods, conventional and selective demolition. Conventional demolition involves the dismantling of a structure, often using heavy machinery (such as excavators) and explosives. In contrast, selective demolition is a careful removal and separation of materials for reuse or recycling. Research has shown that selective demolition can be more cost-effective than conventional methods (Coelho and de Brito, 2011). This method enables the recovery of high-quality materials, such as steel, concrete, bricks, wooden beams and steel reinforcing bars, which can be reused or recycled.

The success of selective demolition pivots on effective sorting during demolition operations, minimising contamination and yielding high-quality reclaimed materials. Studies have demonstrated that selective demolition can significantly reduce environmental impacts, including climate change, when executed thoroughly (Silva et al., 2017). However, partial selective demolition may slightly increase environmental impacts due to extended transportation distances.

It is essential to understand the evolving nature of the demolition industry. Advances in building design, plant design, health and safety, as well as regulatory requirements have transformed the industry from labour-intensive to machine processes (Silva et al., 2016). This shift portrays the need for efficient and sustainable demolition methods, such as selective demolition, to minimise environmental impacts and maximise material recovery.

Demolition of structures offers an enormous potential supply of solid waste and construction rubble for recycling, repurposing, and reuse (Sormunen and Kärki, 2019). Recycling construction rubble as C&D waste helps to conserve the natural resources that are used to manufacture the construction materials (Alsheyab, 2022). They do so at a transportation cost that is cost-effective since quarry sites may be situated at greater distances than demolition sites, which are situated in cities and towns (Hameed and Chini, 2010). The practice of recycling and reusing construction rubble leads to the overall cost savings for construction companies by reducing the need to purchase new construction materials, thus reducing the demand and production of new construction materials.

In addition to a decreased demand, recycling construction rubble increases airspaces and the lifespan of existing landfills. In some drop-off locations in the city of Cape Town, the disposal

of clean rubble is free up to a certain weight (Haywood et al., 2021). While in the city of Johannesburg, according to PIKITUP, construction rubble can be disposed of at no cost in some of their landfills dedicated to reusing such waste. This initiative is a measure to combat illegal dumping (PIKITUP, N.D.). It also motivates drop-offs of clean rubble at recycling centres as opposed to dropping it off in landfills, which have disposal costs.

2.5.3. Application and Uses of Construction Rubble – Recycled Concrete Aggregates

The use of building rubble collected from damaged and demolished structures reduce waste and conserves natural resources (Tabak, 2023). One application of building rubble is the use of broken bricks and concrete from the demolition of structures (rubble) as aggregates in concrete production (Thomsen et al., 2011). This application is one of many ways to solve and mitigate the negative impacts that result from the use of concrete, such as carbon emissions and the depletion of natural resources.

It is important to note that natural aggregates in concrete can be substituted with construction rubble that has been processed into recycled aggregates (Rao et al., 2007). However, construction rubble requires cleaning, crushing, and screening before it can serve as recycled aggregate in concrete (Zhang et al., 2019a).

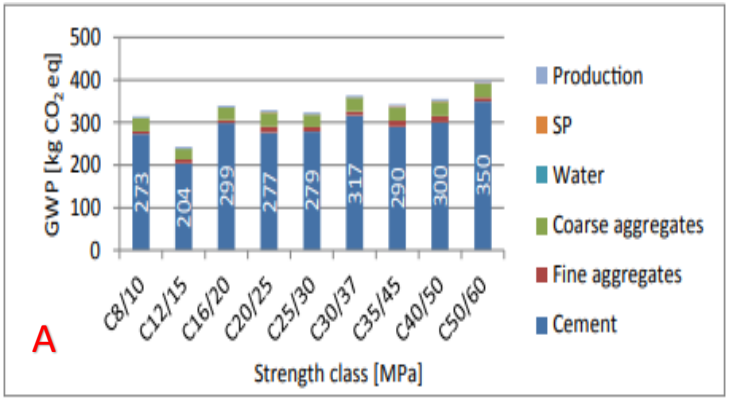
The use of recycled aggregates in concrete has been increasing (Nedeljković et al., 2021), thus, increasing the demand for recycling facilities. The establishment of recycling units is currently limited and to meet the increasing demand, there is a need for more recycling facilities within economic proximity (Kenzhegaliyeva and Lund, 2024). In addition to their use in concrete, the application of these aggregates is seen structurally in masonry load-bearing structures, where

they are used structurally in load-bearing structures and retaining walls (Prajapati et al., 2023). Like natural aggregates, the energy used to manufacture (crushing) these aggregates and the total costs incurred, which include transportation costs, are crucial factors in determining both their economic and environmental viability.

Figure 2.4 and figure 2.5 below show the environmental and economic impact (Braga et al., 2017) while the table shows the performance of concrete with recycled aggregates from different studies (Wang et al, 2023).

Table 2.1: *Results from different studies for performance of concrete that has been manufactured from recycled aggregate (Wang et al., 2023).*

Year and Source	Water Absorption (%)	Compressive strength (MPa)	Slump (mm)
Fernandes et al. (2023)	5.06	32.6	180
Sajan et al. (2022)	4.00	25.5–27.8	76–84
Fernandes et al. (2022)	4.52	39.7–44.8	174–210
Liu et al. (2021)	3.02	30.7–38.1	40–66
Alqarni et al. (2021)	8.21	16.1–34.2	84–140



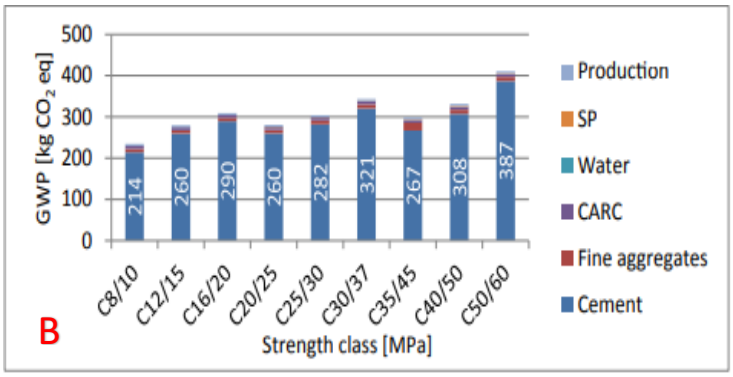
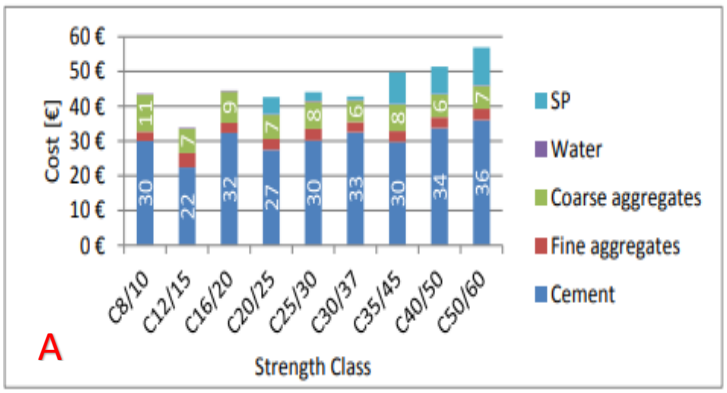


Figure 2.4: *The comparison of the Global Warming Potential (GWP) of concrete (1m^3) manufacturing when recycled aggregates have been incorporated, in **B** and when natural aggregates were used to manufacture concrete in **A** (Braga et al., 2017).*

GWP – Global Warming Potential, SP – Superplasticizers, CARC – Coarse aggregates recycled from concrete



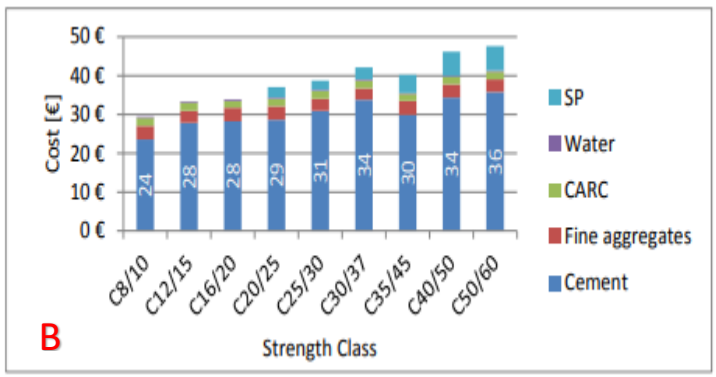


Figure 2.5: *The comparison of the costs of raw materials used in concrete (1m^3) manufacturing of when recycled aggregates have been incorporated, in **B** and when natural aggregates were used to manufacture concrete in **A** (Braga et al., 2017).*

GWP – Global Warming Potential, SP – Superplasticizers, CARC – Coarse aggregates recycled from concrete.

2.5.4. Processing Recycled Aggregates

Plants that recycle demolition waste (construction rubble) have similarities and differences with those that manufacture natural aggregates from quarries. In order to produce granular material of different sizes, they make use of crushers, screens, transfer tools, and systems for eliminating impurities (Silva et al., 2016). Contaminants are a concerning issue in the recycling industry, and the process of removing them lengthens the manufacturing processes of recycled aggregates (Silva et al., 2017). To produce high-quality aggregates, it is necessary to take the time and effort to stockpile, crush, pre-size, sort, screen, and eliminate contaminants (Zeghioud et al., 2022).

The ultimate goal is to produce recycled materials that meet or exceed industry standards while minimising waste, costs, and the environmental impact. This has been achieved in recycling plants like the Centre for Regenerative Design and Collaboration (CRDC) in Cape Town, South Africa or on the demolition site in cases where mobile plants are available on demolition sites. The CRDC is an organisation that transforms waste (plastic) materials into high-value, sustainable materials. Recycling of materials has also been successfully implemented in various parts of the world, including India, where innovative recycling practices are gaining traction to manage construction and demolition waste effectively.

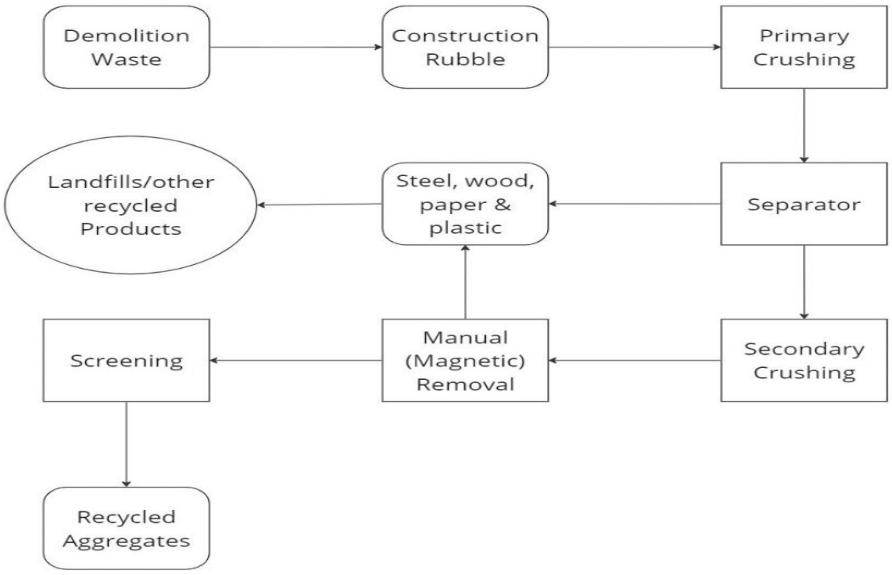


Figure 2.6: *The process of manufacturing recycled aggregates (S.Arora and S.Arora, 2015).*

Figure 2.6 above represents the processes followed in processing the construction rubble into recycled aggregates. The processes are described in detail in the following paragraphs.

Sorting, Separation, and Contamination Removal Stage

There are two approaches to removing contaminants from rubble: pre-crushing separation and post-crushing separation (O'Mahony and O'Mahony, 1990). Pre-crushing separation involves sorting of rubble during demolition, which can be time-consuming but offers significant benefits in terms of environmental and financial benefits (Silva et al., 2016). It can also occur when construction rubble reaches the recycling plant. The initial sorting optimises crushing time, energy spent, and product quality.

Crushing Stage

The recycled aggregates are crushed once the impurities are removed from the construction rubble. The crushing stage is the process stage that follows. For crushing construction rubble, gyratory, impact, and jaw crushers are the three most popular crushers used (Silva et al., 2016). While impact crushers offer superior grain-size distribution and are less susceptible to non-crushing materials, jaw crushers are capable of handling huge chunks of reinforced concrete (Arora and Arora, 2015). Gyratory crushers produce less tiny particles, use less energy, and have control over particle size (Pothina et al., 2007).

Post-crushing separation occurs after crushing stages, using various contaminant removal techniques. Hand sorting is the most straight-forward method, but it is also costlier. Self-cleaning magnets, positioned strategically over conveyor belts, separate bits of steel reinforcements and other ferromagnetic metals (Zhang et al., 2013). The efficiency of these methods depends on factors such as the distance between the magnet and rubble, conveyer belt speed, debris volume, and magnet angle (Silva et al., 2016).

2.5.5. Cost Benefits of Recycled Aggregates

Compared to natural aggregates, recycled concrete aggregates have reduced manufacturing costs as seen in Table 2.2. The production of natural aggregates requires the excavation and transportation of large amounts of raw materials, which can lead to significant carbon emissions and environmental damage. The use of recycled concrete aggregates can help reduce the quantity of the landfill waste and conserve natural resources costs (Silva et al., 2017). Recycled concrete aggregates offer a promising solution for reducing financial costs, environmental costs, and the overall environmental impact of construction projects while promoting sustainability and resource conservation costs (Ohemeng and Ekolu, 2020).

Table 2.2: *A breakdown of costs between natural aggregates and recycled concrete aggregates with reference to the study by Ohemeng and Ekolu (2020).*

Cost Component	Natural Aggregates ($/tonne)	Recycled Concrete Aggregates ($/tonne)
Equipment	8.45	7.15
Working Capital	2.17	1.86
Maintenance	2.59	1.94
Labour	3.05	2.60
Fuel	1.10	0.88
Fixed Overheads	2.26	1.83
Water	0.10	0.12
Total	19.72	16.38

In addition to Ohemeng and Ekolu (2020), a study conducted by Tam (2008) has proven that aggregates produced by recycling methods are more economical in the long term than using natural materials. The cost-benefit analysis of the use of natural aggregates and the use of recycled aggregates reveals that recycling construction rubble is more beneficial, providing a positive net benefit of $30,916,000 annually, while the natural aggregates have negative net benefit of $44,076,000 annually (Tam, 2008).

In contrast to the positive and negative benefit analysis in the Tam (2008) study, the Ohemeng and Ekolu (2020) study concluded a negative benefit (indicated by a negative sign), as seen in Table 2.3, for both natural and recycled aggregates production in South Africa.

Table 2.3: *Comparison of the net benefit analysis of processing the recycled aggregates against processing natural aggregates.*

Aggregates	Total Production Cost (US $/tonne)	Total Benefit (US $/tonne)	Net Benefit (US $/tonne)
Coarse Natural Aggregates (Natural Aggregates)	-76.30	0.73	-75.57
Coarse Recycled Concrete Aggregates (Recycled Aggregates)	-45.77	22.36	-23.41
Fine Manufactured Aggregates (Natural Aggregates)	-68.05	0.73	-67.32
Fine Recycled Coarse Aggregates (Recycled Aggregates)	-34.39	22.36	-12.03

However, it was found that while the net benefit of both was negative, the production costs for recycled concrete aggregates were less than the production costs for natural aggregates in Ohemeng and Ekolu (2020) ‘s study. It is therefore important to encourage the commercial manufacturing of recycled concrete aggregates from construction rubble as a viable and sustainable method for the building sector to use.

2.6. Conclusions from the Literature

The construction industry has evolved over centuries, influencing modern practices and modelling the current built environment. Masonry and concrete are two traditional construction materials that display strength and durability. However, conventional construction practices, construction materials contribute to carbon emissions and resource depletion, necessitating the need for sustainable alternatives. To mitigate these impacts, there are ongoing efforts to promote sustainable practices, such as incorporating renewable energy sources and reducing reliance on fossil fuels.

Sustainability in the construction industry is a call to action that urges stakeholders to re-evaluate practices and materials in light of environmental, economic, and social constraints. Sustainable materials, such as recycled aggregates and locally sourced materials, suggest possible opportunities for reducing environmental impact and promoting resource efficiency. However, perceived cost implications are barriers.

The circular economy shift in the construction industry focuses on resource conservation and waste minimisation. The South African construction industry faces significant environmental and resource depletion challenges, necessitating strategies to minimise waste production and material efficiency. In South Africa, the implementation of circular economy principles can drive positive change by minimising waste generation, enhancing material efficiency, contributing to economic resilience, job creation, and improved sustainability outcomes.

While the literature emphasises the benefits of using recycled aggregates in construction projects, such as reducing landfill space, lowering production costs, and conserving natural resources, it overlooks the logistical challenges associated with transporting these materials over

long distances. Transportation of recycled aggregates involves energy consumption and emissions, which can offset some of the environmental benefits achieved through their use. Moreover, the economic feasibility of transporting recycled aggregates depends on factors such as distance, infrastructure, and the availability of recycling facilities. Understanding the feasible transport distance for recycled aggregates is essential for optimising their use and maximising their environmental and economic benefits. Addressing these issues would provide valuable insights into optimising the use of recycled aggregates in construction projects while minimising environmental impact and maximising cost-effectiveness.

CHAPTER THREE – METHODOLOGY

3.1. Introduction

This study involved an initial review of existing literature, focusing on articles relating to recycled aggregates, natural aggregates, sustainable construction materials, life cycle assessment, and the circular economy. This investigation served as the foundation for the formulation of research questions. In order to delve deeper into the details of the research methodology and design, the research onion framework was employed, as it stands out to be one of the most widely utilised models in research methodology (Saunders et al., 2012).

The research onion framework shown in Figure 3.1 assisted in the breakdown of the research design process, which encompassed various stages such as methodology selection, philosophy, and the planning of data collection, processing, and analysis. It acted as a guiding tool, ensuring well-structured approach to the research project.

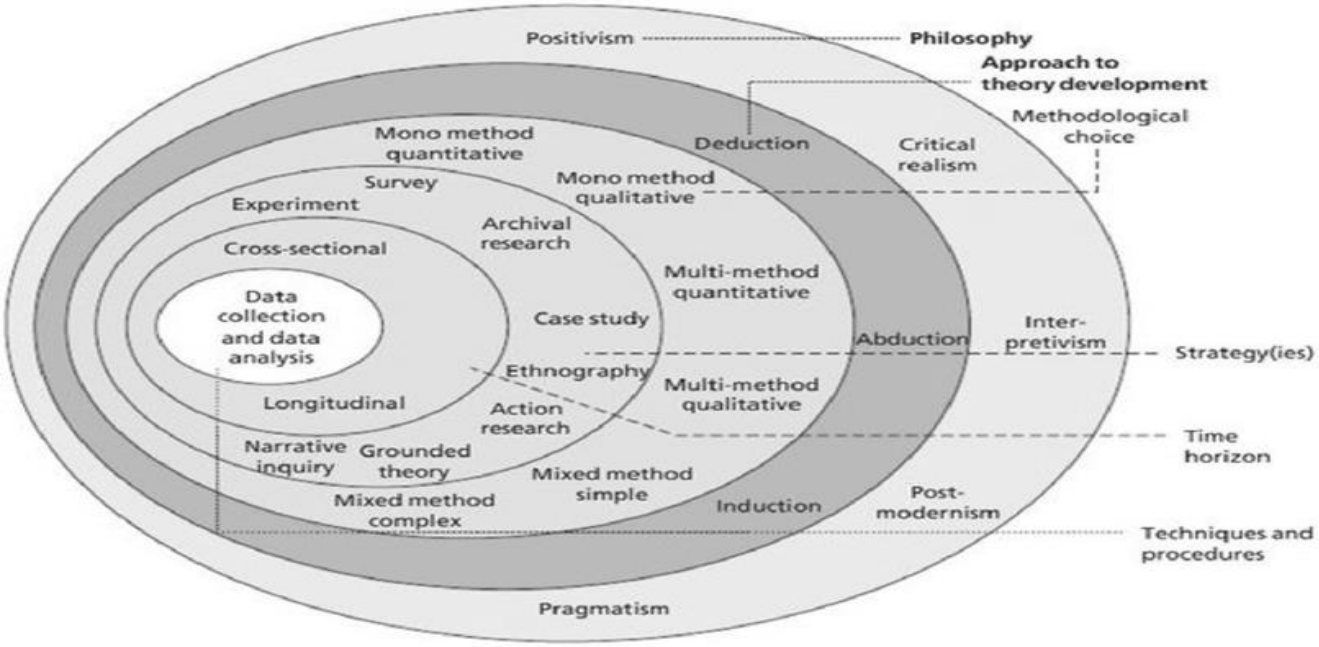


Figure 3.1: *The research Onion (Saunders et al., 2012).*

Figure 3.2 provides a visual representation of the research approach. This diagram serves as an outline of the development of this study, from the review of the literature and data collection to arriving at the final conclusion of the study.

