APPLICATION OF THE ECORCE M TOOL TO INVESTIGATE PAVEMENT PREMATURE FAILURE ON SOUTH AFRICAN ROADS

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DECLARATION OF ORIGINALITY

I, Mothusi Moagi Reginald Ntsie with student number _________ hereby declare and confirm that this dissertation submitted for the degree of Master of Engineering in Civil Engineering in the Department of Civil Engineering, Faculty of Engineering, Built Environment and Information Technology, Central University of Technology, Free State, has never been submitted for any degree at this institution or any other institution. It is my own work and all sources have been acknowledged.

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ABSTRACT

Minimising the consumption of materials, energy and water during construction, and evaluating environmental impact indicators and finding ways of reducing environmental impact indicators can help to build sustainable road networks in South Africa. Ecorce M is a tool that was developed by the French Institute of Science and Technology for Transport, Spatial Planning, Development and Networks (IFSTTAR) in collaboration with CEREMA of the French Ministry of Ecology, Sustainable Development and Energy (MEDDE). This tool deals with construction and structural maintenance of pavements, installation of foundation layers, preparation of upper part of earthworks and construction of fills. It identifies and evaluates possible measures for improving the environment and it provides Life Cycle Inventory. This tool further provides environmental indicators and yields environmental indicators relative to the earthworks undertaken from an overall perspective. The Ecorce M tool is used in this research to measure consumption of materials, energy and water. It is also used to calculate the values of environmental impact produced by indicators during road construction and rehabilitation. Ecorce M reduces the consumption of materials, water and energy by means of evaluating impacts and assessing environmental impact indicators in road construction. These environmental impact indicators are calculated by identifying and quantifying the flows of energy and materials.

Inputs used on this study comprise data gathered from a project that took place in Klerksdorp, namely the Patchwork, Rehabilitation and Reseal of Road P3/ 4 (N12) from Road R503 to Archbishop Desmont Tutu Street Phase 2. The inputs that have been taken into account are: geometry of each layer, composition and mass density of the component layer material, hauling distances and unit consumption values for construction vehicles. The outcomes achieved include, but are not limited to, the amount of material consumption, energy consumption and water consumption. The emissions produced for the following indicators have also been achieved: greenhouse effect indicator; acidification potential, eutrophication indicator; tropospheric ozone; toxicity and eco-toxicity indicators. Most of materials consumption occurs during materials extraction, most of the energy is consumed

during processing of aggregates and most of the water is consumed during mixing and processing layer works. Most of the environmental impact indicators result from materials used with 54% on average, and machinery used weighs 46% on average.

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ACRONYMS AND ABBREVIATIONS

AC	Asphalt Concrete
AP	Acidification Potential
BOF	Basic Oxygen Furnace
CAPEM	Cycle Assessment Procedure for Eco-Materials
CEREMA	Center for Studies and Expertise on Risk, the Environment, Mobility and Development
CH_4	Methane
CNP	Carbon Nitrogen Phosphorus
CO_2	Carbon Dioxide
COLTO	Committee of Land and Transport Officers
DBSA	Development Bank of Southern Africa
DCB	Dichlorobenzene
EEA	European Environment Agency
EI	Eutrophication Indicator
EP	Ecotoxicity Potential
EPA	Environmental Protection Agency
GDRC	Global Development Research Center
GIEC	International Group of Experts on Climate
GWP	Global Warming Potential
HCFCs	Hydrochlorofluorocarbons
HF	Hydrogen Fluoride

HFCs	Hydrofluorocarbons
HNO_2	Nitrious Acid
IDRRIM	Institute Des Routes des Reus et des Infrastructures pour la Mobilite (Institute of Routes Reus and Infrastructure Mobility)
IFSTTAR	French Institute of Science and Technology for Transport, Development and Networks
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
LCPC	Laboratoire Central des Ponts et Chausees (Central Laboratory of Bridges and Pavements)
MDPI	Multidisciplinary Digital Publishing Institute
MEDDE	Ministry of Ecology, Sustainable Development and Energy
MJ	Megajoule
MOD	Module
AASHTO	American Association of State Highway and Transportation Officials
NO	Nitrogen Oxide
N_2O	Nitrous Oxide
NSW	New South Wales
O_2	Oxygen
O_3	Ozone
OH	Hydroxide
PO_4	Phosphate