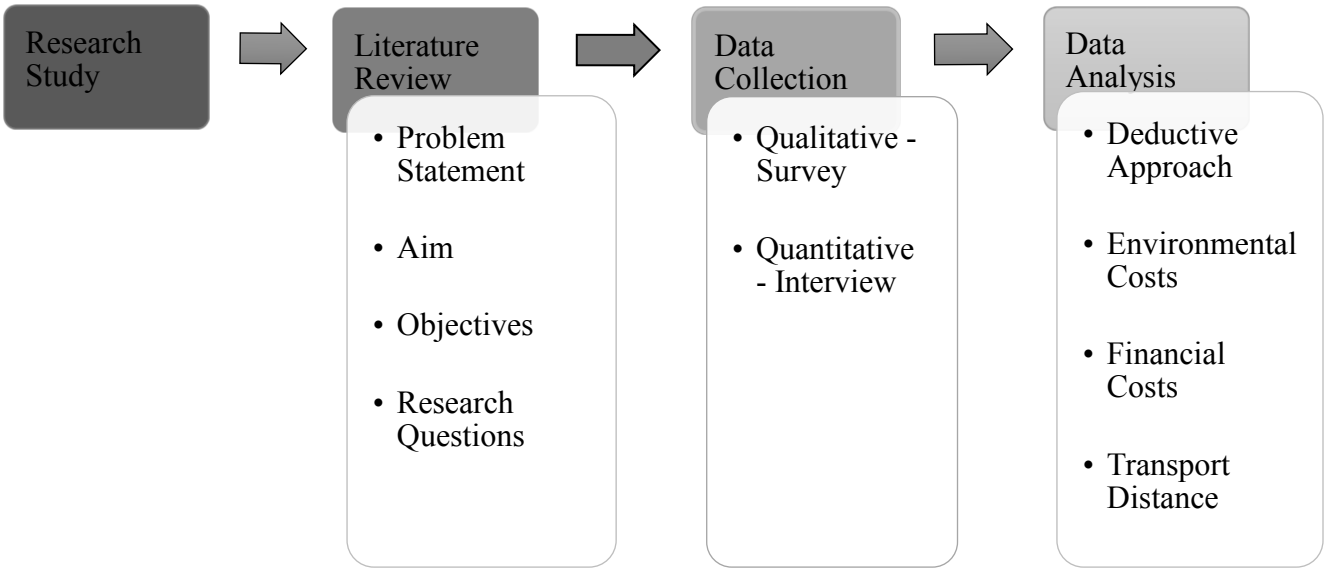


Figure 3.2: *Flow chart illustrating the methodology used for the study.*

3.2. Research Design

The research philosophy for this study is positivist, and the approach to theory development is deductive. The research employed a mixed-method approach, integrating both quantitative and qualitative methods to investigate the aggregates extraction, processing of natural and recycled aggregates, and use of demolition waste. The strategy used was a survey, and the techniques and procedures include sending out questionnaires, carrying out surveys and conducting interviews.

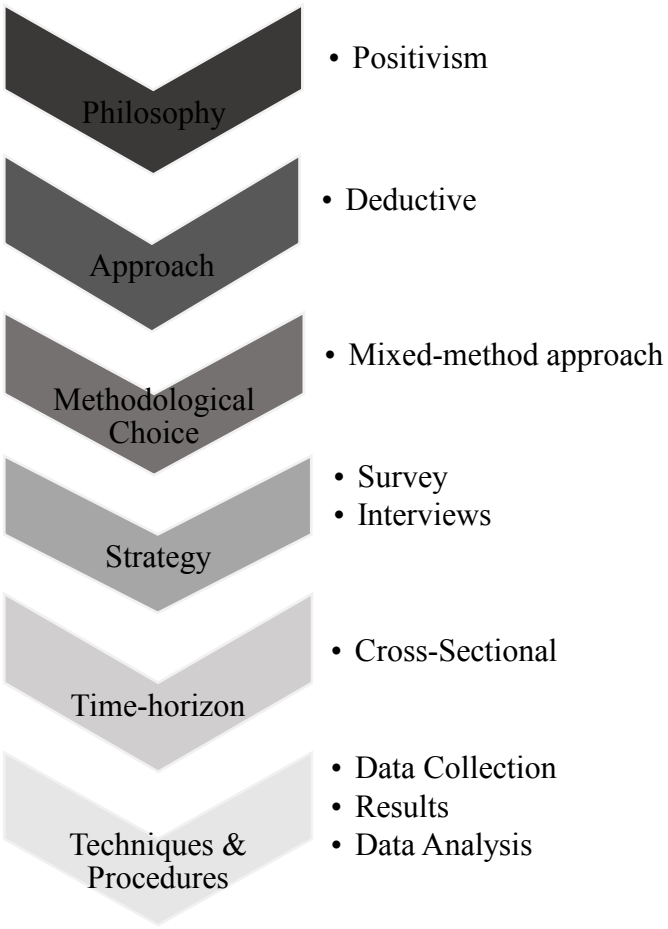


Figure 3.3: *The Research Framework Adopted with Respect to (Saunders et al., 2012)'s Research Onion.*

A positivist approach employed in the study provided evidence that helped to and understand the empirical data, while a deductive approach enabled a logical analysis. By reviewing similar studies, various data collection methods were identified, contributing to the analysis and interpretation of the findings. The deductive approach enabled a logical connection of research questions with the collected data, ensuring that conclusions were grounded in solid evidence. This approach guaranteed validity and reliability.

3.3. Research Instruments

The research instruments used in the conduction of this research were the questionnaires as seen in the appendix. To reach a diverse range of participants, the questionnaires were administered both online and in-person, using surveys and interviews as data collection methods. The questionnaires were sent through emails which were followed up by Google meet, Microsoft teams, direct phone calls and in-person visits. These questionnaires were an important tool to gain information used to meet the study objectives.

To achieve these objectives, two questionnaires were designed for this study: a survey questionnaire for qualitative data and an interview questionnaire for quantitative data. The questionnaires aimed to gather information on demolition practices, recycling practices, quarry practices, costs associated, energy consumption and greenhouse gas emissions. A thorough internet search was conducted to identify a list of potential recycling sites, quarry sites, and demolition contractors to participate in the study. Once the potential participants were identified, invites were sent out to the prospective participants.

The approach that was employed to initiate the participation invitations and issue the questionnaires were emails and calls, to distribute the information sheets, questionnaires (see Annexure A), consent forms (see Annexure B) and permission letters. The respondents had varied preferences as some chose in-person visits and interviews, while others preferred telephone interviews, Google Meet and Microsoft Teams. To accommodate these preferences, questionnaires were presented in hard copy for in-person engagements, while PDF documents sent through email aided interviews conducted remotely. By using a combination of online and in-person engagement, the study aimed to increase the response rate. A minimum response rate was targeted at 60% to ensure an understanding of the industry dynamics.

As stated before, the questionnaires were an important tool used in achieving the aim and objectives of the study as they played an important role in data collection. The study by Ohemeng and Ekolu (2020) aided in the development and formation of the questionnaires. The development of these questionnaires involved considering several aspects which included:

- Clarity and simplicity of language
- Relevance of the questions
- Avoidance of leading questions and bias
- Use of open-ended and closed-ended questions

The questions for different groups of participants: demolition contractors, quarry sites, and rubble recyclers were in the ranges of 19, 13 and 11 questions, respectively. The purpose of using different questionnaires was to address the unique priorities and challenges of each group, making it necessary to create distinct sets of questions for more relevant and focused responses.

3.4. Data Collection

Data was gathered from various participants located in Johannesburg, Gauteng. The participants included demolition contractors, quarry sites, and recycling sites. The flexibility of the setting allowed for engaging interviews. As stated earlier, the collection process involved online and in-person interactions, incorporating surveys and interviews. A survey was used to collect qualitative data from all three groups of data sources mentioned above while interviews were conducted to collect quantitative data from the same data sources.

A survey was conducted on the procedures employed in manufacturing natural aggregates, with a target on five quarry sites in Johannesburg. Qualitative data was collected from quarry sites through surveys, gathering information on natural resource extraction, manufacturing processes,

demographic data of participants, and energy sources of equipment. The survey also aimed to gather information on energy consumption, and greenhouse gas (GHG) emissions at each stage of aggregate production. This formed an important aspect of the qualitative dataset, though it was noted that most companies do not have records of greenhouse gas emissions.

A separate survey was simultaneously undertaken to understand the details of manufacturing recycled aggregates by repurposing construction rubble obtained from demolition waste. The survey initially targeted five recycling sites, reviewing the recycling processes, energy sources for equipment and tools, and greenhouse gas emissions generated during manufacturing. Understanding the environmental footprint of the recycling process is essential for assessing sustainability (Haupt and Hellweg, 2019). Similarly, data on the equipment and tools used in the demolition of buildings was obtained from 5 demolition contractors through surveys. This included data on the types of energy required for operation and the associated carbon dioxide emissions.

With respect to the quantitative aspect of the study, interviews that were conducted allowed collection of data on economic and environmental costs. The data covered information used in the determination of the costs incurred at each stage of the process, quantifying the energy consumption, and documenting data necessary for calculating greenhouse gas emissions for both natural and recycled aggregates.

The economic costs encompassed various elements, such as equipment, working capital, equipment maintenance, labour, energy (fuel), and water expenses. On the other hand, the environmental costs covered the energy consumption. This quantitative data is aimed at providing an understanding of the economic implications and environmental impact associated with different stages of aggregate production and demolition activities.

To ensure data integrity, information was collected, documented, and subsequently transcribed into Microsoft Excel for statistical tests and data presentation. It is important to note that this data, was analysed, reported, and securely stored for five years before being ethically discarded, ensuring compliance with data retention standards according to Section 14 of the South African Protection of Personal Information Act (POPIA). This approach to data collection and management demonstrated the commitment to both accuracy and ethical considerations in the research process.

3.4.1. Population and Sampling

The increasing population growth is the key driver that escalates infrastructural demands, thus increasing their dependence on concrete as the most commonly used material in infrastructural developments (Marinković, 2010). In the context of South Africa, the demographic growth is more pronounced in urban areas compared to rural areas, an observation fueled by the forces of urbanisation (Mthiyane et al., 2022). The pull towards urban areas is connected to the attraction of employment opportunities (Mthiyane et al., 2022). However, rapid urbanisation has brought about a challenge, marked by a high population density and the scarcity of land and space (Lu et al., 2023). This is all a consequence of businesses and individuals relocating to newly developed areas, abandoning previously established structures (Khatleli, 2017).

This challenge creates a cycle where these abandoned structures are demolished, resulting in the generation of construction rubble. The rubble has the potential to be renewed and repurposed into concrete aggregates (Pourkhorshidi et al., 2020). This study pursued researching the details of this trend, with a focus on one city in South Africa, in Gauteng province, Johannesburg. Among the provinces with significant population density, Gauteng was found to be a fitting choice

(Alexander, 2017). Johannesburg, a major city within Gauteng, has a substantial percentage of the province's population. The city's attraction, which contributes to its substantial percentage, lies not only in the potential employment opportunities it offers, but also in its status as a major economic hub.

Figure 3.4 below illustrates the population density in South Africa.

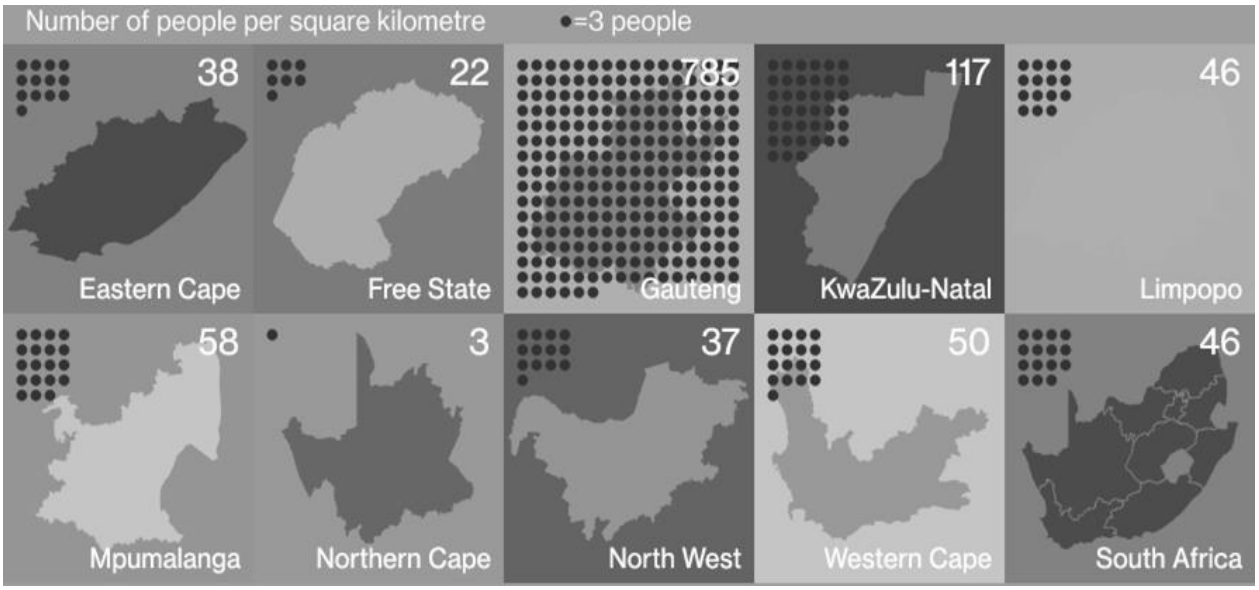


Figure 3.4: *Population Density in South Africa (Alexander, 2017; Lehohla, 2017).*

Gauteng, and Johannesburg in particular, has been selected for its rapid urbanisation (Katumba and Everatt, 2021). The migration of people and businesses towards the northern regions of Gauteng left a trace of deserted buildings in the city centre, the Johannesburg Central Business District (Khatleli, 2018). The surplus of such abandoned structures, coupled with the associated demolition activities, presents a unique scenario. These demolitions not only free up land for potential redevelopment but also produce a collection of construction rubble that can be repurposed into recycled aggregates (Pourkhorshidi et al., 2020).

3.5. Ethical Concerns

The research design prioritised the ethical considerations of ensuring the rights of participants. It included ensuring confidentiality and anonymity, along with obtaining informed consent from participants before their involvement in the study. A crucial aspect involved recognising and addressing any potential risks associated with the study and providing participants with the freedom to discontinue their participation in surveys or interviews if they felt uncomfortable at any point.

An essential procedural step, as stipulated by the university guidelines, involves securing a clearance certificate before the commencement of data collection. The ethics clearance process involved submitting a document containing the participant information sheet, consent form, questionnaires, and interview schedule to the ethics committee. The intent was to adhere to an organised and detailed approach, ensuring that the research aligns with ethical standards. The ethical clearance certificate, as proof of the obligation to research integrity, is included in the appendix for reference.

The rights of participants were safeguarded through a commitment to confidentiality and anonymity. This means that any information shared by participants was treated with the utmost discretion, and their identities were protected. In conjunction with this, the process began with obtaining informed consent, ensuring that participants were fully aware of the nature and objectives of the study before agreeing to take part.

3.6. Data Analysis

3.6.1. Life Cycle Assessment, Analysis of Environmental Costs

Interviews assisted in collecting the data that was used to assess costs and perform a life cycle assessment (LCA). The key input parameters, collected from participants, such as electricity, petrol, and diesel consumption throughout the manufacturing processes of both recycled and natural aggregates, were recorded. Additionally, the relevant output values, specifically carbon dioxide emissions, were calculated using the collected data and recorded. These datasets were used to generate graphical representations, employing a life cycle assessment methodology. Through graphical comparisons, the environmental impacts of recycled and natural aggregates were analysed. This methodology ensured an evaluation of the sustainability aspect of the aggregates throughout their life cycle.

The integration of the LCA methodology in the study was key to evaluating the sustainability of materials located in various geographical locations. Sustainability is based on various factors such as location, availability, and transportation requirements, all of which contribute to varying energy burdens (Reames et al., 2021). The study recognises the nature of sustainability, emphasising the need for an approach that considers the wider environmental impact of construction materials. The sustainability of aggregates encompasses environmental sustainability which looks into the embodied energy of aggregates. Investigating the aspect of embodied energy added an additional insight to the study which attempted to quantify carbon dioxide emissions during production processes.

The data for energy consumed (fuel consumption), which was used in the calculations, was first obtained through interviews with the participants. The emissions data was calculated using the formula from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories:

$$\text{Emissions}_{\text{GHG, Fuel}} = \text{Fuel Consumption}_{\text{Fuel}} * \text{Emission Factor}_{\text{GHG, Fuel}} \quad \text{... } \textit{Equation [1]}$$

Where:

- **Emissions** $_{GHG, fuel}$ = emissions of a given GHG by type of fuel (kg • GHG)
- **Fuel Consumption fuel** = amount of fuel combusted (TJ)
- **Emission Factor** $_{GHG, fuel}$ = default emission factor of a given GHG by type of fuel (kg gas/TJ)

The following emission factors were used in this study, obtained from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories:

- Diesel = 74,100 kg of greenhouse gas per TJ
- Electricity = 112,000 kg of greenhouse gas per TJ

This methodology was applied to both recycled and natural aggregates production.

The integration of the LCA methodology in the study was key to evaluating the sustainability of materials located in various geographical locations. Sustainability is based on various factors such as location, availability, and transportation requirements, all of which contribute to varying energy burdens (Reames et al., 2021). The study recognises the nature of sustainability, emphasising the need for an approach that considers the wider environmental impact of construction materials. The sustainability of aggregates encompasses environmental sustainability which looks into the embodied energy of aggregates. Investigating the aspect of embodied energy added an additional insight to the study which attempted to quantify carbon dioxide emissions during production processes.

3.6.2. Analysis of Financial Costs

The collected data was analysed using system software, Microsoft Excel, presenting the results through tables and graphs for visual representation. Statistical analysis tests were then applied to enhance accuracy and reliability of the collected data. The "Student's t-test" was used to compare the means between natural and recycled aggregates. Mean costs for each aggregate category were computed, facilitating a comparison to determine which category incurred higher costs. The mean difference was used for assessing statistical significance and calculating the distance at which both aggregate costs equate. The distance (km), D, was determined using the equation below, which has been formulated by the researcher.

$$D = \frac{1}{P}\left(\frac{\sum \chi_{i(NA)}}{n_1} - \frac{\sum \chi_{i(RA)}}{n_2}\right) \qquad \text{... Equation [2]}$$

Where;

D = transportation distance

P = price of fuel consumed to travel 1km *(when the price of fuel is highest, lowest and average)*

n_1 = sample size of natural aggregates

n_2 = sample size of recycled aggregates

$\sum \chi_i(NA)$ = summation of financial costs for producing natural aggregates

$\sum \chi_i(RA)$ = summation of financial costs for producing recycled aggregates

Beyond this distance, at which ($Costs_{natural\ aggregates} = Costs_{recycled\ aggregates}$), it then becomes uneconomical to use recycled aggregates since they will be more expensive to use in comparison to natural aggregates. Three fuel prices were used: the lowest price, the mean price, and the highest price, in the last 12 months from January 2023 to December 2023, inclusive. Three fuel prices were used to account for price fluctuations during the year. This provided a more comprehensive analysis by reflecting potential cost variability, rather than relying on a single fixed price, which may not capture the full range of market conditions.

CHAPTER FOUR – RESULTS AND DISCUSSION

4.1. Introduction

Chapter 4 presents an analysis of the results and discussion of the study, focusing on both qualitative and quantitative aspects. This chapter provides an exploration of the environmental and financial implications of using natural and recycled aggregates in the construction industry. It begins with an overview of the response rate and demographics of the study participants, highlighting their roles in the industry. It then delves into the manufacturing processes of natural aggregates.

The discussion covers the manufacturing of recycled aggregates, exploring the methods and tools used in demolition and manufacturing processes. The chapter also compares the energy consumption and greenhouse gas emissions associated with both types of aggregates, providing an assessment of their environmental impacts. In addition to the environmental analysis, the chapter examines the financial costs of manufacturing natural and recycled aggregates. The feasibility of transporting recycled aggregates is also discussed.

The financial costs of manufacturing recycled aggregates are 58.35% higher than those of natural aggregates, primarily due to the high costs associated with demolition activities. Recycled aggregates require more energy to manufacture compared to natural aggregates, highlighting the significant energy demands of the recycling process. Subsequently, the production of recycled aggregates results in higher carbon dioxide emissions than natural aggregates, largely due to the energy-intensive nature of demolition and recycling processes. There is no feasible transport distance for repurposing construction rubble into recycled aggregates in Johannesburg, Gauteng, when demolition costs are included. However, excluding demolition costs, recycling aggregates becomes viable within a 20 km radius.

Qualitative Results

4.2. Response Rate and Demographics Analysis

The study gathered insights from the construction industry on the processing of natural and recycled aggregates from demolition companies, rubble processors (recycling sites), and quarry sites. Despite encountering challenges in securing willing participants. A total of 14 participants responded to participating in the study: 5 demolition companies, 4 rubble processors, and 5 quarry sites. The responses from all 14 participants were analysed and presented in the proceeding sections.

Figure 4.1 illustrates the distribution of positions held by respondents within all the three sectors (the quarries, demolition contractors and rubble processors) that participated in the study. It provides a clear overview of the professional roles within the surveyed companies.

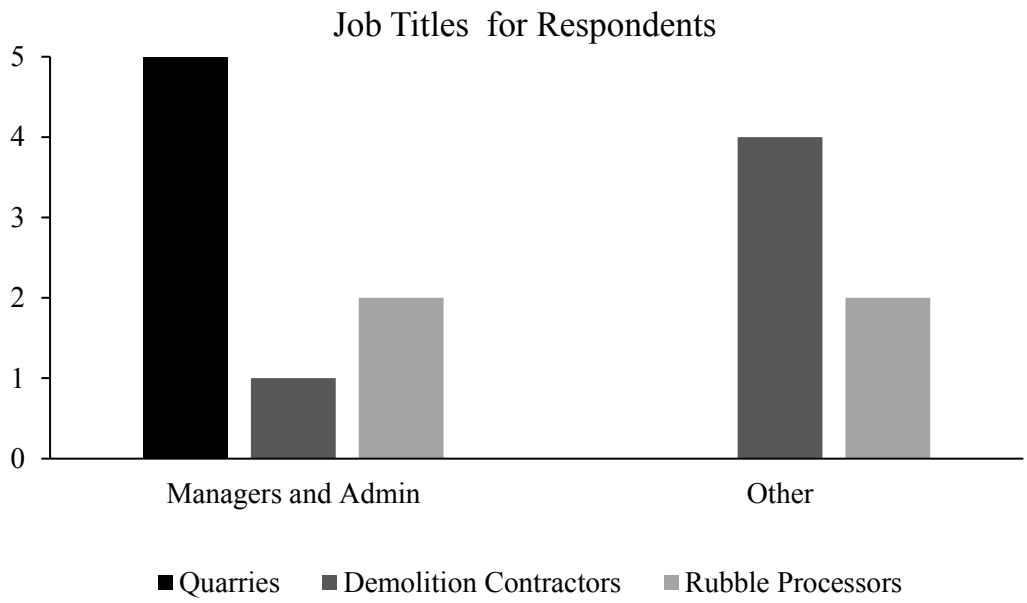


Figure 4.1: *Job position held by participants from the quarries, demolition contractors, and rubble processors in Johannesburg.*

All five respondents from quarry sites identified as managers. While for the demolition contractors, out of the five respondents that participated, only one individual identifying as holding a managerial position and the other four respondents identified as "other". In addition, for the rubble processors, the research initially aimed to include five participants' insights, but locating recycling sites in Johannesburg was a challenge. However, a total of four participants responded to the questionnaires, as seen in Figure 4.1. Two of four respondents held managerial positions within their organisations while the other two individuals classified themselves as holding "other" positions.

The demographics revealed different roles among the participants. An understanding of the different roles represented in the study is important in the feasibility of using recycled aggregates (Vasileiou, 2018) as it provides insights from different backgrounds professionally. This diversity can lead to a more comprehensive analysis of the potential challenges and benefits associated with using recycled aggregates in construction projects. Managerial and administration roles make up 57% of the participants, there was 0% participation from engineers and technicians while the “other” (not listed on the questionnaires) roles 43%.

The managers provided insights into cost structures of manufacturing natural aggregates. Managerial perspectives are important for decision-makers in understanding economic implications and resource allocations. In addition, understanding the economic implications of transporting recycled aggregates against natural aggregates is essential for decision-makers in the construction industry (Wilburn and Goonan, 1998). However, the lack of technical or engineering participants raises concerns on the extent of technical knowledge obtained during the data collection.

4.3. Manufacturing Processes

4.3.1. Natural Aggregates

The results from the quarry sites provided insights on the operations, resource availability, and processes of manufacturing natural aggregates. The results shed light on the sustainability issues and potential challenges associated with natural aggregate manufacturing.

4.3.1.1. Quarries

Aggregate Manufacturing Process and Extraction Period

All five quarry sites manufactured both fine and coarse aggregates. The production of both fine and coarse aggregates shows the versatile use of natural resources in various construction applications (Zega et al., 2010). The similar production process at quarry sites provides a baseline for comparison with recycled aggregates.

The extraction experience of participating quarry sites varied, with two out of five companies having less than twenty years of experience, indicating moderate experience. However, three out of five companies have been extracting raw materials from the same quarry site for over 20 years, indicating substantial experience.

All participating companies project to continue the extraction for twenty more years. However, they have a common foresight about the potential decrease in extraction rates and quantity if quarried at the same rate for many years. This emphasises the need for adopting alternative materials, sustainable resource management, a proactive environmental approach, and long-term planning.

The Need for Sustainable Practices in the Manufacturing Processes and Energy Sources

The industry acknowledges the need for sustainable practices in the natural aggregate production sector due to limited resource availability and a potential decrease in extraction rates. This is in line with global sustainability goals and necessitates a balance between the financial and environmental advantages of natural aggregates while making sure that alternative resources are used (Faleschini et al., 2016).

All five companies involved in natural aggregates manufacturing industry follow standardised processes, including drilling holes, blasting, size reduction, loading and unloading, primary crushing, secondary crushing, and tertiary crushing, with the exception of size reduction (see Figure 4.2).

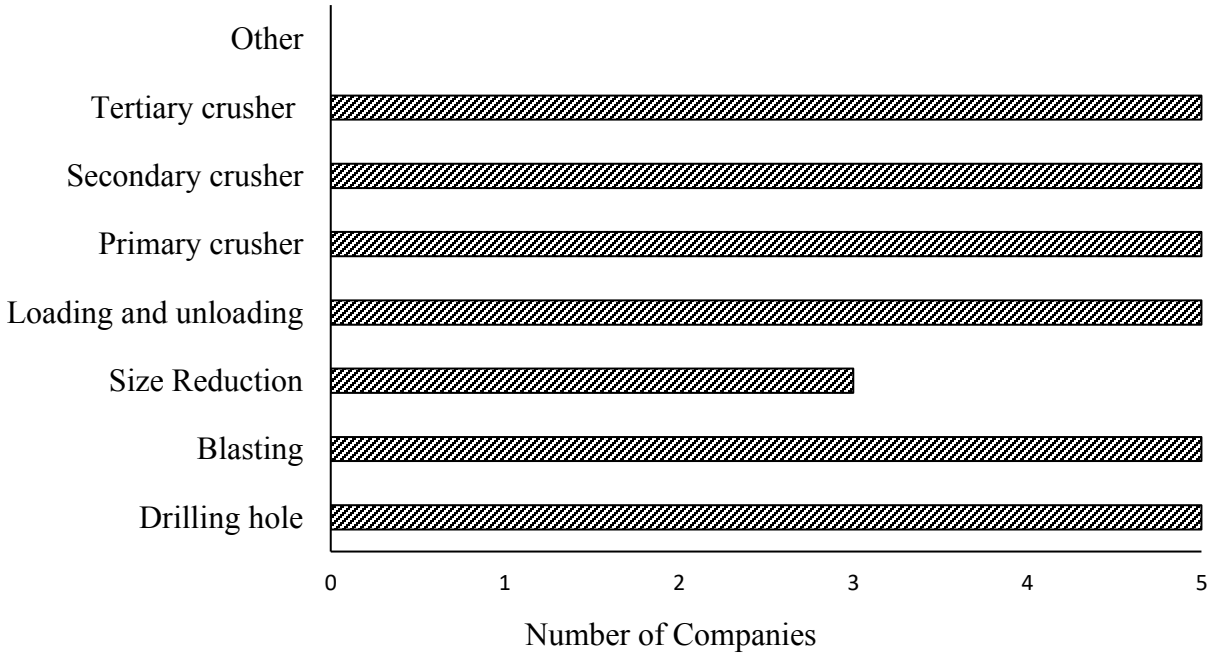


Figure 4.2: *Processes required to manufacture natural aggregates.*

This standardisation highlights common stages in aggregate production. All five companies rely on both diesel and electricity to power their equipment, selecting the energy source based on cost, equipment efficiency, availability and mobility on site.

Aggregate Delivery Methods

Transporting aggregates increases aggregate costs, but some companies allow clients to collect aggregates from quarries, providing flexibility in accessing manufactured aggregates. This dual approach caters to diverse project needs, enables efficient logistics in the supply chain and ensures a responsive and customer-friendly business model.

4.3.2. Recycled Aggregates

Demolishing building structures produces construction rubble, which can then be reused and processed into recycled aggregates. The data from demolition contractors provided insights into the variety of projects and structures involved in demolition, as well as the types and scale of recycling efforts within the construction industry in Johannesburg.

4.3.2.1. Demolition Contractors

Demolition Scope and Project Diversity

Figure 4.3 illustrates that all five participating contractors were involved in the demolition of building structures. This involvement demonstrates the potential for incorporating recycling practices in the construction sector. By having a variety of building structures that can be demolished to obtain construction rubble, it is certain that demolishing buildings will generate a plentiful supply of materials, which can serve as a valuable resource for producing recycled aggregate.

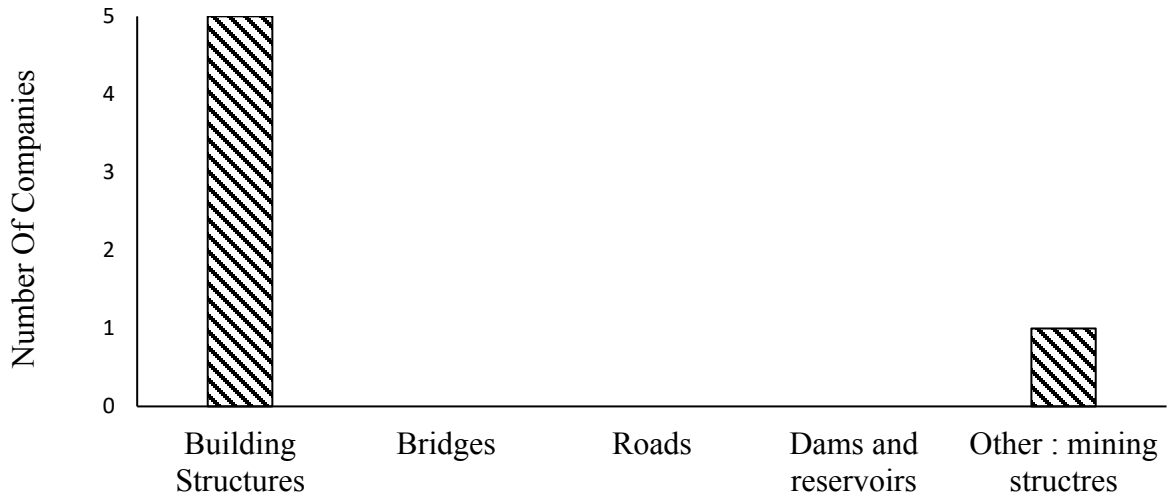


Figure 4.3: *The different types of demolition projects that can be undertaken by demolition contractors.*

In addition to building structures, one of the five companies demolishes mining structures, highlighting a niche area of expertise within the demolition sector. This specialisation suggests that the processing of construction rubble into recycled aggregates is not confined to traditional building structures. It extends to more unconventional projects, such as mining structures portraying the abundance of resources such as, rubble that can be used in the manufacturing of recycled aggregate.

Figure 4.3 shows that the majority of the demolition activities involved building structures, with none of the companies affiliated with other infrastructural structures such as bridges, roads as well as dams and reservoirs.

Residential, Commercial, and Industrial Demolitions

Building structures that are demolished can be categorised in different classes according to their uses. The different categories of building structures that demolition contractors are involved

in are residential, commercial, and industrial demolition projects. Figure 4.4 below illustrates the different types of building structures that can be demolished.

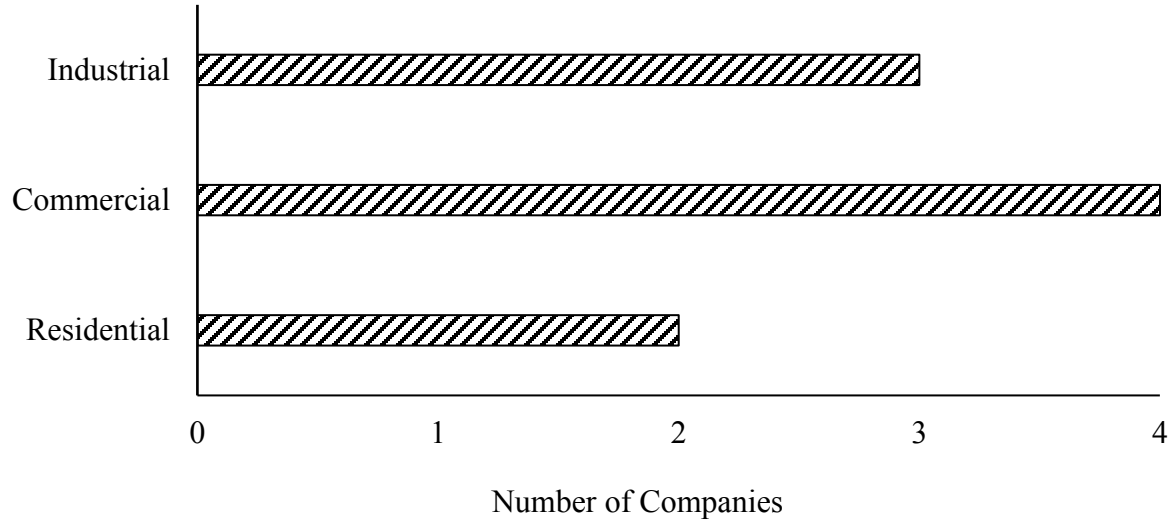


Figure 4.4: *Classifications indicating different uses of building structures that are demolished.*

Contractors in the demolition industry have varying levels of expertise. Some specialise in smaller residential projects, while others focus on large commercial and industrial structures as seen in Figure 4.4. The breakdown of these projects reveals that two out of five contractors have experience in residential demolition, while four out of five have been involved in commercial demolition, and three out of five have participated in industrial demolition. The demolition of commercial and industrial building structures emphasises a significant focus on larger and more complex projects with an ability to produce greater quantities of rubble.

Demolition Methods

Figure 4.5 illustrates the demolition methods that can be used during the demolition processes.

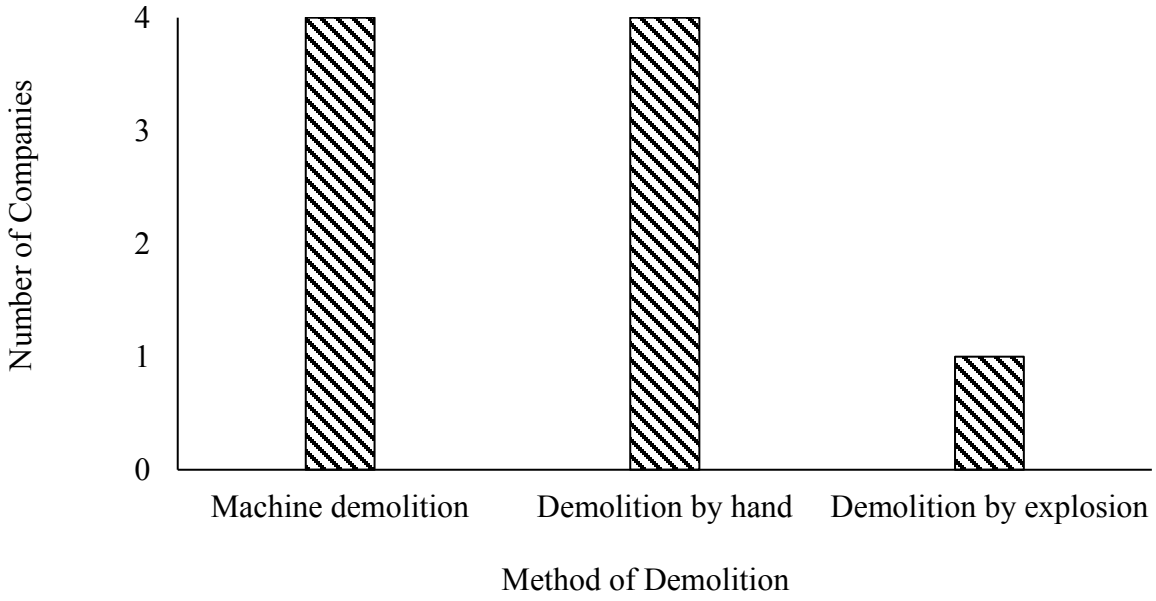


Figure 4.5: *Demolition methods used by various demolition contractors.*

The demolition industry employs various demolition methods, as seen in Figure 4.5, with machine demolition being the most common, used by four out of five companies. It is a preferred method, based on its efficiency and accuracy in larger structures. Manual hand demolition is also used by four out of five companies. Explosives are used by one out of five companies, indicating a specialised controlled demolition method for specific scenarios. The combined use of machine, hand, and explosive demolition methods enable contractors to customise their demolition approach to a particular building structure (Pranav et al., 2015).

Figure 4.6 illustrates that demolition contractors employ varying levels of labour and machine intensity.

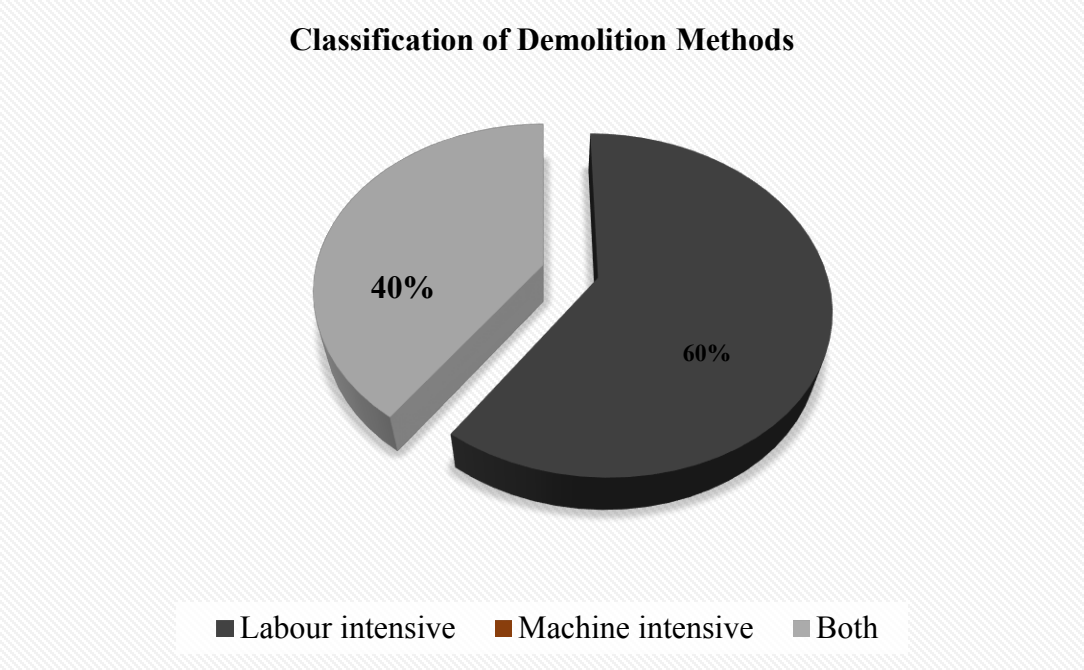


Figure 4.6: *Demolition production methods.*

Three of five companies rely on manual labour, while two out of five adopt a hybrid approach, combining both labour and machine intensive methods. This strategy highlights the industry's ability to balance traditional techniques with technological innovation, leveraging the strengths of both human and machine capabilities for optimal efficiency and effectiveness. The hybrid approach highlights the industry's awareness of the benefits of combining human skills with technological advancements.

Tools, Machinery and Energy Sources

The choice of tools and machinery in demolition activities is crucial in ensuring efficiency, safety, and minimising environmental impacts (Mayowa and Chinda, 2023). Figure 4.7 illustrates the different tools and machinery that can be used during demolition.

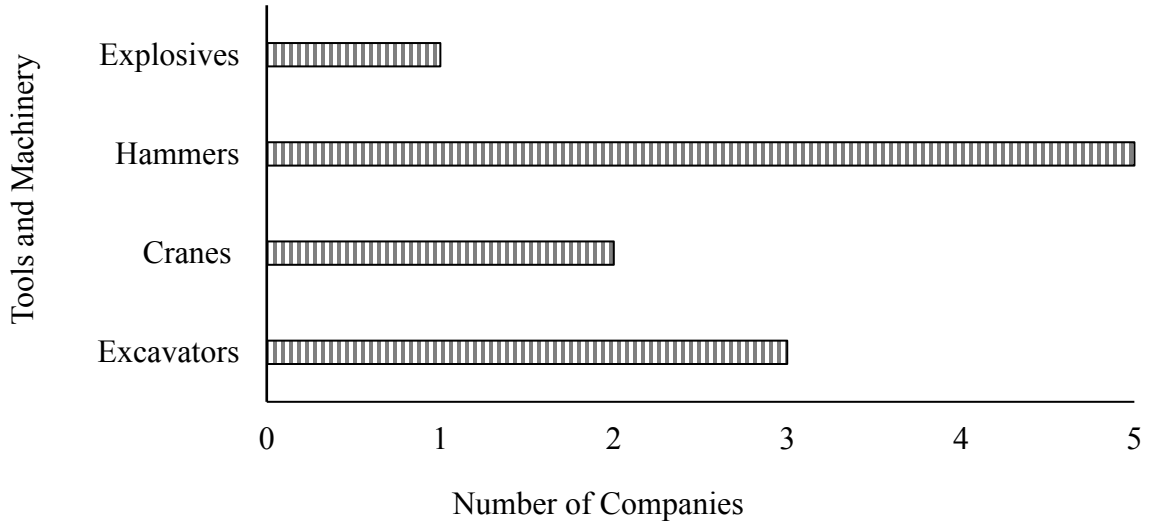


Figure 4.7: *Tools and machinery used to demolish structures.*

As seen in Figure 4.7, excavators are preferred by three of five companies due to their versatility in handling various tasks, while cranes are used by two out of five companies for their specialised lifting capabilities. In addition, hammers are universally applicable for breaking structures while explosives are reserved for controlled precision situations.

The environmental impact of demolition activities is significantly influenced by the different energy sources used as seen in Figure 4.8 below. The choice between diesel-powered and electric-powered machines depends on the availability of the source of energy as well as the available space on site for easy movement of the different plants and equipment.