POCP	Photochemical Ozone Creation Potential
PWR	Public Works and Roads
RAP	Recycled Asphalt Pavement
SANAS	South African National Accreditation System
SO_2	Sulphur Dioxide
SAMDM	South African Mechanistic-Empirical Design Method
TLB	Tractor Loader Backhoe
TP	Toxicity Potential
UCPRC	University of California Pavement Research Center
UCS	Unconfined Compression Strength
UNEPIE	United Nations Environmental Programme Industry and Environmental

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

Life Cycle Assessment (hereinafter referred to as LCA) is an environmental assessment approach that measures the input (e.g. energy and resources) and output (e.g. air emissions and water releases) to a system over its life cycle. It was originally developed in the late 1960s to analyse air, land and water emissions from solid wastes. Later the principles were broadened to include energy, resource use, and chemical emissions (Guinẽe, 2012). Developments shifted to the creation of fully-fledged impact assessment methods and the standardisation of methods by the International Organization for Standardization (hereinafter referred to as ISO). According to ISO standards, there are four phases the in LCA study. These phases are goal definition and scope, inventory analysis, impact assessment and interpretation (Harvey *et al.,* 2014). Attempts at standardising the LCA procedure for pavements have been made (UCPRC, 2010a). Pavement life cycle stages are material production, construction (includes new construction, maintenance and rehabilitation), use, and end of life. LCA is defined as “cradle to grave”. LCA that does not consider the use of end of life stage is referred to as cradle to gate in the transportation area (Harvey *et al.,* 2014).

LCA uses details of environmental data and scientifically derived models to evaluate the environmental impact of the pavement over its entire life. LCA evaluates a full set of environmental impacts and indicators including, amongst other things, land use, resource use, climate change, health effects, acidification and toxicity (Pierce, 2011). South Africa requires sustainable design efforts to reduce consumption of energy, water and materials. This is due to the fact that road infrastructure is due to face many challenges over the coming years. These include significant changes to weather patterns and predicted increase in energy and resource prices. Resource efficiency measures in the construction sector must address renewal and rehabilitation of existing infrastructure as well as new construction.

Road development has major environmental impacts. Some of the major environmental impacts of road projects include damage to sensitive ecosystem, loss of productive agricultural lands, and permanent disruption of local economic activities, demographic change and accelerated urbanisation. Ecological damage occurs mainly in rural areas due to vulnerability of conditions, lack of infrastructure and fragile ecosystems. Roads are critical to economic development and must be constructed, upgraded and maintained in conjunction with management of the ecosystems. This is possible through integrated approach that perceives management of ecological resources as part of the infrastructure development. (Hoban and Tsunokawa, 1997). As the ecological management is the integral part of the infrastructure development, undertaking environmental impact assessment is mandatory for road constructions. The Department of Environmental Affairs and the Department of Transport both recognise the need to protect the ecosystem, hence promote recognition of environmental issues pertaining to road infrastructure provision and use. Provision of support to rural areas is an inevitable aspect of conservation (Oosthizen, 2014).

According to the European Environment Agency, the main products of the combustion of motor fuels are carbon dioxide and water. However, inefficiencies and high temperatures inherent in engine operation encourage the production of other pollutants and effects of these pollutants vary (Pastorello and Mellios, 2016).

Pollutants are:

- Nitrogen oxides: Dinitrogen (N_2) is a relatively inert gas that makes up about 80% of the air we breathe. Nitrogen as a single atom can be reactive and have ionization levels from plus one to plus five. Hence nitrogen can form several different oxides. Automobiles and other mobile sources contribute about half of the Nitrogen Oxides that are emitted. Most of the nitrogen oxide in vehicle emissions is in the form of nitric oxide. Nitric oxide is a by-product of fuel combustion under conditions of extreme heat and pressure (Cox *et al.*, 1999).
- Hydrocarbons: Gasoline engine exhaust is a group of 2B carcinogen combustion-related sources that include automobiles. The combustion related sources are associated with more populated areas, leading to high potential exposure and health risk. The hydrocarbons are produced by the incomplete

combustion of fuel and by its evaporation. Hydrocarbons combine with nitrogen oxide to produce photochemical smog (Straif *et al.,* 2013).