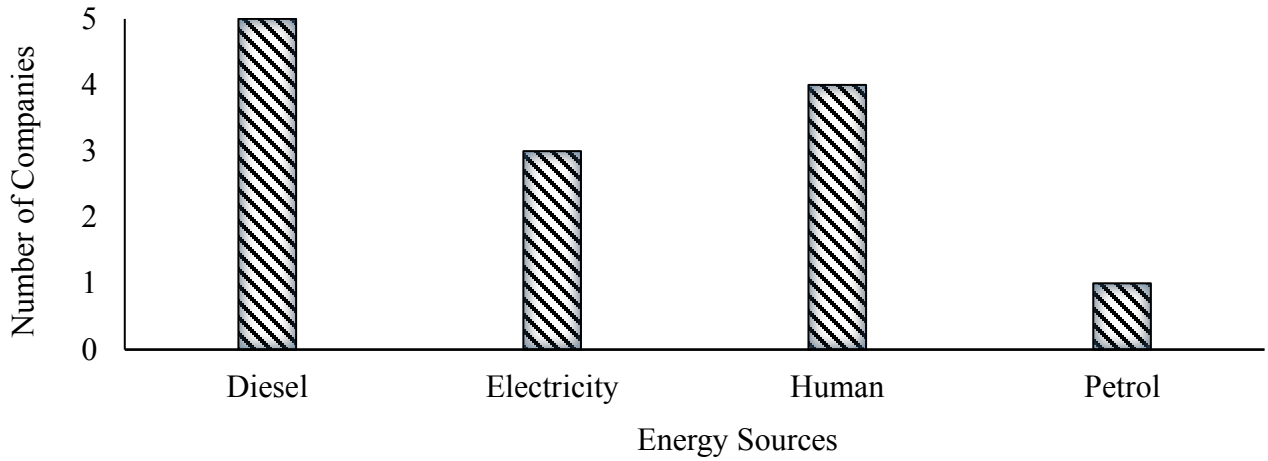


Figure 4.8: *Type of energy used to power the tools and machinery.*

As seen in Figure 4.8, all five companies use diesel, reflecting their traditional dependence on fuel. However, three out of five companies have introduced electricity. Four out of five companies use human power, indicating a commitment to traditional labour-intensive demolition practices. One company uses explosives as an energy source, indicating a controlled, specialised form of energy application in demolition.

Transport Distances

No data was obtained on distances for transporting demolition waste among all five companies as business see no need to track/ monitor transportation cost as part of their operation. While this lack of data may provide operational flexibility of transporting waste at any distance, it also raises concerns about increased transportation costs and carbon emissions associated with longer haul distances (Aminzadegan et al., 2022). The industry must be cautious of these factors and explore strategies to minimise environmental impacts and optimise logistical efficiency (Aminzadegan et al., 2022).

Carting and Disposal of Demolition Waste

One of the five surveyed companies opted for on-site (demolition site) recycling, demonstrating a transition to new sustainable practices at the demolition site. Two out of five companies have the waste collected from the demolition sites, while the other two companies discard their own waste. However, none of the companies transported waste directly to recycling sites. This common practice highlights the challenges of waste management and sustainability in the construction industry as well as worsening the landfills challenge. (Purchase et al., 2022).

4.3.2.2. Recycling Sites (Rubble Processors)

The construction rubble from the demolition waste gets processed into recycled aggregates after the demolition of buildings. The aggregates can be recycled on the demolition sites or at a plant away from the demolition site. The manufacturing of recycled aggregates is important for sustainable construction practices and rubble processors play an important role in this process. The methods employed to process C&D waste into recycled aggregates are discussed in this section.

Recycled Materials

The study reveals that recycling units can recycle a diverse range of materials. Three out of four companies recycled construction and demolition waste only, while one out of four adopted a holistic waste management plan that includes recycling all waste materials. This approach goes beyond the singular conventional waste management approaches and contributes to a more sustainable waste management system.

Recycling Processes

All four companies are engaged in the two major recycling processes of crushing and screening rubble. Crushing involves breaking down the rubble into smaller pieces that are easy to

work with, while screening separates the crushed material into different size fractions. These processes are essential in preparing the recycled aggregates for use in construction applications (Silva et al., 2017).

Quantitative Results

4.4. Environmental Costs

The study also examined the energy consumption of recycled and natural aggregates in the construction industry, focusing on the extraction, processing, and transportation stages. This include energy consumption in demolition companies, rubble processors (recyclers), and quarries, highlighting the environmental impacts of processing natural and recycled aggregates.

4.4.1. Energy Consumption

4.4.1.1. Natural Aggregates - Energy Consumed During the Manufacturing Processes of Natural Aggregates

Table 4.1 indicates electricity consumption across various quarry sites, averaging 34.50 MJ/m^3, with the minimum (7.1% < mean) and maximum (mean < 3.2%) consumption values of 33.15 MJ/m^3 and 35.6 MJ/m^3. In contrast, diesel consumption shows a mean of 32.58 MJ/m^3 with a wider range of energy consumption, from 20.84 MJ/m^3 (36% < mean) to 48.64 MJ/m^3 (mean < 49%). This difference suggests potential differences in operational approaches, equipment efficiency, geological conditions, and scale of operations among different quarry operations. Factors such as proximity to power grids, the availability of renewable energy sources, and access to diesel fuel can also influence energy sources and consumption patterns.

Table 4.1: *Energy consumed by quarries in the manufacturing of natural aggregates.*

Quarries	Electricity (MJ/m^3)	Diesel (MJ/m^3)	Total Energy Consumption (MJ/m^3)
1	34.96	24.70	59.66
2	34.16	20.84	55.00
3	35.60	48.64	84.24
4	33.15	37.06	70.21
5	34.63	31.65	66.28
Mean	34.50	32.578	67.08

The combined mean of the energy consumed to manufacture a cubic metre (1 m^3) of natural aggregates is 67.08 MJ, the minimum energy consumed is 18% less than the mean and the maximum energy consumption is 44% greater than the mean. This reflects the combined impact of both electricity and diesel sources on the production of natural aggregates.

4.4.1.2. Recycled Aggregates - Energy Consumed during the Manufacturing Processes of Recycled Aggregates

Energy Consumption during the Demolition of Building Structures

Table 4.2 illustrates a mean energy consumption 247.43 MJ/m^3, showing a variety of energy consumption ranging from 123.52 MJ/m^3 to 370.56 MJ/m^3 (50% < mean < 50%). This indicates varying degrees of energy efficiency within the industry.

Table 4.2: *Energy consumed to during the demolition of building structures.*

Demolition contractors	Energy (MJ)
1	308.80
2	251.29
3	182.96
4	123.52
5	370.56
Mean	247.43

Energy Consumption during the Processing of Rubble

Table 4.3 below shows the amount of energy consumed when processing the construction rubble into recycled aggregates. Energy efficiency in rubble processing is crucial, with electricity and diesel playing significant roles in the sector's overall energy consumption. It illustrates that processing rubble consumes roughly equivalent amounts of electricity and diesel fuel, of approximately 26 MJ/m^3 each. The minimum consumption values for electricity and diesel are 18% and 23% less than the mean, respectively. The maximum consumption values for electricity and diesel are 20% and 11% greater than the mean, respectively. The mean for the overall energy consumption (Energy consumption from electricity powered equipment + Energy consumption from diesel powered equipment) is 52 MJ/m^3 with the minimum and maximum energy consumption values 9% less and 15% greater than the mean, respectively.

Table 4.3: *Energy consumed by rubble processors when manufacturing recycled aggregates*

Rubble Processors	Electricity (MJ/m^3)	Diesel (MJ/m^3)	Energy Consumption (MJ/m^3)
1	24.07	26.83	50.90
2	21.27	28.99	50.26
3	31.30	28.43	59.73
4	27.50	20.17	47.67
Mean	26.04	26.11	52.14

Total Energy Consumption of Manufacturing Recycled Aggregates

Table 4.4 illustrates the combined energy consumption from demolition contractors and rubble processors. Data shown below are the summations of the energy consumption values from demolition contractors in Table 4.2 and rubble processors in Table 4.3 (DC + RP) and the mean energy consumption. The mean energy consumed in manufacturing (demolishing a building structure and processing the construction rubble into recycled aggregates) is 304.83 MJ/m^3. The lowest energy that can be consumed to manufacture $1m^3$ is 171.19 MJ which is 56% less than the mean while the highest energy consumed to manufacture $1m^3$ is 430.29 MJ which is 41% higher than the mean.

Table 4.4: *Combined energy consumption values of manufacturing 1m^3 of recycled aggregates from demolition contractors and rubble processors.*

Energy Consumption (MJ/m^3)		Energy Consumption from Demolition Contractors					Mean
		DC01	DC02	DC03	DC04	DC05	
Energy Consumption from Rubble Processors	RP01	359.70	302.19	233.86	174.42	421.46	**298.33**
	RP02	359.06	301.55	233.22	173.78	420.82	**297.69**
	RP03	368.53	311.02	242.69	183.25	430.29	**307.16**
	RP04	356.47	404.14	230.63	171.19	418.23	**316.13**
Mean		**360.94**	**329.73**	**235.10**	**175.66**	**422.70**	**304.83**

Abbreviations: DC - Demolition Contractors, RP – Rubble Processors

4.4.1.3. Comparison of Recycled Aggregates Production and Natural Aggregates Production

Figure 4.9 shows a comparison of the energy consumed during the manufacturing of natural and recycled aggregates. The figure illustrates a significantly higher energy consumption for the manufacturing of recycled aggregates (304.83 MJ/m^3) compared to natural aggregates (67.08 MJ/m^3) ($p < 0.0001$). This indicates that the process of recycling aggregates requires more energy compared to producing natural aggregates.

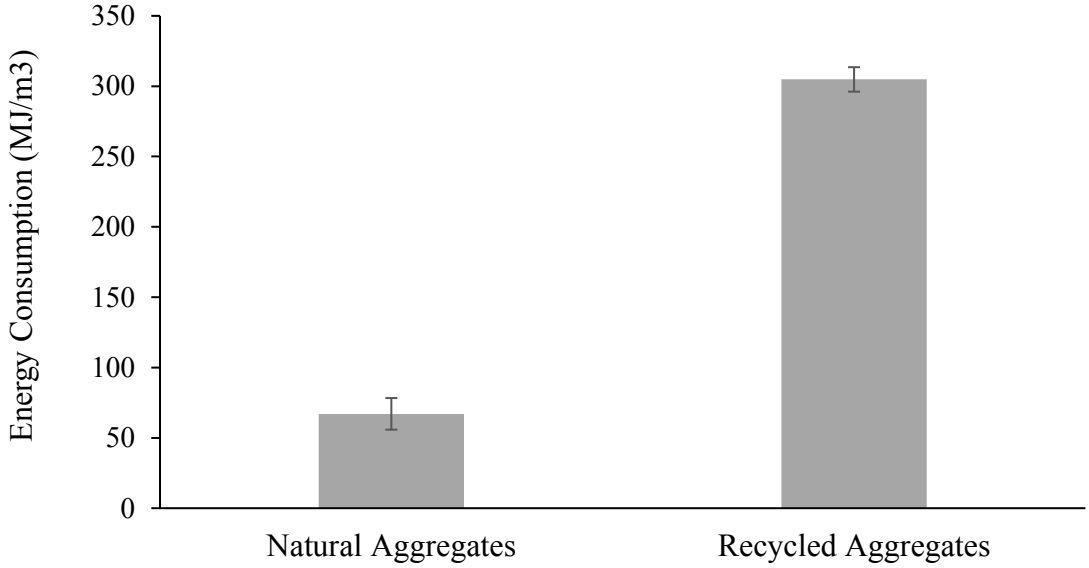


Figure 4.9: *The mean values for energy consumption recycled aggregates and natural manufacturers.*

4.4.2. Energy Emissions

This section of the report discusses energy emissions associated with the manufacturing of aggregates. Examining energy emissions, an important aspect of sustainability, the study focuses on three key sectors to comprehend their environmental impact in the production of concrete aggregates as construction materials. The research examines energy emissions in the production of concrete aggregates as construction materials. Difficulties emerged as many companies lacked records on energy emissions, which led to the calculation of the greenhouse gas (GHG) emissions.

The emission data was calculated using the following formula from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*:

$$\text{Emissions}_{\text{GHG, Fuel}} = \text{Fuel Consumption}_{\text{Fuel}} \bullet \text{Emission Factor}_{\text{GHG, Fuel}} \quad \text{... } \textit{Equation [1]}$$

Where:

Emissions $_{GHG, fuel}$ = emissions of a given GHG by type of fuel (kg • GHG)

Fuel Consumption $_{fuel}$ = amount of fuel combusted (TJ)

Emission Factor $_{GHG, fuel}$ = default emission factor of a given GHG by type of fuel (kg gas/TJ).

The following emission factors were used from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*:

Diesel = 74 100 kg of greenhouse gas per TJ

Electricity = 112 000 kg of greenhouse gas per TJ

4.4.2.1. Greenhouse Gas Emissions Released during the Manufacturing of Natural Aggregates

Figure 4.10 illustrates the amount of carbon dioxide gas that gets emitted into the atmosphere when manufacturing natural aggregates. The mean carbon dioxide emission among the five quarries that participate is 6.28 kg•CO_2. The lowest carbon dioxide that gets emitted among all the five quarries is 5.37 kg•CO_2, 14% lower than the mean emissions while the highest emission is 7.59kg•CO_2, 21% higher than the mean.

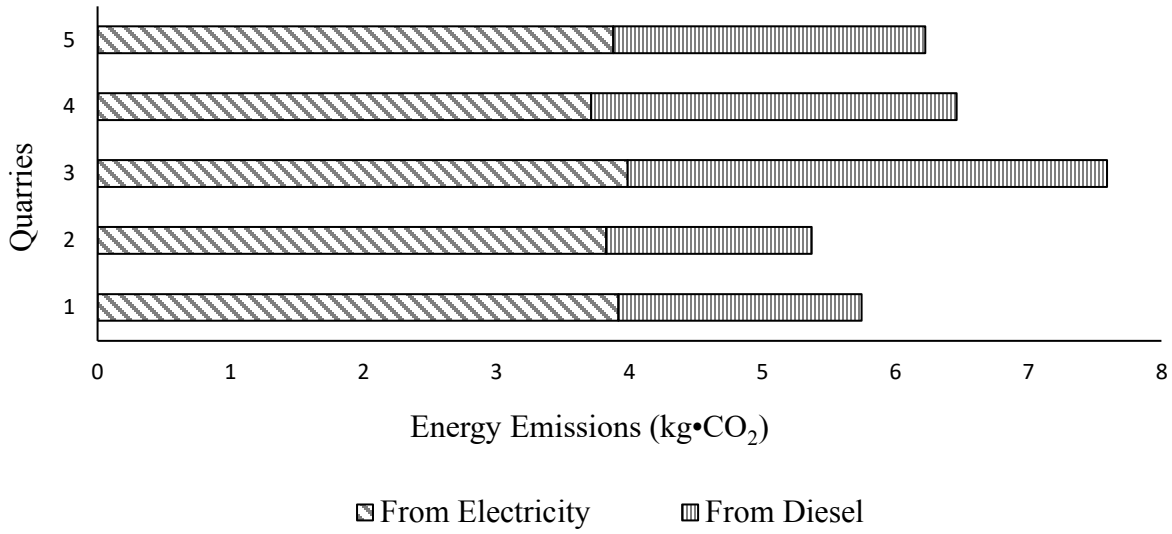


Figure 4.10: *Greenhouse gases emitted during the manufacturing of natural aggregates from the use of electricity and diesel.*

The mean emission value of 6.28 kg•CO_2 may serve as a benchmark for evaluating the environmental sustainability of conventional aggregate extraction. By acknowledging and addressing the greenhouse gas emissions associated with quarry operations, the construction sector can work towards minimising its environmental impact and fostering a more environmentally responsible approach to material resourcing.

4.4.2.2. Greenhouse Gas Emissions Released during the Manufacturing of Recycled Aggregates

Carbon dioxide Emissions released during the Demolition of Structures

In Johannesburg, Gauteng, demolition contractors display a mean emission of 27.71 kg•CO_2 as seen from Figure 4.11 below. Both the minimum and maximum emission values are 50% less and 50 % greater than the mean carbon dioxide emitted during demolition, respectively.

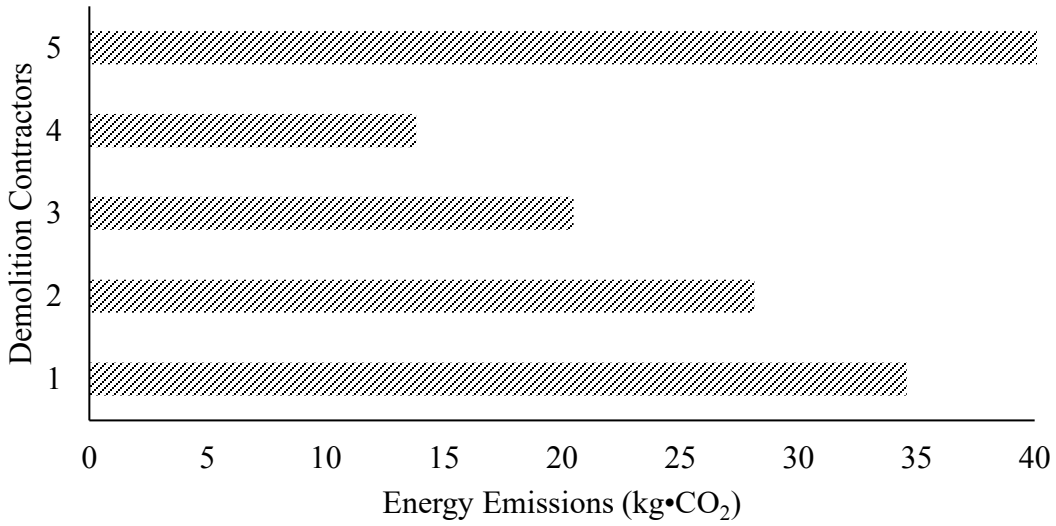


Figure 4.11: *Greenhouse gases emitted during the demolition of building structures.*

Demolition processes emit the greatest carbon dioxide gas, therefore, it is important to look into minimising the CO_2 emissions at this stage of recycle aggregates manufacturing. Strategies to reduce emissions may include the adoption of greener technologies (Yang et al., 2023). Integrating these practices may enhance the environmental performance of demolition activities, positioning them as effective contributors to a circular economy (Sparrevik et al., 2021).

Carbon dioxide Emissions released during the Processing of Rubble

The mean carbon dioxide emission during the processing of rubble is 4.85 kg•CO_2, with the minimum emissions of 4.53 kg•CO_2 (7% less than the mean) and the maximum emissions of 5.61 kg•CO_2 (16% greater than the mean).

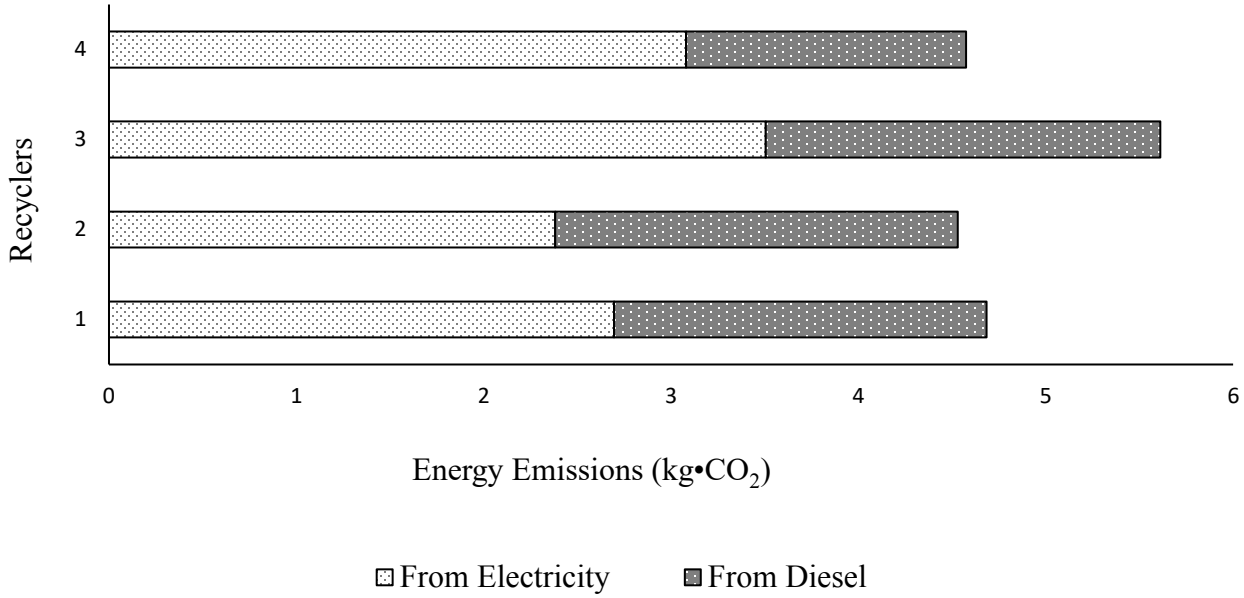


Figure 4.12: *Greenhouse gases emitted during recycled aggregates manufacturing from the use of electricity and diesel.*

Total Carbon dioxide Gas Emitted during the of Manufacturing Recycled Aggregates

The mean carbon dioxide emitted during manufacturing (demolishing a building structure and processing the construction rubble into recycled aggregates) is 33.11 kg•CO_2. Data shown below are the summations of the greenhouse gas emission values from demolition contractors and rubble processors (DC + RP) and the mean carbon dioxide emissions. The lowest carbon dioxide that is emitted when manufacturing 1m3 is 18.51 kg•CO_2 which is 44% less than the mean while the highest carbon dioxide that is emitted when manufacturing 1m^3 is 47.11 kg•CO_2 which is 42% higher than the mean.

Table 4.5: *Combined carbon dioxide emission values of manufacturing 1m^3 of recycled aggregates from demolition contractors and rubble processors.*

Carbon dioxide Emissions (kg • CO_2)		Carbon dioxide Emissions from Demolition Contractors					**Mean**
		DC01	DC02	DC03	DC04	DC05	
Carbon dioxide Emissions from Rubble Processors	RP01	39.27	32.82	25.17	18.51	46.18	**32.39**
	RP02	39.12	32.67	25.02	18.36	46.03	**32.24**
	RP03	40.20	33.75	26.10	19.44	47.11	**33.32**
	RP04	39.16	43.74	25.06	18.40	46.07	**34.49**
Mean		**39.44**	**35.75**	**25.34**	**18.68**	**46.35**	**33.11**

Abbreviations: DC - Demolition Contractors, RP – Rubble Processors.

4.4.2.3. Comparison of Carbon dioxide Emitted during the Recycled Aggregates Production and Natural Aggregates Production

The study reveals significant differences in greenhouse gas emissions between recycled and natural aggregates production (p-value < 0.0001). As seen from Figure 4.14, recycled aggregates production emits greater quantities of carbon dioxide (33.11 kg•CO_2) than natural aggregates production (6.28 kg•CO_2). The greatest source of emissions are a result of demolition and the energy used to demolish the building structures.

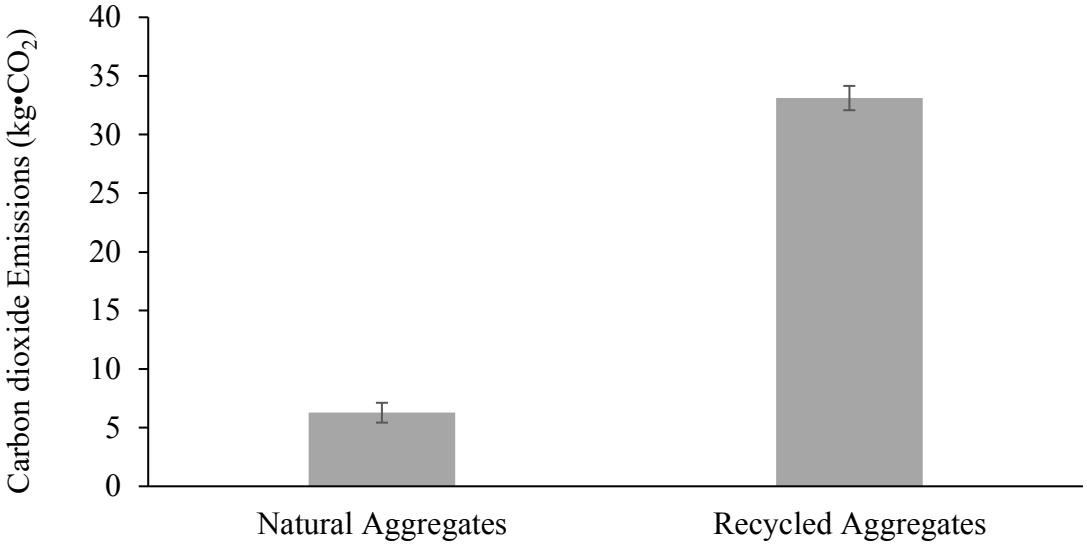


Figure 4.13: *Greenhouse gases emitted by rubble processors and quarries from manufacturing recycled aggregates and natural aggregates, respectively.*

4.5. Financial Costs

The study explored the economic aspect of aggregates, focusing on financial costs in the production processes. It compares the costs of extracting natural aggregates from quarries.

4.5.1. Financial Costs of Manufacturing Natural Aggregates in Quarries

The study examined the financial costs of natural aggregates manufacturing in quarry operations, revealing a range of costs among companies, with 693.70 ZAR/m^3 being the minimum total cost of manufacturing a cubic metre of aggregates and a maximum of 874.68 ZAR/m^3. The range is a result of factors like geological conditions, material type, extraction technologies, and transportation logistics. The mean cost of 765.86 ZAR/m^3 as seen from Table 4.6, serves as a benchmark, while factors like equipment efficiency and market demands optimise financial performance.

The results indicate that the highest cost component for quarry operations is equipment costs, accounting for approximately 53% of total costs. This is likely due to the significant investment required for heavy machinery and vehicles necessary for extraction and processing. This is followed by labour costs, making up around 16% of total costs, highlighting the importance of human resources in quarry operations. Maintenance costs are approximately 13% and significant, emphasizing the need for regular upkeep and repair of equipment to ensure efficient operations. Energy costs, at around 5%, reflect the high energy demands of quarry operations, particularly for powering equipment and machinery. Notably, water costs are the lowest, at approximately 1%, likely due to the recycling technique employed by quarries. These findings suggest that quarry operators should prioritize efficient equipment use, effective labour management, and regular maintenance to minimize costs and maximize profitability.

Table 4.6: *Financial costs for manufacturing natural aggregates in quarries.*

Costs	QM01 (ZAR/m^3)	QM02 (ZAR/m^3)	QM03 (ZAR/m^3)	QM04 (ZAR/m^3)	QM05 (ZAR/m^3)	Mean Cost per cost category (ZAR/m^3)
Equipment & Working Capital	390.06	373.40	422.94	460.36	389.58	407.23
Maintenance	94.98	90.92	102.98	119.70	102.90	102.30
Labour	112.38	107.58	121.86	142.70	124.96	121.90
Energy	40.46	38.72	43.86	46.04	44.10	42.64
Water	3.70	3.54	4.00	4.60	4.42	4.05
Other	83.08	79.54	90.10	101.28	84.54	87.71
Total per company	724.66	693.70	785.74	874.68	750.50	765.86

4.5.2. Financial Costs of Manufacturing Recycled Aggregates

Financial Cost Associated with the Demolition of the Structure

The study explored financial costs associated with demolition activities, influenced by factors like the complexity of a building structure and material composition. The cost of demolishing $1m^3$ of a building structure is 573.35 ZAR on average, with the minimum value of 415.81 ZAR and a maximum of 649.98 ZAR.

The study's results indicate that the highest cost component for demolition operations is equipment and working capital, accounting for approximately 66% of total costs. This is likely due to the significant investment required for specialized demolition equipment, such as excavators, and bulldozers. Energy costs follow closely, making up around 24% of total costs, reflecting the high energy demands of operating heavy machinery and equipment. Labour costs, at approximately 9%, are also significant, highlighting the importance of skilled personnel in operating and maneuvering demolition equipment. Maintenance costs, at approximately 1%, are lower compared to equipment and energy costs, but still essential for ensuring the reliability and efficiency of demolition equipment. Notably, there are no water costs associated with demolition operations, as water is not a significant input in the demolition process. Other costs, such as overheads and miscellaneous expenses, were not recorded, likely due to the focus on equipment-intensive operations and minimal administrative requirements. These findings suggest that demolition contractors should prioritise efficient equipment use, energy management, and skilled labour to minimise costs and maximise profitability.

Table 4.7: *Financial costs for demolishing building structures.*

Costs	DM01	DM02	DM03	DM04	DM05	Mean cost per cost category
	(ZAR/m^3)	(ZAR/m^3)	(ZAR/m^3)	(ZAR/m^3)	(ZAR/m^3)	(ZAR/m^3)
Equipment & Working Capital	428.57	481.48	280.00	420.00	274.81	376.97
Maintenance	5.43	2.41	6.00	8.00	1.37	4.64
Labour	42.86	37.04	48.00	100.00	37.04	52.99
Energy	173.12	141.06	69.25	207.74	102.59	138.75
Total Costs per company	649.98	661.99	403.25	735.74	415.81	**573.35**

Financial Cost Associated with Processing Rubble

The rubble processors' results have provided insights into the economic aspects of the recycling sector, particularly in the production of recycled aggregates. The average financial investment required by a typical company to produce recycled aggregates is 639.35 ZAR/m^3, as shown in Table 4.8.

The present study's results indicate that the highest cost component for rubble processing operations is equipment and working capital, accounting for approximately 56% of total costs. This is likely due to the significant investment required for processing machinery, conveyors, and other specialised equipment necessary for transforming rubble into reusable aggregates. Labour costs follow, making up around 16% of total costs, highlighting the importance of skilled personnel in operating and maintaining the processing facilities. Maintenance costs, at approximately 12%, are also significant, emphasizing the need for regular upkeep and repair of equipment to ensure

efficient processing operations. Other costs, including overheads, account for around 11% of total costs. Energy costs, at approximately 6%, are relatively lower, reflecting the more efficient energy use in processing operations compared to quarrying. Water costs are the lowest, at approximately 1%, likely due to the minimal water requirements in rubble processing. These findings suggest that rubble processors need to prioritise efficient equipment use, effective labour management, and regular maintenance to minimise costs and maximise profitability.

Table 4.8: *Financial costs for repurposing the construction rubble into recycled aggregates.*

Costs	RP01 (ZAR/m^3)	RP02 (ZAR/m^3)	RP03 (ZAR/m^3)	RP04 (ZAR/m^3)	Mean per cost category (ZAR/m^3)
Equipment & Working Capital	341.14	331.49	406.67	261.59	359.77
Maintenance	73.08	70.99	87.09	68.24	77.05
Labour	98.44	95.66	117.35	70.64	103.82
Energy	33.43	32.49	39.85	95.18	35.26
Water	4.33	4.21	5.17	32.32	4.57
Other	68.72	66.78	81.92	66.44	72.47
Total per company	619.14	601.62	738.05	598.60	639.35

Total Financial Cost Associated with Manufacturing Recycled Aggregates

The mean financial cost of manufacturing $1m^3$ (demolishing a building structure and processing the construction rubble into recycled aggregates) is 1212.71 ZAR. Data shown above are the summations of the financial costs from demolition contractors in Table 4.8 and rubble processors in Table 4.9 (DC + RP) and the mean financial costs. The lowest it costs to manufacture $1m^3$ of recycled aggregates is 1001.85 ZAR which is 17% less than the mean while the highest it cost is 1473.79 ZAR which is 42% higher than the mean.

Table 4.9: *Combined financial costs of manufacturing $1m^3$ of recycled aggregates from demolition contractors and rubble processors.*

Financial Cost (ZAR/m^3)		Financial Cost from Demolition Contractors					**Mean**
		DC01	DC02	DC03	DC04	DC05	
Financial Costs from Rubble Processors	RP01	1269.12	1281.13	1022.39	1354.88	1034.95	**1192.49**
	RP02	1251.60	1263.61	1004.87	1337.36	1017.43	**1174.97**
	RP03	1388.03	1400.04	1141.3	1473.79	1153.86	**1311.40**
	RP04	1248.58	1260.59	1001.85	1334.34	1014.41	**1171.95**
Mean		**1289.33**	**1301.34**	**1042.60**	**1375.09**	**1055.16**	**1212.71**

Abbreviations: DC - Demolition Contractors, RP – Rubble Processor

4.5.3. Comparison of Recycled Aggregates Production and Natural Aggregates Production Costs

The mean financial cost of producing recycled aggregates is 1212.71 ZAR/m^3, while the mean cost of manufacturing natural aggregates is 765.86 ZAR/m^3, which is 36.8% lesser, with a statistically significant P-value less than 0.0001 ($p < 0.001$). The higher financial costs of demolishing building structures has resulted in the higher costs for manufacturing recycled aggregates. However, the recycling process, which involves repurposing the already demolished materials (rubble), was found to be more cost efficient.

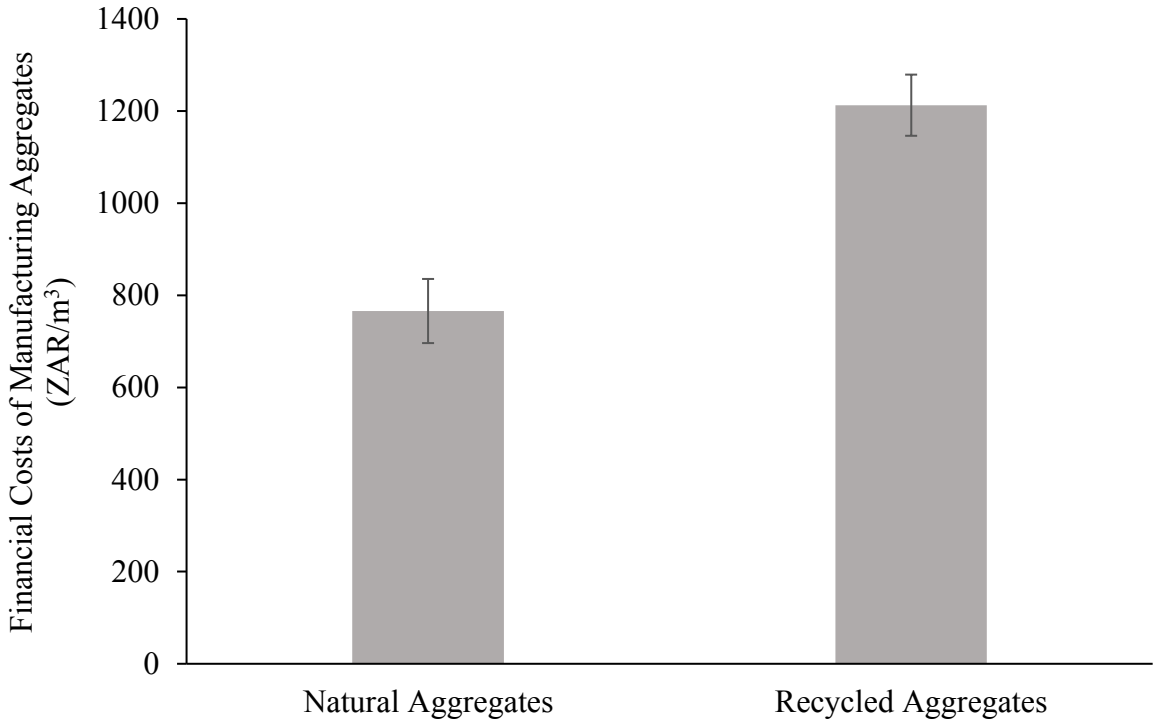


Figure 4.14: *Total Costs of Producing Recycled Aggregates and Natural Aggregates from Rubble Processors and Quarry Sites, respectively.*

4.6. Computation of the Feasible Transportation Distance

4.6.1. Calculation of the Feasible Transport Distance

The study aimed to determine the feasible transport distance for repurposing rubble into recycled aggregates by comparing the environmental benefits and economic viability of aggregates supply.

To calculate the feasible transport distance, the following formula was used;

$$D = \frac{1}{P}\left(\frac{\sum \chi_{i(NA)}}{n_1} - \frac{\sum \chi_{i(RA)}}{n_2}\right) \quad \text{... Equation [2]}$$

Where;

D = transportation distance

P = price of fuel consumed to travel 1km *(when the price of fuel is highest, lowest, and average between the months of January 2023 and December 2023 inclusive)*

n_1 = sample size of natural aggregates

n_2 = sample size of recycled aggregates

$\sum \chi_{i}(NA)$ = summation of financial costs for producing natural aggregates

$\sum \chi_{i}(RA)$ = summation of financial costs for producing recycled aggregates

Three fuel price scenarios were used, the first scenario is when the fuel price was highest between January 2023 and December 2023, the second scenario was the lowest fuel price in 2023 while the last scenario was the average fuel price of all the 12 months of 2023.

When price of fuel (diesel), was the highest

Fuel price = 25.22 ZAR per 1L of diesel, and 0.46L of fuel travels 1 kilometre (1 km)

P = 11.60 ZAR per kilometre,

$$D = \frac{(765.86-1212.71)ZAR}{11.60\ ZAR/km}$$

= -38.52 km

When the price of fuel (diesel), was the lowest

Fuel price = 19.31 ZAR per 1L of diesel, and 0.46L of fuel travels 1km.

P = 8.88 ZAR per kilometre,

$$D = \frac{(765.86-1212.71)ZAR}{8.88\ ZAR/km}$$

= -50.32 km

When price of fuel (Diesel), was the average

Fuel price = 21.64 ZAR per 1L of diesel, and 0.46L of fuel travel 1 kilometre

P = 9.95 ZAR per kilometre,

$$D = \frac{(765.86 - 639.35) ZAR}{9.95\ ZAR/km}$$

$$= -44.91 \text{ km}$$

The results indicate that all the calculated values for feasible transport distances are negative. This outcome suggests that there is no feasible transport distance for repurposing construction rubble into recycled aggregates in Johannesburg, Gauteng. This outcome is location specific and may be different for other regions in Gauteng or South Africa as a whole.

4.6.2. Calculation of the Feasible Transport Distance excluding the Demolition Costs

The costs for recycled aggregates (1212.71 ZAR/m^3) used to compute the transport distance in the above section, 4.6.1 was inclusive of the costs of first demolishing building structures and then processing the construction rubble into recycled aggregates. This section computes the transport distance using the recycled aggregates cost (639.35 ZAR/m^3) that is exclusive of demolition costs, assuming that the construction rubble is readily available.

The same formula as well as same scenarios for fuel prices that was used in section 4.6.1 were used to calculate the distance:

$$D = \frac{1}{P} \left(\frac{\sum \chi_{i^{(NA)}}}{n_1} - \frac{\sum \chi_{i^{(RA)}}}{n_2} \right) \qquad \text{…Equation [2]}$$

<u>When price of fuel (diesel), is highest</u>

Fuel price = 25.22 ZAR per 1L of diesel, and 0.46L of fuel travels 1 kilometre (1 km)

P = 11.60 ZAR per kilometre,

$$D = \frac{(765.86 - 639.35)ZAR}{11.60\ ZAR/km}$$

= 10.90 km

When the price of fuel (diesel), is lowest

Fuel price = 19.31 ZAR per 1L of diesel, and 0.46L of fuel travels 1km.

P = 8.88 ZAR per kilometre,

$$D = \frac{(765.86 - 639.35)ZAR}{8.88\ ZAR/km}$$

= 14.25 km

When price of fuel (Diesel), is average

Fuel price = 21.64 ZAR per 1L of diesel, and 0.46L of fuel travel 1 kilometre

P = 9.95 ZAR per kilometre,

$$D = \frac{(765.86 - 639.35)ZAR}{9.95\ ZAR/km}$$

= 12.71 km

The hypothesis of the study stated that the most effective aggregate production method involved supplying rubble, which is processed into recycled aggregates for use within a 20 kilometre radius of construction sites and concrete plants. All the three different scenarios in this section result in positive transport distances, illustrating feasible distances, all within a 20 km radius.

4.7. Summary and Discussion

4.7.1. Summary of Main Findings

The present study compared the financial costs, energy consumption, and carbon dioxide emissions of manufacturing recycled aggregates in comparison to natural aggregates. Firstly, the financial costs of manufacturing recycled aggregates are 58.35% higher than the costs of manufacturing natural aggregates. Secondly, the energy consumption during the manufacturing process of natural aggregates is less than the energy consumption of recycled aggregates. This indicates that recycled aggregates require 354% more energy to manufacture. Thirdly, the carbon dioxide emissions during the manufacturing process of recycled aggregates are 427% higher than those of natural aggregates.

Lastly, there was no feasible transport distance, this motivates for the need for more recycling sites in Johannesburg. Furthermore, that on-site recycling at the demolition site is the most efficient and effective approach. This may suggest that recycling aggregates closer to the source can minimize transportation costs and potentially associated environmental impacts. This approach is not new and has already been adopted, as the company with the lowest energy consumption, which was attributed to by recycling on-site. Since for that one company, rubble was crushed at the demolition site, there was no transportation distance, which resulted in less energy consumption. This is in line with the Hameed and Chini (2010) concept, where it was discovered that the best cost-effective and energy-efficient approach is to crush concrete waste at the demolition site, where the subsequent recycled aggregate is reused in new construction project.

As the construction industry continues to grow, it is essential to adopt sustainable practices that reduce environmental impacts. The use of recycled aggregates may offers a promising solution.

4.7.2. Discussion

4.7.2.1. Manufacturing Processes of Natural Aggregates and Recycled Aggregate

Traditionally, natural aggregates were and are still being used to manufacture concrete. Currently, recycled aggregates are being incorporated into concrete manufacturing to mitigate some of the environmental challenges associated with natural aggregates. Manufacturing processes of natural aggregates and recycled aggregates have some similarities and differences. The findings of this study show that the most common processes of manufacturing natural aggregates are extraction of the parent rock, where the rock is drilled and blasted, followed by crushing and screening. This is corroborated in the study by Gbeve (2013).

In contrast, recycled aggregates are made from materials that have been previously used in construction projects, such as construction and demolition waste. For this study, the focus was on the demolition waste, construction rubble. Similar to natural aggregates, processing rubble encompasses crushing the clean rubble and screening it to produce various sizes. These processes support those discussed in much earlier studies and more recent research by O'Mahony and O'Mahony (1990), Duan et al. (2020) Arora and Arora (2015) and Silva et al. (2016).

In summary, some similarities picked in the study were seen in the manufacturing processes of natural aggregates and recycled aggregates which are the crushing and screening processes while the main differences are in the extraction and demolition activities, respectively. Another similarity that was observed is the type of fuel types used to power machinery of the natural and recycled aggregates manufacturing, which similar to the study conducted by Ghanbari et al. (2017) are diesel and electricity. Understanding these processes is crucial as they can aid stakeholders to make informed decisions on adopting sustainable practices in the aggregate industry.