- Carbon monoxide (CO): This is produced when combustion reactions are partly completed. This can be due to lack of oxygen or low mixing. CO is a colourless and odourless gas. Low excess O_2 increases formation of CO (Vakkilainen, 2017).
- Sulphur dioxide (SO_2): Sulphur is chemically bonded to the hydrocarbons of the fuel; it is oxidised to SO_2 during combustion. The emissions rate of sulphur dioxide is directly linked to the sulphur content of the fuel. Diesel engines produce more sulphur dioxide than gasoline engines. In conjunction with nitrogen oxide, sulphur dioxide is involved in the formation of acids in the atmosphere. The main environmental concerns that relate to SO_2 emissions are acid rain and the formation of particulate matter (Olatunji, 2015).
- Particulates: Oil-related particulate emissions are modelled by hydrocarbons, ash, carbons and sulphate oil particulate emissions. Under low-load and monitoring conditions, hydrocarbons have proved to be the main contributor to oil-related particulate emissions. Typical particulates include suspended airborne particles from diesel fuel combustion, dust and materials produced by tire, brake and road wear (Tornehed, 2010).
- Lead (pb): The use of lead as a petrol additive has led to disaster in public health. Lead is added to gasoline to raise the octane rate and help lubricate engine components. Lead enters the atmosphere as a fine dust which is easily dispersed and settles on any available surface (Landrigan, 2002).
- Aldehydes: These are produced when alcohols are oxidised. They are a major pollutant group associated especially with engines burning alcohol. They are also produced by diesel engines and, to a lesser degree, by gasoline combustion. Other emissions produced are formaldehyde and acetaldehyde (Bhatia, 2014).

The EEA have also indicated that the volume and composition of individual vehicle emissions are determined by the following factors:

- Fuel consumption: fuel consumption depends on the engine, type of fuel used and the efficiency which the output of the engine is transmitted to the wheels.

The fuel energy is used to overcome rolling resistance primarily due to flexing of the tyres, aerodynamic drag as the vehicle motion is resisted by air and inertia and hill-climbing forces that resist vehicle acceleration (Jones, 2011).

- Level of engine maintenance: vehicle maintenance is another area of emissions measurement. There are number of countries worldwide that operate mandatory vehicle inspection and maintenance programmes where vehicles must pass a periodic emission check (Majewski and Burtsher, 2011).
- Vehicle age: Road transport constitutes a major source of air pollution, and its shares are expected to rise in the future due to rising global demand for private mobility. The age of the vehicle is relevant in developing regions of the world. It is where a significant portion of the vehicle fleet consists of imported second –hand and often poorly maintained vehicles from developed countries (Zachariadis *et al.,* 2001).
- Engine temperature: Cold engines run inefficiently. Catalytic converters on gasoline engines do not function until normal operating temperatures are attained. Particulate matter emissions increase exponentially as temperature decrease. In general, PM emissions double for every 20 degrees in ambient temperature. This increase is independent of the vehicle model year (Nam *et al.,* 2010).
- Road geometry: The road geometry effect upon the energy performance of the vehicle is assessed through detailed energy balances discriminating the mechanical energy change, the rolling and drag resistances, and the energy losses ensuing from braking and powertrain friction (Ferreira *et al.,* 2019).
- Type of vehicle: Vehicles that use diesel are one of the main sources of emissions of air pollutants. These pollutants toxic compounds, nitrogen oxides and particulate matter. Heavy vehicles with large engines emit more pollutants as compared to lighter vehicles (Nelson *et al.,* 2008).
- Speed and congestion: Congestion lowers the average speed and this leads to increase in travelling time and exposure on a per-vehicle basis. Congestion can also change driving patterns, which results in increased number of speedups, slowdowns, stops and starts and ultimately increased emissions (Zhang and Batterman, 2013).

1.2 Problem Statement

Pollution of the environment is one of the main concerns in pavement construction. There are different types of environmental impact indicators which are greenhouse effect indicator, eutrophication indicator, media acidification indicator, indicator of the formation of tropospheric ozone, ecotoxicity and toxicity indicators. Each environmental impact indicator can be linked to a different phase of a project (Marzouk *et al.,* 2017). South Africa have taken efforts to enhance road performance and improve the sustainability of pavement infrastructure. However, these efforts are incomplete if environmental impacts are not considered. Currently, there are no protocols in place to quantify the environmental impacts of pavement infrastructure through LCA approach in South Africa (Blaauw and Maina, 2021). South Africa is faced with a challenge of implementing an Environmental Management Plan in construction projects. The barriers to implementing Environmental Management System are lack of relevant training programs, employees resistance to change habits and relying on old work pattern, general low environmental awareness in the industry, limited influence of contractors in choosing environment friendly materials and lack of required technologies within organisations (Nyamazana and Ozumba. 2017).

South Africa is one of the highest emitters of greenhouse gases CO_2 per capital in the world. The existing energy policy aim is to provide the nation with wider access to energy services and to ensure that the environmental impacts of energy conversion and use are minimised. South Africa is starting to face the challenge of altering the way that energy is utilised so that social, environmental and economic aims of sustainable development are supported (DME, 2005). Transport energy demand is expected to double by 2050. The vehicle fleet is expected to exceed 24 million road vehicles by 2050 from 8.2 million in 2010. The CO_2 emissions from transport are projected to be more than double by 2050, this takes into account the use of electric vehicles, diesel, gasoline, hybrid diesel, hybrid gasoline, natural gas and fuel cell (Merven *et al.*, 2012). According to the Energy Research Centre of the University of Cape Town, the targeted emissions reduction is 142Mt CO_2 by 2025; this amounts to 24% of the project base case emissions. South Africa is Africa's highest emitter of greenhouse gases (Davidson *et al.*, 2006).

The population of South Africa is increasing; hence the transport infrastructure should expand. Natural resources are required for this expansion to happen. It is therefore key to evaluate the use of non-renewable resources in order to maximise sustainability. The use of construction materials obtained from borrow pit results in depletion of natural capital since these materials are non-renewable. The reuse of pavement layer materials is increasing in South Africa; however, there is concern regarding recycled asphalt (Steyn and Paige-Green, 2009). During construction, water consumption is associated with compaction of pavement layers and dust suppression to meet minimum quality requirements. The estimated quantity for construction is 150 litres per cubic metre (Smith, 2020). Efforts to measure consumption of materials, water and energy, and environmental impact indicators during construction/ rehabilitation of roads are required. Ecorce M tool can be used to achieve this goal and the results can be shared with the research entities and government institutions.

1.3 Research Aim

The aim of this research is to establish the use of the Ecorce M tool to calculate environmental impact indicators and calculate consumptions and identify possible ways of reducing environmental indicators, and consumption of materials, water and energy in pavement construction. The calculated indicators are a representation of a pressure exerted on the environment by different technical solutions.

1.4 Research Objectives

- To use the Ecorce M tool to calculate values of consumptions for materials, water and energy.
- To use the Ecorce M tool to calculate values of environmental impact indicators which are greenhouse effect, acidification potential, eutrophication indicator, indicator of the formation of tropospheric ozone, ecotoxicity indicator and toxicity indicator.
- To identify ways of reducing consumption of materials, water and energy.
- To identify ways of reducing environmental impact indicators in pavement construction.
- Identifying possible ways of improving the environment.

1.5 Research Area

The research site is in the North West province, Dr Kenneth Kaunda District Municipality, Matlosana Local Municipality in Klerksdorp. The project is situated on the N12 (Joe Slovo Road) from Road R503 to Archbishop Desmont Tutu Street Phase 2.

1.6 Research Significance

Research regarding pavement LCA is limited in South Africa. The significance of this research is to assist the country to calculate the impact of environmental indicators and to calculate consumption of materials, water and energy.

This research is intended to assist the following:

- Decision makers and designers at transportation agencies who are seeking to quantify environmental impacts of asphalt pavement designs.
- Manufacturers of asphalt who want to quantify and declare the environmental impacts of mixtures they produce at their plants.
- Any downstream users of products that contain asphalt mixtures seeking to conduct an LCA for their products and services.

1.7 Research Tools and Methodology

The Ecorce M tool is used to calculate environmental impact indicators and calculate consumption of materials, water and energy. Data is collected from the project Patchwork, Rehabilitation and Reseal of Road P3/ 4 (N12) from Road R503 to Archbishop Desmont Tutu Street Phase 2. Data collected is entered into the Ecorce M tool. Ecorce M tool is used to calculate environmental impact indicators which include greenhouse effect indicator, eutrophication indicator, media acidification indicator, indicator of the formation of tropospheric ozone, ecotoxicity and toxicity indicators. This includes results of consumption of materials, water and energy. Results are analysed in order to determine the impact of environmental indicators and consumption of materials, water and energy in pavement construction.

This study is 'cradle to grave'. This means all phases of the LCA are considered; namely goal and scope definition, life cycle inventory, impact assessment and interpretation phase. 'Cradle to gate' is a study that excludes end of life stage.