4.7.2.2. Environmental Costs of Manufacturing Natural and Recycled Aggregates

The environmental costs of producing both natural and recycled aggregates are crucial factors to consider when selecting materials for a sustainable construction industry. Natural aggregates are commonly used in construction projects, however, they can come with high extraction and transportation costs. On the other hand, recycled aggregates - produced from demolition waste in this study - may offer a more sustainable alternative, offering several benefits, as discussed in the following.

Previous studies (Tam, 2008; Hossain et al., 2020; Ohemeng and Ekolu, 2020) have found environmental costs of manufacturing natural aggregates to be greater than the manufacturing costs of recycled aggregates. Although recycled aggregates are often considered a more environmentally friendly option, the present study shows that the embodied energy of recycled aggregates exceeds that of natural aggregates. This is largely due to the high demolition costs associated with recycled aggregates, with demolition contractors contributing the most to the overall environmental costs. In this study, environmental costs include the embodied energy of both the natural aggregates and recycled aggregates. The results indicate that the energy consumption and carbon dioxide emitted during the production processes are higher for recycled aggregates than natural aggregates.

While this study shows that the processes involved in recycled aggregates result in higher embodied energy, the environmental costs of quarry extraction are significant and, to some extent, immeasurable. The environmental impact of natural aggregates includes the depletion of natural resources, emissions from transportation, habitat destruction, and potential environmental degradation, as highlighted in previous studies (Coelho and de Brito, 2011; Moeletsi, 2018; Kafu-Quvane and Mlaba, 2024). These factors were not quantified in this study, making natural

aggregates appear to be a more cost-effective option. However, when selecting materials, the long-term consequences of resource depletion and the environmental impacts of extraction and transportation must also be taken into account.

Quarrying changes landscapes negatively, causing permanent changes in topography and water table (Kindiga, 2017; Moeletsi, 2018; Samba et al., 2022). It can cause severe impacts on biodiversity and wildlife, disrupting habitat quality. While it offers job opportunities and economic growth, it also has adverse impacts on biodiversity and wildlife (Kafu-Quvane and Mlaba, 2024). The economic growth comes at a significant cost, affecting future generations and the environment which often cannot be rehabilitated. Furthermore, quarrying sites generate dust and indirect emissions during blasting operations, causing air pollution and affecting the ecosystem (Mathe, 2022; Kafu-Quvane and Mlaba, 2024). Dust affects animals and plants, leading to lung problems (Mathe et al., 2022).

Recycled aggregates, on the other hand, come with their own challenges, including higher embodied energy, dust generation, and potential contamination risks. The high costs of demolition significantly contribute to the overall manufacturing costs of recycled aggregates. While both demolition and quarrying generate dust, demolition is a relatively short-term activity, typically lasting about a year, whereas quarries can operate for up to 50 years. The longer operational lifespan of quarries results in a more prolonged and substantial dust impact.

However, despite the costs of recycled aggregates observed, they also offer benefits such as reduced waste sent to landfills and conservation of natural resources. Begum et al. (2006) indicate that waste minimization offers environmental benefits such as extending landfill site lifespan and reducing primary resource demands. Other benefits include reduced liability for

environmental problems and a lower chance of soil and groundwater contamination (Begum et al., 2006).

In addition, unlike quarrying, which involves energy-intensive processes of material extraction, transportation, and processing (Alqadi et al., 2023), recycling leverages existing materials (Olawumi et al., 2023). This addresses concerns related to resource depletion (Ferrandez et al., 2023). It has been shown that the construction sector, a major contributor to carbon emissions (Sizirici et al., 2021), can benefit from promoting the widespread use of recycled aggregates. This could involve urging governments and companies to prioritise recycled materials, implementing strict environmental standards, and fostering stakeholder collaborations to establish more recycling site and streamline the integration of recycled aggregates into construction projects.

4.7.2.3. Financial Costs of Manufacturing Natural and Recycled Aggregates

In addition to environmental impacts, financial costs play an important role in the production of aggregates. The costs incurred by companies vary significantly due to differences in equipment, operating costs, building complexity, material composition, and waste management strategies.

Previous studies (Tam, 2008; Ohemeng and Ekolu, 2020) conducted a cost-benefit analysis for the use of natural aggregates and the use of recycled aggregates. They revealed that recycling construction waste is more cost efficient. Tam et al. (2018) has demonstrated the use of recycled aggregates in concrete to provide a promising solution to the problem of construction and demolishing waste.

However, the studies by Tam (2008) and Ohemeng and Ekolu (2020) do not account for demolition costs, as their cost-benefit analyses begin with the transportation of construction waste

to the recycling plant. This may also suggest that the type of construction and demolition waste used in their studies did not include demolition waste.

Therefore, in the present study, the costs incurred during the demolition processes have been added to the total costs of manufacturing recycled aggregates, making the demolition of building structures the first stage. Furthermore, it was observed that the financial cost of manufacturing recycled aggregates are greater than the financial costs of manufacturing natural aggregates. The increase in costs for the recycled aggregates may be explained by the additional costs of demolition activities which were not covered in the previous studies (Tam, 2008; Ohemeng and Ekolu, 2020).

In addition to the previous studies mentioned above, Begum et al. (2006), in their case study highlighted the cost savings and efficiency that result from on-site waste minimisation, which further corroborates that the benefits of recycled aggregates by some studies outweighs the benefits of natural aggregates. In their case study (Begum et al., 2006), the total benefits exceed the total costs, resulting in the positive net benefit of reusing and recycling waste on-site.

Moreover, the present study's findings highlight the need for an understanding of the holistic costs and benefits associated with natural and recycled aggregates. Cost efficiency is crucial for a sustainable and economically viable recycling sector, contributing to the circular economy and reducing environmental impact (Barros et al., 2021; Knäble et al., 2022). To enhance the viability of recycled aggregates, strategies must be explored to reduce their costs and environmental impacts. Optimising demolition techniques, and working towards minimising demolition costs would promote the use of recycled aggregates. Proper deconstruction design and planning for material recovery prior to demolition processes are two of the possible strategies that may contribute in the demolition cost minimisation (Schultmann and Sunke, 2007; Pitso, 2020).

Furthermore, to transition towards a circular economy, the construction industry may have to prioritize material conservation and value throughout their lifecycle. This transition is not only dependent on environmental considerations but also on the potential for long-term cost savings, contributing to the resilience and competitiveness of construction projects. This requires innovative thinking, collaboration, and policy support. Collaboration of the industry stakeholders are key to achieving waste reduction, conservation of resources, and building a sustainable future.

Policymakers and industry stakeholders should collaborate to create incentives that encourage the use of recycled aggregates, such as investing in research and development, providing subsidies for recycled construction products, and offering tax credits to companies that utilize these materials. By understanding the full costs associated with each material type, including their entire lifecycle from extraction to end-of-life disposal or recycling, a more sustainable future for the construction industry can be achieved.

4.7.2.4. Feasible Transport Distance for Repurposing Construction Rubble into Recycled Aggregates

One of the primary objectives of this study was to calculate the feasible transport distance for repurposing demolition rubble into recycled aggregates. According to this study, the transportation of aggregates in Gauteng primarily relies on road transport, with the environmental impact varying based on distance. Therefore, the discussion focuses specifically on road transport impacts. The findings of the present study reveal a significant difference (-50.32 km to 14.25 km) in the feasible transport distances when demolition costs are added to the rubble processing costs versus when they are not considered. This difference highlights the impact of demolition costs on the feasibility of adopting recycling aggregates. The previous study by Zhang et al. (2019a)

corroborates the difference and uncertainty of the recycled aggregates transport distances that are observed in the present study.

It was observed that high embodied energy of demolition processes contributes substantially to the overall costs of demolition. Demolition requires significant energy inputs for machinery, labour, and waste management, which translates to a considerable carbon footprint. Moreover, the financial costs of demolition, such as equipment purchase or rental as well as labour expenses, add to the economic costs. These costs are typically high due to the complex and labour-intensive nature of demolition processes as observed from the results.

When demolition costs are factored into the overall costs of repurposing rubble into recycled aggregates, the resulting transport distances are negative. The negative transport distance suggests that there is no feasible distance to repurpose the rubble, in Johannesburg. The energy and financial costs of demolition outweigh the environmental and economic benefits of recycling.

On the other hand, excluding demolition costs reveals a positive transport distance, indicating that the environmental benefits of recycling aggregates outweigh the costs of manufacturing virgin aggregates. This suggests that if the demolition processes in Johannesburg could be made more efficient or cost-effective, recycling aggregates could become a more viable option. In this scenario, the energy savings and reduced greenhouse gas emissions from recycling outweigh those of natural aggregates and the costs of transportation, making it a more viable choice.

The positive distance results suggest that processing rubble into recycled aggregates is economically viable if demolition costs are not included. However, since demolition is an integral part of the recycling process, excluding these costs from calculations does not provide a comprehensive picture of the overall feasibility. Furthermore, computation of the feasible distance with the exclusion of demolition costs indicates that if the rubble is already available and does not require demolition, repurposing it becomes more cost-effective than using natural materials up to a distance of 14.25 km. Beyond this point, the costs of transportation and processing exceed the costs of extracting and processing natural aggregates. While in the present study, no feasible distance was observed, the findings from a previous study (Marinkovic et al., 2010) revealed recycled aggregates transportation distance of 20 km.

Furthermore, the present study findings have significant implications for the construction industry in Johannesburg. They suggest that recycling rubble is only cost-effective when the demolition costs are minimal, and the transportation distance is relatively short.

The results of this study underscore the importance of understanding the costs and benefits associated with repurposing rubble compared to using natural materials. By factoring in transportation and demolition costs, construction contractors and policymakers can make informed decisions about the most environmentally sustainable and cost-effective options for their projects.

Furthermore, the findings suggest opportunities for innovation and optimization within the recycling process. By reducing demolition costs and enhancing transportation efficiency, the cost-effectiveness of repurposing rubble could be extended over longer distances, making it a more viable option for the construction industry. Additionally, understanding the optimal distance for

recycling enables stakeholders to make informed decisions regarding the placement of recycling facilities and the logistics of transporting construction waste.

It was noted that fuel costs influence the distance at which recycling becomes more cost-effective (Zhang et al., 2019b). This is evident in the results, as varying fuel price scenarios led to different optimal distances. This indicates that both transportation costs and economic factors significantly affect the viability of recycling construction waste and its overall environmental impact.

CHAPTER FIVE – CONCLUSIONS & RECOMMENDATIONS

5.1. Navigating Towards Sustainable Aggregate Production in Johannesburg

By assessing the feasibility of using construction rubble within nearby distances, this study analysed the environmental and financial costs, as well as the transport limitations associated with aggregate production in Johannesburg, Gauteng, South Africa. This evaluation facilitated a comparison of the production and supply models for natural and recycled aggregates. The research focused on the manufacturing processes of aggregates, which included the extraction of natural aggregates, demolition of building structures, processing, energy consumption, emissions, economic costs, and the financial distribution of rubble processing units.

The hypothesis, stated the effectiveness of a distributed recycling model within 20km, is not validated. However, efforts were made to investigate why this was not the case. By excluding demolition costs from the total costs of manufacturing recycled aggregates, the study revealed that high demolition costs make the recycling aggregates manufacturing economically and environmentally costly, resulting in an unfeasible distance.

5.2. Objective Review

The objectives in chapter one guided the research, motivating a review of extraction and processing methods for natural aggregates as well as the manufacturing processes of recycled aggregates. From drilling and blasting of natural aggregates to the demolition, sorting, and recycling processes for recycled aggregates, through which construction materials are sourced and manufactured were studied.

5.2.1. Environmental and Financial Costs

The objectives were centred on evaluating the environmental and financial costs of the two aggregate production and supply models. Natural aggregates portrayed lesser manufacturing costs, both financially and environmentally, compared to recycled aggregates. However, the use of

recycled aggregates helps in reducing the pressure on natural resources and decreases the amount of waste sent to landfills. Thus, more research is required to investigate on ways in which recycled aggregates manufacturing can be more energy efficient and cost efficient. Ultimately achieving a greater economic and environmental sustainability in the manufacturing and supply of recycled aggregates in Johannesburg.

Furthermore, while the embodied energy is greater for recycled aggregates compared to natural aggregates, the former are still the best alternative materials to use in concrete production as quarrying activities have other unquantified long-term environmental costs.

5.2.2. Economic Distribution of Recycling Sites

In conclusion, the study's findings indicate that the economic distribution of recycling aggregates in the Johannesburg is not feasible, disproving the initial hypothesis of 20 km. This has significant implications for the construction industry, highlighting the need for on-site recycling and localised aggregate sources to make recycling economically viable.

5.3. Towards a Sustainable Future

The present study explored the production and supply of aggregate in Johannesburg, Gauteng. By integrating these insights into industry practices, stakeholders can contribute to a greener, more economically efficient, and environmentally responsible construction industry in Johannesburg. The study is a step towards promoting economic prosperity and environmental responsibility in the procurement of construction material in South Africa.

5.4. Implications and Recommendations

The current study emphasises the significance of recycling units as not just waste processors but also economic entities in promoting sustainable construction practices, emphasising their role in transitioning to a circular construction environment. Furthermore, the findings covered suggestions for the construction industry, policymakers, and environmental advocates. Recommendations include further research on demolition and deconstruction practices, how to plan for salvaging wasting and reduce the embodied energy and financial costs. Other recommendations include motivating the establishment of recycling infrastructure, fostering collaborative efforts between stakeholders, and formulating policies that promote sustainable material sourcing practices.

5.5. Limitations

- The study focuses on the city of Johannesburg, located in the province of Gauteng, South Africa.
- The fuel prices fluctuate from time to time, only three fuel prices were considered, the lowest, highest, and average fuel prices were used in the analysis, as we do not have a fixed fuel price.

5.6. Recommendation for Future Studies

Future research should focus on the following:

- Refining and enhancing sustainable practices in recycled aggregate production especially in demolition processes to further reduce energy emissions and consumption.

- Investigating innovative technologies and methods to minimise the environmental impact of the production process, such as exploring renewable energy sources for demolition equipment, crushers and screeners, can be an area of exploration.
- Examination of the use of demolition waste in Johannesburg, addressing potential barriers such as regulatory constraints, a lack of awareness, or perceived quality issues.
- Identifying strategies to overcome demolition challenges and promoting the incorporation of demolition waste into the construction material stream will be crucial for promoting a circular economy.
- To facilitate the adoption of recycled aggregates by contractors, investigation on ways to simplify the procurement process is essential. Exploring initiatives like introducing incentives for contractors to choose recycled aggregates can simplify decision-making and boost confidence in the material's performance. These measures will contribute to creating a more user-friendly environment, promoting the widespread adoption of sustainable construction practices.
- Understanding the factors contributing to the high amount of demolition processes in Johannesburg compared to other regions is essential. Future studies can explore the challenges and opportunities associated with expanding recycle aggregates processing facilities in Johannesburg as well as Gauteng province as a whole. By addressing these key areas, future research can play a role in advancing the knowledge and implementation of sustainable practices in construction material sourcing and waste management.

REFERENCES

Abeysundara, U.Y., Babel, S. and Gheewala, S. (2009) "A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka." *Building and environment*, *44*(5), pp.997-1004. https://doi.org/10.1016/j.buildenv.2008.07.005

Abu Seif, E.S.S. (2014) "Geotechnical approach to evaluate natural fine aggregates concrete strength, sohag, governorate, Upper Egypt." *Arabian Journal of Geosciences*, 8(9), pp. 7565–7575. https://doi.org/10.1007/s12517-014-1705-3

Adeleke, O., Akinlabi, S., Jen, T.C. and Dunmade, I. (2021) "Towards sustainability in municipal solid waste management in South Africa: a survey of challenges and prospects." *Transactions of the Royal Society of South Africa*, *76*(1), pp. 53-66. https://doi.org/10.1080/0035919X.2020.1858366

Adesina, A. and Zhang, J. (2024) "Impact of concrete structures durability on its sustainability and climate resiliency." *Next Sustainability*. https://doi.org/10.1016/j.nxsust.2024.100025

Ajamu, S.O. and Ige, J.A. (2015) "Influence of coarse aggregate type and mixing method on properties of concrete made from natural aggregates in ogbomoso oyo state Nigeria." *International Journal of Engineering and Technology*, *5*(7), pp. 426-433 https://www.researchgate.net/profile/Ajamu-Olalere-2/publication/328265586

Akhimien, N.G., Latif, E. and Hou, S.S. (2021) "Application of circular economy principles in buildings: A systematic review." *Journal of Building Engineering*. Elsevier Ltd. https://doi.org/10.1016/j.jobe.2020.102041

Alexander, M. (2017) *South Africa's population (South Africa Gateway)*. INTERNET. https://southafrica-info.com/people/south-africa-population/

Almusaed, A. and Almssad, A. (2018) "Introductory chapter: overview of a competent sustainable building." *Sustainable Buildings—Interaction Between a Holistic Conceptual Act and Materials Properties*. https://books.google.co.za/books?id=techniquethathasbeensuccessfullyusedsinceancienttimes

Alqadi, S.B., Alamleh, D., Eldin, I.N. and Eldin, H.N., (2023) "A comparative life cycle energy and green house emissions of natural and artificial stone-manufacturing phase." *Results in Engineering*, *18*. https://doi.org/10.1016/j.rineng.2023.101055

Alsheyab, M.A.T. (2022) "Recycling of construction and demolition waste and its impact on climate change and sustainable development." *International Journal of Environmental Science and Technology*, *19*(3), pp. 2129-2138. https://doi.org/10.1007/s13762-021-03217-1

Althoey, F., Ansari, W.S., Sufian, M. and Deifalla, A.F. (2023) "Advancements in low-carbon concrete as a construction material for the sustainable built environment." *Developments in the Built Environment, 16*.
https://doi.org/10.1016/j.dibe.2023.100284

Aminzadegan, S., Shahriari, M., Mehranfar, F., & Abramović, B. (2022) "Factors affecting the emission of pollutants in different types of transportation: A literature review." *Energy Reports*, *8*, pp. 2508–2529.
https://doi.org/10.1016/j.egyr.2022.01.161

Arora, S. and Arora, S. (2015) "Recycled aggregates: a sustainable solution of construction and demolished waste." *IOSR Journal of Mechanical and Civil Engineering*, pp.2278-1684.
https://www.researchgate.net/publication/284714936

Arumningsih, D., Priyanto, K.J. and Mowo, C.L. (2022) "Sustainable Green Concrete Using Shellfish Waste Powder, and Rice Husk Ash." *Jurnal Teknik Sipil dan Arsitektur*, *27*(2), pp.18-27.
https://doi.org/10.36728/jtsa.v27i2.1857

B. Muhit, I., Haque, S. and Alam, Md. (2013) "Influence of Crushed Coarse Aggregates on Properties of Concrete." *American Journal of Civil Engineering and Architecture*, 1(5), pp. 103–106.
https://doi.org/10.12691/ajcea-1-5-3

Barbhuiya, S., Kanavaris, F., Das, B.B. and Idrees, M. (2024) "Decarbonising cement and concrete production: Strategies, challenges and pathways for sustainable development." *Journal of Building Engineering*.
https://doi.org/10.1016/j.jobe.2024.108861

Barros, M.V., Salvador, R., do Prado, G.F., de Francisco, A.C. and Piekarski, C.M. (2021) "Circular economy as a driver to sustainable businesses." *Cleaner Environmental Systems*, *2*.
https://doi.org/10.1016/j.cesys.2020.100006

Barton, J.R., Dalley, D. and Patel, V.S. (1996) "Life Cycle Assessment for Waste Management." *Waste Management*.
https://doi.org/10.1016/S0956-053X(96)00057-8

Bascompta, M. *et al.* (2022) 'LCA analysis and comparison in quarrying: Drill and blast vs mechanical extraction', *Journal of Cleaner Production*, 369.
https://doi.org/10.1016/j.jclepro.2022.133042

Batayneh, M., Marie, I. and Asi, I. (2007) "Use of selected waste materials in concrete mixes." *Waste management*, *27*(12), pp.1870-1876.
https://doi.org/10.1016/j.wasman.2006.07.026

Begum, R.A., Siwar, C., Pereira, J.J. and Jaafar, A.H. (2006) "A benefit–cost analysis on the economic feasibility of construction waste minimisation: The case of Malaysia." *Resources, conservation and recycling*, *48*(1), pp.86-98.

https://doi.org/10.1016/j.resconrec.2006.01.004

Berge, S. and Von Blottnitz, H., (2022) "An estimate of construction and demolition waste quantities and composition expected in South Africa." *South African Journal of Science*, *118*, pp.1-5. http://dx.doi.org/10.17159/sajs.2022/12485

Bi, J., Sai, Q., Wang, F. and Chen, Y. (2022) "Identification of working trucks and critical path nodes for construction waste transportation based on electric waybills: A case study of Shenzhen, China." *Journal of Advanced Transportation* (1). https://doi.org/10.1155/2022/7647121

Braga, A.M., Silvestre, J.D. and de Brito, J. (2017) "Compared environmental and economic impact from cradle to gate of concrete with natural and recycled coarse aggregates." *Journal of Cleaner Production*, 162, pp. 529–543. https://doi.org/10.1016/j.jclepro.2017.06.057

Careddu, N. and Siotto, G. (2011) "Promoting ecological sustainable planning for natural stone quarrying. The case of the Orosei Marble Producing Area in Eastern Sardinia." *Resources Policy*, *36*(4), pp.304-314. https://doi.org/10.1016/j.resourpol.2011.07.002

Chen, W., Jin, R., Xu, Y., Wanatowski, D., Li, B., Yan, L., Pan, Z. and Yang, Y. (2019) "Adopting recycled aggregates as sustainable construction materials: A review of the scientific literature." *Construction and Building Materials*, pp. 483–496. https://doi.org/10.1016/j.conbuildmat.2019.05.130

Coelho, A. and de Brito, J. (2011) "Economic analysis of conventional versus selective demolition - A case study." *Resources, Conservation and Recycling*, 55(3), pp. 382–392. https://doi.org/10.1016/j.resconrec.2010.11.003

Dammann, S. and Elle, M. (2006) "Environmental indicators: establishing a common language for green building." *Building Research & Information*, *34*(4), pp.387-404. https://doi.org/10.1080/09613210600766377

de Bortoli, A. (2023) "Understanding the environmental impacts of virgin aggregates: Critical literature review and primary comprehensive life cycle assessments." *Journal of Cleaner Production*, 415. https://doi.org/10.1016/j.jclepro.2023.137629

Department of Mineral Resources. (2014) "The Role of Aggregates and Sands in the Construction Industry." *Report R109/2014*. Pretoria: Directorate: Mineral Economics. https://www.dmre.gov.za/LinkClick.aspx?

De Marsily, G. and Abarca-del-Rio, R. (2016) "Water and food in the twenty-first century." *Remote sensing and water resources*, pp. 313-337. https://doi.org/10.1007/978-3-319-32449-4_13

Dias, A., Nezami, S., Silvestre, J., Kurda, R., Silva, R., Martins, I. and de Brito, J. (2022) "Environmental and economic comparison of natural and recycled aggregates using LCA." *Recycling*, *7*(4), p.43. https://doi.org/10.3390/recycling7040043

Dosumu, O. and Aigbavboa, C. (2019) "An investigation of the benefits and challenges of adopting alternative building materials (ABM) in the construction industry." *Innovative Production and Construction*, pp. 261–277. https://doi.org/10.1142/9789813272491_0016

Drew, L.J., Langer, W.H. and Sachs, J.S. (2002) "Environmentalism and natural aggregate mining." *Natural Resources Research*, *11*, pp.19-28. https://doi.org/10.1023/A:1014283519471

Duan, Z., Singh, A., Xiao, J. and Hou, S. (2020) "Combined use of recycled powder and recycled coarse aggregate derived from construction and demolition waste in self-compacting concrete." *Construction and Building Materials, 254*. https://doi.org/10.1016/j.conbuildmat.2020.119323

Eldesouki, M.H., Rashed, A.E. and El-Moneim, A.A. (2023) "A comprehensive overview of carbon dioxide, including emission sources, capture technologies, and the conversion into value-added products." *Clean Technologies and Environmental Policy*. Springer Science and Business Media Deutschland GmbH, pp. 3131–3148. https://doi.org/10.1007/s10098-023-02599-9

Faleschini, F., Zanini, M. A., Pellegrino, C., and Pasinato, S. (2016) "Sustainable management and supply of natural and recycled aggregates in a medium-size integrated plant." *Waste Management*, *49*, 146–155. https://doi.org/10.1016/j.wasman.2016.01.013

Ferrández, D., Saiz, P., Zaragoza-Benzal, A., and Zúñiga-Vicente, J.A. (2023) "Towards a more sustainable environmentally production system for the treatment of recycled aggregates in the construction industry: An experimental study". *Heliyon*, *9*(6). https://doi.org/10.1016/j.heliyon.2023.e16641

Fitchett, A. and Rambuwani, P. (2022) "Waste control in South African construction projects." *Transactions of the Royal Society of South Africa*, *77*(2), pp.105-112. https://doi.org/10.1080/0035919X.2022.2045383

Florez, L. and Castro, D. (2013) "Optimization model for sustainable materials selection using objective and subjective factors." *Materials & Design (1980-2015)*, *46*, pp.310-321. https://doi.org/10.1016/j.matdes.2012.10.013

Florez, L., Castro, D. and Irizarry, J. (2013) "Measuring sustainability perceptions of construction materials." *Construction innovation*, *13*(2), pp. 217-234. https://doi.org/10.1108/14714171311322174

Gamage, I., Senaratne, S., Perera, S. and Jin, X. (2024) "Implementing Circular Economy throughout the Construction Project Life Cycle: A Review on Potential Practices and Relationships." *Buildings*, *14*(3), pp. 653. https://doi.org/10.3390/buildings14030653

Ganesh, A.H., Shobana, A.H. and Ramesh, R., (2021) "Identification of critical path for the analysis of bituminous road transport network using integrated FAHP–FTOPSIS method." *Materials Today: Proceedings*, *37*, pp. 193-206. https://doi.org/10.1016/j.matpr.2020.05.015

Gbeve, B. (2013) *Environmental Impacts of Construction Aggregate Mining in the Greater Accra Region (A Case–Study of Amasaman in the Ga West Municipal)* (Doctoral dissertation). https://ir.knust.edu.gh/handle/123456789/5763

Ghanbari, M., Monir Abbasi, A., & Ravanshadnia, M (2017) "Environmental life cycle assessment and cost analysis of aggregate production industries compared with hybrid scenario." *Applied Ecology and Environmental Research*, *15*(3), pp. 1577–1593. https://doi.org/10.15666/aeer/1503_15771593

Ghisellini, P., Ripa, M. and Ulgiati, S. (2018) "Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review." *Journal of Cleaner Production*, *178*, pp. 618-643. https://doi.org/10.1016/j.jclepro.2017.11.207

Glavič, P. and Lukman, R. (2007) "Review of sustainability terms and their definitions." *Journal of cleaner production*, *15*(18), pp. 1875-1885. https://doi.org/10.1016/j.jclepro.2006.12.006

Godfrey, L., Roman, H., Smout, S., Maserumule, R., Mpofu, A., Ryan, G. and Mokoena, K. (2021) "Unlocking the opportunities of a circular economy in South Africa." *Circular Economy: Recent Trends in Global Perspective*, pp. 145-180. Singapore: Springer Nature Singapore. https://link.springer.com/chapter/10.1007/978-981-16-0913-8_5

Govender, D., Govender, T. and Whyte, C. (2023) *2023 Market Study of the Circular (& Waste) Economy of South Africa.* INTERNET. https://www.rvo.nl/sites/default/files/2023-10/SA-Circular-Economy-Opportunities.pdf

Guimaraes, M.S., Valdes, J.R., Palomino, A.M. and Santamarina, J.C. (2007) "Aggregate production: fines generation during rock crushing." *International journal of mineral processing*, *81*(4), pp. 237-247. https://doi.org/10.1016/j.minpro.2006.08.004

Habert, G., Bouzidi, Y., Chen, C. and Jullien, A. (2010) "Development of a depletion indicator for natural resources used in concrete." *Resources, conservation and recycling*, *54*(6), pp. 364-376. https://doi.org/10.1016/j.resconrec.2009.09.002

Hack, H.R.G.K. (2020) "Weathering, Erosion, and Susceptibility to Weathering." *Soft Rock Mechanics and Engineering*, pp. 291–333. https://doi.org/10.1007/978-3-030-29477-9_11

Hameed, M. and Chini, A. (2010) "Impact of transportation on cost and energy for recycled concrete aggregate." https://www.researchgate.net/publication/290860932

Harte, J. (2007) "Human population as a dynamic factor in environmental degradation." *Population and Environment*, 28(4–5), pp. 223–236. https://doi.org/10.1007/s11111-007-0048-3

Haupt, M. and Hellweg, S. (2019) "Measuring the environmental sustainability of a circular economy." *Environmental and Sustainability Indicators*, pp. 1–2. https://doi.org/10.1016/j.indic.2019.100005

Haywood, L.K., Kapwata, T., Oelofse, S., Breetzke, G. and Wright, C.Y. (2021) "Waste disposal practices in low-income settlements of South Africa." *International Journal of Environmental Research and Public Health*, *18*(15), pp. 8176. https://doi.org/10.3390/ijerph18158176

Hoekstra, A.Y. (2015) "The water footprint of industry." In *Assessing and measuring environmental impact and sustainability*, pp. 221-254. https://doi.org/10.1016/B978-0-12-799968-5.00007-5

Hoosain, M.S., Paul, B.S., Doorsamy, W. and Ramakrishna, S. (2023) "Comparing South Africa's sustainability and circular economic roadmap to the rest of the world." *Materials Circular Economy, 5*(1), pp. 2. https://doi.org/10.1007/s42824-023-00073-x

Hossain, M.U., Ng, S.T., Antwi-Afari, P. and Amor, B. (2020) "Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction." *Renewable and Sustainable Energy Reviews*, *130*. https://doi.org/10.1016/j.rser.2020.109948

Igogo, T., Awuah-Offei, K., Newman, A., Lowder, T. and Engel-Cox, J. (2021) "Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches." *Applied Energy*, *300*. https://doi.org/10.1016/j.apenergy.2021.117375

Janev, D., Nakov, D. and Arangjelovski, T. (2023) "Concrete for resilient infrastructure: review of benefits." *Challenges and Solutions*.

Kafu-Quvane, B., and Mlaba, S. (2024) "Assessing the impact of quarrying as an environmental ethic crisis: A case study of limestone mining in a rural community." *International Journal of Environmental Research and Public Health* 21(4).

https://doi.org/10.3390/ijerph21040458

Kats, G. (2013) *Greening our built world: costs, benefits, and strategies*. Island Press. https://books.google.co.za/books/Greening_Our_Built_World:_Costs_Benefits_and_Strategies

Katumba, S. and Everatt, D. (2021) "Urban Sprawl and Land Cover in Post-apartheid Johannesburg and the Gauteng City-Region, 1990–2018." *Environment and Urbanization*, 12, pp. S147–S164. https://doi.org/10.1177/0975425321997973

Kenzhegaliyeva, A. and Lund, H.B. (2024) "The role of proximity in environmental upgrading: plastics recycling in Norwegian aquaculture." *Geoforum*, *150*. https://doi.org/10.1016/j.geoforum.2024.103969

Khalaf, M.A., Ban, C.C. and Ramli, M. (2019) "The constituents, properties and application of heavyweight concrete: A review." *Construction and building materials*, *215*, pp.73-89. https://doi.org/10.1016/j.conbuildmat.2019.04.146

Khan, K., Ishfaq, M., Amin, M.N., Shahzada, K., Wahab, N. and Faraz, M.I. (2022) "Evaluation of mechanical and microstructural properties and global warming potential of green concrete with wheat straw ash and silica fume." *Materials*, *15*(9), pp. 3177. http://dx.doi.org/10.3390/ma15093177

Khan, M. and McNally, C. (2023) "A holistic review on the contribution of civil engineers for driving sustainable concrete construction in the built environment." *Developments in the Built Environment*. https://doi.org/10.1016/j.dibe.2023.100273

Khatleli, N. (2017) "Corporate Nodal Destination Choices in the Exodus from Johannesburg Central Business District, South Africa." *Inclusive City Growth and the Poor: Policies, Challenges and Prospects*, pp. 351. http://dx.doi.org/10.14455/ISEC.res.2017.128

Kindiga, S.W. (2017) "Environmental and land use impacts of quarrying along Ngong River in Embakasi." *Doctoral dissertation, University of Nairobi.* http://hdl.handle.net/11295/102654

Klanfar, M., Korman, T. and Kujundžić, T. (2016) "Fuel consumption and engine load factors of equipment in quarrying of crushed stone." *Tehnički vjesnik*, *23*(1), pp.163-169. https://doi.org/10.17559/TV-20141027115647

Knäble, D., de Quevedo Puente, E., Pérez-Cornejo, C. and Baumgärtler, T. (2022) "The impact of the circular economy on sustainable development: A European panel data approach." *Sustainable production and consumption*, *34*, pp.233-243. https://doi.org/10.1016/j.spc.2022.09.016

Kohler, N., van Niekerk, M., Manchidi, D., Nemakhavhani, L., Gordon, M., Mokoena, K., Pillay, A., Soobramany, S., Sehaswana, D. and Sibande, J. (2018) *South Africa State of Waste: A report on the state of the environment (Department of Environmental Affairs).* INTERNET. https://soer.environment.gov.za/Waste_Report_2018.pdf

Krishna, N.K., Sandeep, S. and Mini, K.M. (2016) "Study on concrete with partial replacement of cement by rice husk ash." *IOP Conference Series: Materials Science and Engineering*. Institute of Physics Publishing. https://doi.org/10.1088/1757-899X/149/1/012109

Kuter, N. (2013) "Reclamation of degraded landscapes due to opencast mining." *Advances in landscape architecture*. http://dx.doi.org/10.5772/55796

Labaran, Y.H., Mathur, V.S. and Farouq, M.M. (2021) "The carbon footprint of construction industry: A review of direct and indirect emission." *Journal of Sustainable Construction Materials and Technologies*, *6*(3), pp.101-115. https://doi.org/10.29187/jscmt.2021.66

Lehohla, PJ. (2017) *Mid-year population estimates 2017.* INTERNET. Available at: https://www.statssa.gov.za/publications/P0302/P03022017.pdf

Li, Y., Shen, J., Lin, H., Lv, J., Feng, S. and Ci, J. (2022) "Properties and environmental assessment of eco-friendly brick powder geopolymer binders with varied alkali dosage." *Journal of Building Engineering*, *58*. https://doi.org/10.1016/j.jobe.2022.105020

Ljungberg, L.Y. (2007) "Materials selection and design for development of sustainable products." *Materials & Design*, *28*(2), pp. 466-479. https://doi.org/10.1016/j.matdes.2005.09.006

Lourenço, P.B. (2014) "Masonry Structures, Overview." *Encyclopedia of Earthquake Engineering*. Springer Berlin Heidelberg, pp. 1–9. https://doi.org/10.1007/978-3-642-36197-5_111-1

Lu, H., Shang, Z., Ruan, Y. and Jiang, L. (2023) "Study on Urban Expansion and Population Density Changes Based on the Inverse S-Shaped Function." *Sustainability*, 15(13). https://doi.org/10.3390/su151310464

Luoma, K. (2016) "How does population growth impact rapid urbanization." *Population Education.* INTERNET. https://www.populationeducation.org/how-does-population-growthimpact-rapid-urbanization

Maluleke, R. (2022) *Mid-year population estimates 2022*. INTERNET. https://www.statssa.gov.za/publications/P0302/P03022022.pdf

Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010) "Comparative environmental assessment of natural and recycled aggregate concrete." *Waste Management*, *30*(11), pp 2255–2264. https://doi.org/10.1016/j.wasman.2010.04.012

Mathe, N.C., Rani, Z.T. and Mkhize, N.R. (2022) "The impact of quarrying activities and communal perceptions towards the environmental and animal welfare in the Ashburton community located in KZN Province, South Africa." *Masters Dissertation, UKZN.* https://researchspace.ukzn.ac.za/handle/10413/21471

Mavi, R.K., Gengatharen, D., Kiani Mavi, N., Hughes, R., Campbell, A. and Yates, R. (2021) "Sustainability in construction projects: A systematic literature review." *Sustainability*, *13*(4). https://doi.org/10.3390/su13041932

Mayowa, B. and Chinda, T. (2023) "Environmental Assessment of Demolition Tools Used in Townhouse Demolition: System Dynamics Modeling." *Sustainability (Switzerland)*, *15*(19). https://doi.org/10.3390/su151914382

Meddah, M.S. (2017) "Recycled aggregates in concrete production: engineering properties and environmental impact." *MATEC Web of Conferences*, 101(05021). https://doi.org/10.1051/matecconf/201710105021

Mfon, I.E. and Bassey, L. (2023) "Sustainable Materials and Construction Practices in Industrial Buildings." *International Journal of Developmental Studies and Environmental Monitoring*, *2*(1). https://www.researchgate.net/publication/375495465

Mhlanga, J., Haupt, T.C. and Loggia, C. (2024) "Shaping circular economy in the built environment in Africa. A bibliometric analysis." *Journal of Engineering, Design and Technology*. https://doi.org/10.1108/JEDT-03-2022-0175

Mistri, A., Bhattacharyya, S.K., Dhami, N., Mukherjee, A. and Barai, S.V. (2020) "A review on different treatment methods for enhancing the properties of recycled aggregates for sustainable construction materials." *Construction and Building Materials*, *233*. https://doi.org/10.1016/j.conbuildmat.2019.117894

Moeletsi, R.S. (2018) "Remote sensing of land cover change within granite quarries" *Master's thesis, University of Johannesburg (South Africa)*. https://ujcontent.uj.ac.za/vital/access/manager/moeletsi

Mohamad, N., Muthusamy, K., Embong, R., Kusbiantoro, A. and Hashim, M. H. (2022) "Environmental impact of cement production and Solutions: A review." *Materials Today: Proceedings*, *48*, pp. 741–746. https://doi.org/10.1016/j.matpr.2021.02.212

Mthiyane, D.B., Wissink, H. and Chiwawa, N. (2022) "The impact of rural–urban migration in South Africa: A case of KwaDukuza municipality." *Journal of Local Government Research and Innovation*, *3*, pp. 9. https://doi.org/10.4102/jolgri.v3i0.56

Muazu, A.G. and Alibaba, H.Z. (2017) "The use of traditional building materials in modern methods of construction (a case study of northern Nigeria)." *International Journal of Engineering Science Technology and Research*, *2*(6), pp. 30-40. https://www.researchgate.net/publication/322083008

Mundra, S., Agrawal, V. and Nagar, R., 2021, February. Microstructure of Concrete Containing Sandstone Cutting Waste-A Technical Report. In *Materials Science Forum* (Vol. 1019, pp. 92-101). Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/MSF.1019.92

Nedeljković, M., Visser, J., Šavija, B., Valcke, S. and Schlangen, E. (2021) "Use of fine recycled concrete aggregates in concrete: A critical review." *Journal of Building Engineering*, *38*. https://doi.org/10.1016/j.jobe.2021.102196

Neves, S.A. and Marques, A.C. (2022) "Drivers and barriers in the transition from a linear economy to a circular economy." *Journal of Cleaner Production*, 341. https://doi.org/10.1016/j.jclepro.2022.130865

Ngowi, A.B. (1999) *Institute for Research in Construction*.

Ngwepe, L. and Aigbavboa, C. (2015) "A theoretical review of building life cycle stages and their related environmental impacts." https://hdl.handle.net/10210/69042

Nilimaa, J. (2023) "Smart materials and technologies for sustainable concrete construction." *Developments in the Built Environment*, *15*. https://doi.org/10.1016/j.dibe.2023.100177

Ogundairo, T.O., Adegoke, D.D., Akinwumi, I.I. and Olofinnade, O.M. (2019) "Sustainable use of recycled waste glass as an alternative material for building construction – A review." *IOP conference series: materials science and engineering*, *640*(1). http://dx.doi.org/10.1088/1757-899X/640/1/012073

Ogunmakinde, O.E., Egbelakin, T. and Sher, W. (2022a) "Circular economy in Africa's built environment: A Conceptual Bibliometric analysis." *IOP Conference Series: Earth and Environmental Science*, 1101(6). http://dx.doi.org/10.1088/1755-1315/1101/6/062016

Ogunmakinde, O.E., Egbelakin, T. and Sher, W. (2022b) "Contributions of the circular economy to the UN sustainable development goals through sustainable construction." *Resources, Conservation and Recycling*, *178*.

https://doi.org/10.1016/j.resconrec.2021.106023

Ohemeng, E.A. and Ekolu, S.O. (2020) "Comparative analysis on costs and benefits of producing natural and recycled concrete aggregates: A South African case study." *Case Studies in Construction Materials*, 13. https://doi.org/10.1016/j.cscm.2020.e00450

Olawumi, M.A., Oladapo, B.I., Ikumapayi, O.M. and Akinyoola, J.O. (2023) "Waste to wonder to explore possibilities with recycled materials in 3D printing." *Science of the Total Environment*, *905*. https://doi.org/10.1016/j.scitotenv.2023.167109

Olofinnade, O.M., Oyawoye, I.T., Ogara, J.I., Ede, A.N., Ndambuki, J.M., Akinwumi, I.I. and Ajao, A.M. (2019) "The use of recycled concrete aggregate for concrete production incorporating calcined clay as pozzolanic admixture." *IOP Conference Series: Materials Science and Engineering* 640(1). http://dx.doi.org/10.1088/1757-899X/640/1/012047

O'Mahony, M. and O'Mahony, M.M. (1990) *Recycling of materials in civil engineering* (Doctoral dissertation, Oxford University, UK). https://ora.ox.ac.uk/objects/uuid:25b3c922-4720-4424-a2c6-b19f00013148

Orhon, A.V. and Altin, M. (2019) "Utilization of alternative building materials for Sustainable Construction." *Environmentally-Benign Energy Solutions*, pp. 727–750. https://doi.org/10.1007/978-3-030-20637-6_36

Ortiz, O., Castells, F. and Sonnemann, G. (2009) "Sustainability in the construction industry: A review of recent developments based on LCA." *Construction and building materials*, *23*(1), pp. 28-39. https://doi.org/10.1016/j.conbuildmat.2007.11.012

Owens G (2013) *Fundamentals of Concrete*. Cement & Concrete Institute.