1.8 Research and Data Limitations

Version 2.0 of Ecorce M involves a homogeneous environmental system in terms of boundaries relative to upstream processes; this is particularly true for energy production, the indirect impact of which must also be factored in. The environmental system used in this tool is not explicitly defined by the user for each case study since it is already defined in a global way. This system includes all limitations associated with the following processes:

- Material production within industries
- Production and storage of non-hazardous wastes that may be reused as materials in pavement infrastructure
- Materials and worksite machinery transportation;
- Mix production (asphalt mixing plants, concrete plants, etc.);
- Earthworks activities, pavement construction and maintenance.

Data limitations refer to limitation of the study. The data contained in this document is collected from a road project in Klerksdorp. The following information was received from the project and it was made available by the engineer's representative: soil classification test results, compaction test results, unconfined compression strength test results, mix design for asphalt, machinery used in the project. However, it was difficult to get consumption capacity of machinery used. The diesel consumption capacity was determined through the catalogue of companies selling construction machinery. The time spent through each task was determined by adding daily times recorded by the contractor.

1.9 Data Analysis

The results of this research are achieved through the use of the Ecorce M tool. The analysis is divided into consumptions and environmental impact indicators. The consumptions are materials, water and energy consumption. The environmental impact indicators are the greenhouse effect, acidification potential, eutrophication indicator, indicator of the formation of tropospheric ozone, ecotoxicity indicator and toxicity indicator. The results have been analysed in line with activities that results in more consumptions and what generates more emissions between materials used and machinery used.

1.10 Dissertation Structure

Figure 1 shows how the research is carried out:

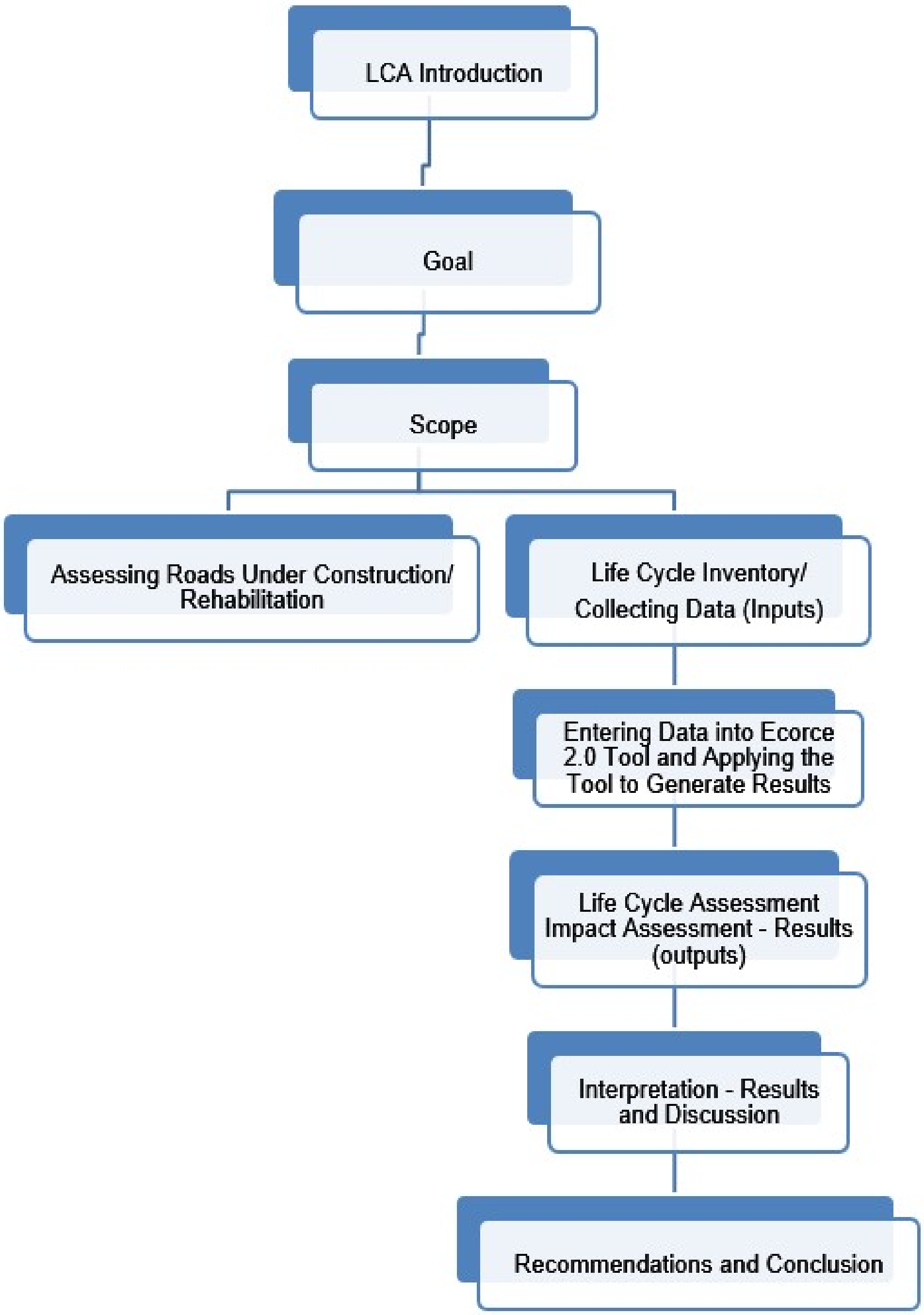

Figure 1. 1. Dissertation Structure

Chapter 1

This chapter gives an overview of the research. It introduces the reader to what the research is about, the problem this research is solving, research aims and objectives, tools and methodology used, research and data limitations, and data analysis.

Chapter 2

This chapter covers work that was done by other researchers relating to the research topic. It explains what LCA is. It explains LCA phases and stages, and consumptions and environmental impact indicators. It further discusses other LCA tools used.

Chapter 3

This chapter show fundamental steps that need to be followed to achieve the aim and objectives of this research. It covers the research method, data collection strategy and trustworthiness.

Chapter 4

In this chapter, results are being discussed and analysed. The results are consumptions figures and environmental impact indicators.

Chapter 5

This chapter concludes how the aim and objectives are achieved and discusses the recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Efforts have been made to develop a list of sustainable developments goals which involve the infrastructure. The aim is to increase resource-use efficiency and greater adoption of clean and environmentally sound technologies to achieve a sustainable future. Pavement engineers are using innovative asphalt materials made up of waste in substitution of natural aggregates, and they are also using alternative production technologies with primary focus of reducing the asphalt mixture production temperature from 170 - 180°C to 50 - 60°C. This saves energy and fossil fuels, and it extends the service life of pavements (Oreto *et al.,* 2021). In 2015 countries adopted the 2030 agenda for sustainable development and its 17 sustainable development goals defined by the United Nations. The widely accepted definition of sustainable development is the one provided in 1987 by the United Nations in the Brudtland Report.

Sustainability assessment is an approach for exploring the combined environmental, social and economic impacts of products and systems. Concerns regarding sustainability of development started being published in the 1960s. The concern regarding global population explosion and environmental impact were raised in the same decade. Those concerns suggested a link between development and human activities. In the late 1970s these concerns were translated into a call for the integration of environmental and development strategies. This approach was emphasised at the United Nations Conference on the Human Environment in 1972. The Brandtland Report of 1987 states “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brent, 2004). Definitions of sustainability include three interrelated elements: economy, environment and society. The importance of environmental sustainability is becoming increasingly recognized. Pavement pose a challenge of achieving the goal of sustainable transportation infrastructure since construction and maintenance of pavements requires the consumption of large quantities of non-renewable materials and creates environmental impacts. Pavement is a significant component of the infrastructure. It is fundamental to economic prosperity and personal mobility. Apart from large amount investment, pavement communities have ambiquous recognition about the environmental impacts of pavement system. The environmental burdens have been ignored in the development of the next generation pavement design system. The increase in fuel consumption demand, rapid raw materials depletion, and urgent environmental protection requirements are driving the development of an environment-friendly pavement design. In order to achieve environmental-friendly pavement, a clear understanding of the environmental impacts of pavement system is required. It is also important to assess the impact of pavement components to the environment and to determine how they can be improved (Yu., 2013).

Sustainability and environmental aspects of the expansion of the pavements development and road networks are a concern. The severe environmental impacts are neglected, such as those due to immense pavement projects, growth issue with toxic gaseous emissions, pollutant emissions and added fuel consumption. In order to overcome the issues of sustainability throughout the project life cycle, significant monetary procedures are required. The user phase in the project life cycle needs timely upgrading since it has the longest duration in the life cycle (Alaloul *et al.,* 2021). Studies have shown the availability and condition of transportation infrastructure directly affects the cost of operating vehicles on the infrastructure. Pavement condition affects vehicle operation and costs directly. The pavement condition is expressed in terms of the riding quality of the road. A timely management of the road riding quality can be used as a tool to extend the service life of pavement (Steyn *et al.,* 2014).