Ozcelik, M. (2018) "Energy consumption analysis for natural aggregate processing and its results (Atabey, isparta, turkey)." *Mining of Mineral Deposits*, 12(3), pp. 80–86. https://doi.org/10.15407/mining12.03.080

Parvathikumar, G., Balachandran, G.B. and Sahadevan, B. (2023) "Performance of green concrete paving block imbibed with industrial scrap steel mill scale for sustainable construction." *Materials Research Express*, *10*(3). http://dx.doi.org/10.1088/2053-1591/acc56b

Perera, F. (2017) "Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: Solutions exist." *International Journal of Environmental Research and Public Health*. https://doi.org/10.3390/ijerph15010016

Pitso, R. (2020) "Feasible Use of Recycled Concrete Aggregates as Unbound Road Base Material in South Africa." *Dissertation, CUT.*

http://ir.cut.ac.za/handle/11462/10

Population Division, United Nations Department of Economic and Social Affairs (2022) "World Population Prospects 2022: Summary of Results." United Nations population estimates and projections (UN DESA/POP/2022/TR/NO 3). INTERNET. file:///C:/Users/hp/Downloads/WPP2022_Summary-of-Results.pdf

Pothina, R., Kecojevic, V., Klima, M.S. and Komljenovic, D. (2007) "Gyratory crusher model and impact parameters related to energy consumption." *Mining, metallurgy & exploration*, *24*, pp.170-180. https://doi.org/10.1007/BF03403212

Pourkhorshidi, S., Sangiorgi, C., Torreggiani, D., and Tassinari, P. (2020) "Using Recycled Aggregates from Construction and Demolition Waste in Unbound Layers of Pavements." *Sustainability,* 12(22), pp. 1–20. https://doi.org/10.3390/su12229386

Prajapati, R., Gettu, R., Singh, S. and Rathod, B.J. (2022) "A novel beneficiation process for producing high-quality recycled concrete aggregates using concentrated solar energy." *Materials and Structures*, *55*(9), pp. 233. https://doi.org/10.1617/s11527-022-02065-w

Pranav, P., Pitroda, J., and Bhavsar, J.J. (2015) "Demolition: Methods and Comparison." https://www.researchgate.net/publication/281174903

Premanand, R., Sundari, K.T., Aishwarya, N. and Karthikeyan, B. (2023) "An experimental analysis on the replacement of fine aggregate by manufacture sand." *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.05.582

Purchase, C. K., Al Zulayq, D. M., O'brien, B. T., Kowalewski, M. J., Berenjian, A., Tarighaleslami, A. H. and Seifan, M. (2022) "Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits." *Materials,* 15. https://doi.org/10.3390/ma15010076

Qian, L.P., Xu, L.Y., Huang, B.T., Li, Y., Lan, J., Gong, F. and Guan, H. (2024) "Functionalization of waste-derived artificial aggregates: A state-of-the-art." *Resources, Conservation & Recycling.* https://doi.org/10.1016/j.resconrec.2024.107999

Rao, A., Jha, K.N. and Misra, S. (2007) "Use of aggregates from recycled construction and demolition waste in concrete." *Resources, Conservation and Recycling*, 50(1), pp. 71–81. https://doi.org/10.1016/j.resconrec.2006.05.010

Reames, T.G. and Wright, N.S. (2021) "The three E's revisited: How do community-based organizations define sustainable communities and their role in pursuit of." *Sustainability*, *13*(16), pp.8825. https://doi.org/10.3390/su13168825

Reddy, V.S. (2016) “Sustainable construction: Analysis of its costs and financial benefits.” *International Journal of Innovative Research in Engineering & Management*, 3(6), pp. 522–525. https://doi.org/10.21276/ijirem.2016.3.6.12

Sabău, M., Bompa, D.V. and Silva, L.F. (2021) “Comparative carbon emission assessments of recycled and natural aggregate concrete: Environmental influence of cement content.” *Geoscience Frontiers*, *12*(6). https://doi.org/10.1016/j.gsf.2021.101235

Samba, G., Fokeng, R.M., Nfor, J.T., Ngwaimbi, R.C. and Youogo, C.M.K. (2022) “Effects of quarrying activities on environmental sustainability in Makenene, Centre Region, Cameroon.” *J Environ Earth Sci*, *12*(1), pp.12-19. https://doi.org/10.7176/jees/12-1-03

Saunders, M., Lewis, P. & Thronhill, A. (2012) Research Methods for Business Students (4th ed.). Harlow: Pearson Education Ltd.

Schoeneberger, C., Zhang, J., McMillan, C., Dunn, J.B. and Masanet, E. (2022) “Electrification potential of US industrial boilers and assessment of the GHG emissions impact.” *Advances in Applied Energy*, *5*. https://doi.org/10.1016/j.adapen.2022.100089

Schultmann, F. and Sunke, N. (2007) “Energy-oriented deconstruction and recovery planning.” *Building Research & Information*, *35*(6), pp.602-615. https://doi.org/10.1080/09613210701431210

Serdar, M., Bjegović, D., Štirmer, N. and Pečur, I.B. (2019) “Research challenges for broader application of alternative binders in concrete.” *Građevinar*, *71*(10.), pp. 877-888. http://dx.doi.org/10.14256/JCE.2729.2019

Sharma, H.B., Vanapalli, K.R., Samal, B., Cheela, V.S., Dubey, B.K. and Bhattacharya, J. (2021) “Circular economy approach in solid waste management system to achieve UN-SDGs: Solutions for post-COVID recovery.” *Science of the Total Environment*, *800*(149605). https://doi.org/10.1016/j.scitotenv.2021.149605

Sierra-Pérez, J., López-Forniés, I., Boschmonart-Rives, J., and Gabarrell, X. (2016) “Introducing eco-ideation and creativity techniques to increase and diversify the applications of eco-materials: The case of cork in the building sector.” *Journal of Cleaner Production*, *137*, pp. 606–616. https://doi.org/10.1016/j.jclepro.2016.07.121

Silva, R. V., de Brito, J. and Dhir, R.K. (2017) “Availability and processing of recycled aggregates within the construction and demolition supply chain: A review.” *Journal of Cleaner Production*, pp. 598–614. https://doi.org/10.1016/j.jclepro.2016.12.070

Silva, R.V., De Brito, J. and Dhir, R.K. (2016) "Performance of cementitious renderings and masonry mortars containing recycled aggregates from construction and demolition wastes." *Construction and Building Materials*, *105*, pp. 400-415. https://doi.org/10.1016/j.conbuildmat.2015.12.171

Simion, I.M., Fortuna, M.E., Bonoli, A. and Gavrilescu, M. (2013) "Comparing environmental impacts of natural inert and recycled construction and demolition waste processing using LCA." *Journal of environmental engineering and landscape management*, *21*(4), pp.273-287. https://doi.org/10.3846/16486897.2013.852558

Sizirici, B., Fseha, Y., Cho, C.S., Yildiz, I. and Byon, Y.J. (2021) "A review of carbon footprint reduction in construction industry, from design to operation." *Materials*, *14*(20). https://doi.org/10.3390/ma14206094

Sormunen, P. and Kärki, T. (2019) "Recycled construction and demolition waste as a possible source of materials for composite manufacturing." *Journal of building engineering*, *24*. https://doi.org/10.1016/j.jobe.2019.100742

Sparrevik, M., De Boer, L., Michelsen, O., Skaar, C., Knudson, H. and Fet, A.M. (2021) "Circular economy in the construction sector: advancing environmental performance through systemic and holistic thinking." *Environment Systems and Decisions*, pp. 1-9. https://doi.org/10.1007/s10669-021-09803-5

Sundayi, S., Tramontin, V. and Loggia, C. (2015) "An investigation into the costs and benefits of green building in South Africa." *2015 World Congress on Sustainable Technologies (WCST)*. https://doi.org/10.1109/WCST.2015.7415122

Tabak, Y. (2023) "Perspective towards construction and demolition waste management: Case study on kahramanmaraş earthquake." *Solid Waste Management - Recent Advances, New Trends and Applications*. http://dx.doi.org/10.5772/intechopen.1002338

Tam, V.W.Y. (2008) "Economic comparison of concrete recycling: A case study approach." *Resources, Conservation and Recycling*, 52(5), pp. 821–828. https://doi.org/10.1016/j.resconrec.2007.12.001

Thomsen, A., Schultmann, F. and Kohler, N. (2011) "Deconstruction, demolition and destruction." *Building Research & Information*, 39(4), pp. 327–332. https://doi.org/10.1080/09613218.2011.585785

Tsakiroglou, C.D. (2002) "Determination of the transport properties of single fractures with the aid of critical path analysis." *Industrial & engineering chemistry research*, *41*(14), pp.3462-3472. https://doi.org/10.1021/ie010936w

Ulubeyli, S., Kazaz, A. and Arslan, V. (2017) "Construction and demolition waste recycling plants revisited: management issues." *Procedia Engineering*, *172*, pp. 1190-1197.

https://doi.org/10.1016/j.proeng.2017.02.139

United Nations. (2018) *Department of Economic and Social Affairs*. INTERNET. https://www.un.org/development/population/2018-revision-of-world-urbanization-prospects

Unni, A. and Anjali, G. (2022) "Cost-benefit analysis of conventional and modern building materials for sustainable development of social housing." *Materials Today: Proceedings*, *51*, pp. 1649–1657. https://doi.org/10.1016/j.matpr.2021.12.113

Vagtholm, R., Matteo, A., Vand, B. and Tupenaite, L. (2023) "Evolution and current state of building materials, construction methods, and building regulations in the UK: implications for sustainable building practices." *Buildings*, *13*(6), pp.1480. https://doi.org/10.3390/buildings13061480

Van Damme, H. and Houben, H. (2018) "Earth concrete. Stabilization revisited." *Cement and Concrete Research*, *114*, pp.90-102. https://doi.org/10.1016/j.cemconres.2017.02.035

Van Wyk, L.V. (2017) "The Green Building Handbook South Africa" *The Essential Guide, 11.* CSIR. file:///C:/Users/hp/Downloads/Van%20Wyk_20701_2017.pdf

Vasileiou, K., Barnett, J., Thorpe, S., and Young, T. (2018) "Characterising and justifying sample size sufficiency in interview-based studies: Systematic analysis of qualitative health research over a 15-year period." *BMC Medical Research Methodology*, *18*(1). https://doi.org/10.1186/s12874-018-0594-7

Verma, A.K. (2019) "Sustainable development and environmental ethics." *International Journal on Environmental Sciences*, *10*(1), pp.1-5. https://ssrn.com/abstract=3689046

Visintin, P., Xie, T. and Bennett, B. (2020) "A large-scale life-cycle assessment of recycled aggregate concrete: The influence of functional unit, emissions allocation, and carbon dioxide uptake." *Journal of Cleaner Production*, 248. https://doi.org/10.1016/j.jclepro.2019.119243

Wang, J., Fan, Y., Che, Z., Zhang, K. and Niu, D. (2023) "Study on the durability of eco-friendly recycled aggregate concrete with supplementary cementitious materials: The combined action of compound salt solution of MgSO4, Na2SO4, and NaCl and dry-wet cycles." *Construction and Building Materials*, *377*. https://doi.org/10.1016/j.conbuildmat.2023.131149

Wembe, J.T., Ngueyep, L.L.M., Moukete, E.E.A., Eslami, J., Pliya, P., Ndjaka, J.M.B. and Noumowe, A. (2023) "Physical, mechanical properties and microstructure of concretes made with natural and crushed aggregates: Application in building construction." *Cleaner Materials*, *7*. https://doi.org/10.1016/j.clema.2023.1001733

Western Cape Government. (2018) *Construction and Demolition Waste Management Guideline for Municipalities*. INTERNET. https://www.enviro-eap.co.za/ConstructionDemolition_Waste_Management_Guidelines

Wilburn, D.R. and Goonan, T.G. (1998) "Aggregates from natural and recycled sources." *US Geological survey circular*, *1176*. http://greenwood.cr.usgs.gov/pub/circulars/c1176/c1176.html

Willis, K.G. and Garrod, G.D. (1999) "Externalities from extraction of aggregates." *Resources Policy*, 25(2), pp. 77–86. https://doi.org/10.1016/S0301-4207(99)00012-4

Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A.I., Fawzy, S., Rooney, D.W. and Yap, P.S. (2023) "Circular economy strategies for combating climate change and other environmental issues." *Environmental Chemistry Letters*, *21*, pp. 55-80. https://doi.org/10.1007/s10311-022-01499-6

Yu, Y., Yazan, D.M., Junjan, V. and Iacob, M.E. (2022) "Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies." *Journal of cleaner production*, *349*. https://doi.org/10.1016/j.jclepro.2022.131335

Zega, C.J., Villagrán-Zaccardi, Y.A., and Di Maio, A.A. (2010) "Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates." *Materials and Structures/Materiaux et Constructions*, *43*(1–2), pp. 195–202. https://doi.org/10.1617/s11527-009-9480-4

Zeghioud, H., Fryda, L., Djelal, H., Assadi, A. and Kane, A. (2022) "A comprehensive review of biochar in removal of organic pollutants from wastewater: Characterization, toxicity, activation/functionalization and influencing treatment factors." *Journal of Water Process Engineering*, *47*. https://doi.org/10.1016/j.jwpe.2022.102801

Zhang, L.W., Sojobi, A.O., Kodur, V.K.R. and Liew, K.M. (2019a) "Effective utilization and recycling of mixed recycled aggregates for a greener environment." *Journal of Cleaner Production*, *236*. https://doi.org/10.1016/j.jclepro.2019.07.075

Zhang, Y., Luo, W., Wang, J., Wang, Y., Xu, Y. and Xiao, J. (2019b) "A review of life cycle assessment of recycled aggregate concrete." *Construction and Building Materials*, *209*, pp. 115-125. https://doi.org/10.1016/j.conbuildmat.2019.03.078

Zuo, C., Birkin, M., Clarke, G., McEvoy, F., & Bloodworth, A. (2018) "Reducing carbon emissions related to the transportation of aggregates: Is road or rail the solution?." *Transportation Research Part A: Policy and Practice*, *117*, pp. 26–38. https://doi.org/10.1016/j.tra.2018.08

ANNEXTURE A

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SAMPLE QUESTIONNAIRE & INTERVIEW SCHEDULE

DEMOLITION COMPANIES

Survey for the Qualitative Data

1. Job position of the participant

Managerial and Admin	
Engineer, Technician, and craftsmen	
Other	

2. What are the demolition projects the company has worked on?

Building Structures	
Bridges	
Roads	
Dams and reservoirs	
Other	
If other, please specify:	

3. If building structures, what were the buildings used for?

Residential	
Commercial	
Industrial	

4. What approach do you consider when demolishing a structure?

Manual Demolition	
Mechanical Demolition	
Chemical (Explosives and non-explosives)	
Other Please Specify_____	

5. How would you classify your demolition method(s)?

Labour Intensive	
Capital Intensive	
Both	

6. What tools and machinery do you use for demolition?

Explosives	
Excavators	
Bulldozers	

Cranes	
Hammers	
Other	
If other, please specify:	

7. What type of energy is used to operate the above machinery?

Petrol	
Electricity	
Diesel	
Human	
Other Please specify_____	

8. Is there a particular size/ mass that a material must be demolished to?

No	
Yes	
If yes, please specify:	

9. What happens to the waste (Rubble; concrete, bricks & stone) after demolition?

Taken to landfills	
Taken to recycling sites	
Recycling companies collect the rubble from demolition sites	
Recycled on site	

10. Does your company or recycling companies have a limit for transporting the rubble? (In terms of distance?)

Yes	
No	

11. Any challenges experienced in the demolition process?

No	
Yes	
If yes, please specify:	

Interview schedule for the Quantitative data

1. What is the unit of production that your company uses for recording energy and how much energy is required (per unit of production) for the tools and equipment to operate?

2. Do you measure the amount of carbon dioxide and carbon dioxide equivalents that are emitted into the atmosphere? If yes, how much is emitted?

3. What kind of vehicles does your company use for transporting rubble? And what is the maximum weight for each vehicle per trip?

4. How much costs do you estimate to spend on transporting rubble per kilometre? And how is it broken down? (Labour costs for loading and driving included?)

5. How much does your company charge for services per unit of production?

6. What are most expensive charges for services (demolition services) offered?

7. What are the most volatile costs encountered when demolishing?

8. How much are the cost (per category) for tools and machinery used?

Categories / Tools/Machinery	Equipment	working Capital	Maintenance	Labour	Energy	Water	Other
Explosives							
Excavation							
Bulldozers							
Cranes							
Hammers							
Other							

RECYCLING SITES

Survey for the Qualitative Data

1. Job position of the participant

Managerial and Admin	
Engineer, Technician, and Craftsmen	
Other	

2. What materials does your company recycle?

Construction & Demolition waste Please specify the type of C&D waste you recycle:	
Other Please specify _____ _____ _____	
All	

3. How do you get waste (rubble)?

Delivered by Demolition Companies	
Collection from Demolition Companies	

4. How do you manufacture recycled aggregates?

Weighing, unloading, and storage (1)	
Segregation (2)	
Size reduction (3)	
Primary crushing (4)	
Vibrating Screens (5)	
Secondary crushing (6)	
Dry process (7)	
Washing (8)	
Size-based screening and storage (9)	
Any other process? (10) Please specify_____ _____	

5. What kind of energy does your tools and machinery require for manufacturing recycled aggregates?

Petrol	
Electricity	
Diesel	
Human	
Other	

6. Any challenges experienced in the demolition process?

No	
Yes	
If yes, please specify:	

Interview schedule for the Quantitative data

1. What is the delivery charge (if delivered) /costs spent on the collection of rubble from demolition sites (if collected)?

2. What is the unit of production that your company uses for recording energy and how much energy is required (per unit of production) for the tools and equipment to operate?

3. Do you measure the quantity of carbon dioxide and carbon-dioxide equivalents emitted in the atmosphere? If yes how much is the quantity emitted?

4. What are the sizes of aggregates produced and what is the aggregates production per week?

5. How much are the cost (per category) for each process?

Categories / Processes	Equipment	Working Capital	Maintenance	Labour	Energy	Water	Other
Weighing, unloading and storage							
Segregation							
Size reduction							
Primary crushing							
Vibrating Screens							
Secondary crushing							
Dry process							
Washing							
Size-based screening and storage							
Other							
TOTAL COSTS							

QUARRY SITES

Survey for the Qualitative Data

1. Job position of the participant

Managerial and Admin	
Engineer, Technician, and craftsmen	
Other	

2. What raw materials does your company extract?

Sand (Fine)	
Stone (Gravel)	
Both	

3. For how many years have they been mined from this location?

Less than 5 years	
Less than 10 years	
Less than 15 years	
Less than 20 years	
More than 20 years	

4. For how many more years will the material still be available for use if mined at the same rate and quantity?

Less than 5 years	
Less than 10 years	

Less than 15 years	
Less than 20 years	
More than 20 years	

5. Do you foresee an increase or a decrease in the rate of extraction?

Increase	
Decrease	

6. How are aggregates transported?

Collected	
Delivered	

7. What are the processes that your company follows to produce natural aggregates?

Drilling hole (1)	
Blasting (2)	
Size Reduction (3)	
Loading and unloading (4)	
Primary crusher (5)	
Secondary crusher (6)	
Tertiary crusher (7)	
Other (8) Please specify_____	

_____	

8. What kind of energy do your tools, machinery, and plants require to process natural aggregates?

Petrol	
Electricity	
Diesel	
Human	
Other	

Interview schedule for the Quantitative data

1. What is the delivery charge (if delivered) for transporting natural aggregates to construction sites?

2. What is the unit of production that your company uses for recording energy and how much energy is required (per unit of production) for the human, plants, tools, and equipment to operate?

3. Do you measure the quantity of carbon dioxide and carbon-dioxide equivalents emitted in the atmosphere? If yes, how much of these gases get emitted?

4. What are the sizes of aggregates produced and what is the aggregates production per week?

5. How much are the cost (per category) for each process?

Categories / Processes	Equipment	working Capital	Maintenance	Labour	Energy	Water	Other
Drilling hole							
Blasting							
Size Reduction							
Loading & unloading							
Primary Crusher							
Secondary Crusher							
Tertiary Crusher							
Other							
TOTAL COSTS							

ANNEXTURE B

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CONSENT FORM

Comparative Material Analysis of the Feasible Transport Distance for Repurposing Construction Rubble in Gauteng, South Africa

I, _____, agree that Tsireletso Thulo, an MSc (Eng) student from the University of the Witwatersrand will conduct her interview with me to gather data that will be used for a research project.

I agree to the following:

	YES	NO
• The research study was explained to me, and I understand the purpose of the study.		
• I understand the purpose of the interview and I volunteer to take part in the study.		
• The researcher has been granted permission to record the interview and use the information provided.		
• I agree that direct quotations from this interview may be used in the research report.		
• I agree that the researcher may use the information I provide in this interview, but my name will not be used.		

I understand that:

- I have the right to discontinue the interview at any point and choose to not answer all the questions.
- I will not get incentives for this interview.
- I am free to contact the supervisor for this study.
- The information that I will provide will be secured.

(signature of participant)	(signature of the researcher)
(date)	(date)

ANNEXTURE C

SCHOOL OF CIVIL AND ENVIRONMENTAL
CONSTITUTED UNDER THE UNIVERSITY HUMAN R

CLEARANCE CERTIFICATE **PROT**

PROJECT TITLE COMPARATIVE MATERIAL AN
REPURPOSING CONSTRUCTI

INVESTIGATOR/S Tsireletso Thulo

SCHOOL/DEPARTMENT OF INVESTIGATOR

DATE CONSIDERED

DECISION OF THE COMMITTEE

RISK LEVEL Minim

EXPIRY DATE

ISSUE DATE OF CERTIFICATE 24 July 2023

cc: Supervisor: Ms Janina Kanjee

DECLARATION OF INVESTIGATOR

To be completed in duplicate and **ONE COPY** returned
committee.

I/we fully understand the conditions under which I am/w
and I/we guarantee to ensure compliance with these co
research procedure as approved, I/we undertake to sub

T. Thulo

Signature

PLEASE QUOTE THE PROTO

ANNEXTURE D

MSc Engineering Report - Tsirele

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