LCA is a method of characterising and quantifying environmental sustainability. It measures inputs and outputs of a system. Some of the inputs are water, materials and energy. Some of the outputs are air emissions and waste. The three key elements of LCA are goal and scope definition, life cycle inventory assessment and impact assessment. Scope refers to function and functional unit and system boundaries. LCI analysis is the accounting stage of life cycle assessment. It is the phase where data is collected and evaluated. This phase focuses on data quality considerations. The LCIA phase is where life cycle inventory data is translated into meaningful metrics and indicators. There are impact categories for climate change, air pollutants and water effluents (Kendall and Santero 2011). LCA is a standard method mostly used to assess comprehensively the potential environmental impact of product. All environmental aspects of product life cycle are taken into account. The ISO 14040 and 14044 describe the LCA method. LCA takes only ecological aspects into account. The social and economical factors are excluded (Milachowski *et al.,* 2017). In order to improve the sustainability of road pavement infrastructure, road agencies and construction companies are adopting appropriate methodologies and tools to identify priority areas for improvement. As a result, it is important to know the impact of pavements on the environment to develop and implement approaches and procedures that can produce gains in all aspects and dimensions of the system. There are different types of tools for conducting LCA and there are notable differences between them (Santos *et al.,* 2017). Pavements form an important portion of the transportation infrastructure that has impact on the natural environment. Most of the pavement environmental impact occurs due to the vehicles travelling along the pavement. This takes place during the use phase of the road. It is established that 95% of the energy consumed occurs during use phase of the pavement life cycle, 2% to 5% is consumed during construction and maintenance. More energy consumption leads to increase in greenhouse emissions (Bryce, 2014). Climate change is one of the major global issues in today's time. Hence a substantial research is being conducted to study the environmental impacts of road pavement designs and construction practices using LCA methodologies. Pavement LCA is a comprehensive approach to evaluating the environmental impacts of a pavement section. Roadway construction study shows that the construction of the surface layer of an asphalt pavement alone generates a carbon footprint of 65.8kg of CO_2 per kilometre (Alam, 2020).

LCA can be used to evaluate the environmental impact of a single product to reduce the impact of that product, hence it is important that the process be as comprehensive as possible to truly reflect the environmental impacts of a given pavement design (Akbarian *et al.,* 2019). The service life capacity of any pavement type depends on prevailing factors within the environment it is to be constructed in; those factors include; social impact, economic development, weather conditions, material properties, design considerations, etc., (Abejide *et al.,* 2019). Pavement infrastructure comprises assets for the society since they do not only ensure mobility, they also strengthen society's economy. To study the pavement LCA can help improve the technology in order to achieve a system that has a lower impact on the environment. The earliest pavement LCA was established in the 1990s and since then a great deal of knowledge and data has been generated (Butt, 2014).

2.2 Defining LCA

The Department of Environmental Affairs and Tourism of South Africa defines LCA as "the calculation and evaluation of the environmentally relevant inputs and outputs and the environmental impacts of the life cycle of a product, material or service. It consists of the technical system of processes and transport routes needed for raw materials extraction, production, use and after use" (DEAT, 2004).

Four Element Consulting defines it as "an analytical tool used to comprehensively quantify and interpret the environmental flows to and from the environment (this includes air emissions, water effluents, solid waste, and the consumption/ depletion of energy and other resources), over the life cycle of a product or process" (Greig, 2018). LCA should be performed in accordance with ISO 14040. According to ISO 14040 LCA is a "comprehensive approach avoids the misallocation of environmental effects and provides an overview for possible impact reduction" (Adams, 2021).

Cycle Assessment Procedure for Eco-Materials defines it as "the factual analysis of a product's entire life cycle in terms of sustainability. It is a standardized methodology, which gives reliability and transparency. It is an iterative methodology where you refine things as you go along" (Golsteijn, 2020).

The European Environmental Agency defines it as follows "Life Cycle Assessment (LCA) involves the evaluation of some aspects often the environmental aspects of a product system through all stages of its life cycle" (Jesen *et al.,* 2016).

The European Commission and Institute for Environment and Sustainability define it as "LCA is the best framework for assessing the potential environmental impacts of products, but the debate is ongoing about good practice" (Wolf *et al.,* 2011).

Definition by DEAT is selected for the purpose of this research. The selection relies on DEAT being the main government department responsible for regulating the environmental activities in the country. The definition also relates to the topic of this study as one of the objectives is to calculate and analyse environmental impact indicators.

2.3 Phases of LCA

2.3.1 Goal definition and scope

The goal definition addresses these questions: why do we perform LCA, what is the product under LCA study, and who are the target audiences. The scope definition defines product system boundary, functional unit, target for data quality, data parameters, and impact assessment methods (Lee and Inaba, 2004). Goal definition is the crucial part in the LCA. It determines and guides the choice to be made in the other phases of the study. According to ISO 14040, the standard goal of the study should define the reason for carrying the study, intended audience, and whether the results are intended to be used in comparative assertions disclosed to the public. When defining the scope of the study the following aspects should be considered and described: the product system, environmental impact methodology, system boundary, functions of the product system, allocation procedures, assumptions and limitations, data requirements, critical review considerations, data quality requirements, and type and format of the report required for the study (Palsson and Riise, 2011). The selection of a suitable allocation procedure for co-production and recycling in LCA relies on the goal and scope of the analysis. However, it is not clear when partitioning or system expansion can be applied, or when to conduct an attributional or a consequential LCA for LCA practitioners (Schrijvers *et al.,* 2020).

Goal definition determines the purpose of the study in detail. There are six aspects of a goal definition: intended application of the results, decision context and reasons for carrying out the study, target audience, limitations due to methodological, comparative studies to be disclosed to the public, and commissioner of the study and other influential actors (Bjorn *et al.,* 2018).

2.3.2 Life cycle inventory assessment

Inventory analysis is the third phase of LCA and it is guided by goal and scope definition. The inventory analysis is where environmental flows are tracked for the system being studied. The environmental flows refer to the inputs and outputs. In order to perform inventory analysis, a model of the process being analysed is set up, with definitions of the functional unit and system boundaries (USDOT, 2014). LCI is defined by ISO as the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle." The inventory relates to various environmental inputs and outputs involved in the life cycle of a product. LCI analysis requires quantification of these elements: raw material needs, energy requirements, atmospheric emissions, waterborne emissions, emissions to land, solid wastes, and other releases to the environment (Muthu, 2020). LCI is the straight-forward accounting of everything involved in the LCA analysis. It has details of all resources and activities that flowed in and out of the product system boundary. These include raw materials, energy by type, water, and emissions to air. The required data for analysis must be related to the functional unit that was defined in the initial goal and scope phase (Torabi and Ahmadi, 2019).

There are four key steps in life cycle inventory analysis: to develop a flow diagram of the process being evaluated, develop a data collection plan, collect data, and evaluate and report results. A flow diagram is a tool to map the inputs and outputs to a system. LCI data collection plan ensures that the quality and accuracy of data meet the expectations of the decision-makers. The efforts regarding data collection involve a combination of research, site visits and direct contact with experts. It is important to thoroughly describe the methodology used in the analysis when writing report to present the final results of the LCI. The LCI studies generate a great deal of information (Babu, 2006).

2.3.3 Life cycle impact assessment

Life cycle impact assessment has been standardised within the ISO 14000 family standards and its aim is to quantify the environmental impacts of economic activities. The quantification process takes into account regional and global effects. LCIA methods have been developed in Europe and they have been applied and they provided a comparatively quick indication of the environmental influences of the industrial and economic systems evaluated. However, in South Africa problems have been encountered in terms of comprehensiveness and modelling approaches (Brent, 2003). LCIA is a method used in the life cycle stage. It has been adopted in various studies such as; construction, maintenance and rehabilitation, estimation of asphalt, and concrete impact on from the production process to the disposal by using the ReCipe and SimaPro software and environmental protection and sustainable development requirements among others. LCIA is divided into four steps: classification, characterisation, normalisation and weighting (Hatmoko *et al.,* 2021).

2.3.4 Interpretation

Interpretation phase is the fourth and last phase of LCA. It is the pivot phase since it links all other three phases. There are five steps of interpretation and they are explained as in ISO 14040-44. These steps are: completeness check, consistency check, sensitivity check, identification of significant issues and conclusions, limitations, and recommendations. Interpretation phase is the phase where results of LCI and LCIA are summarised and discussed as a basis for conclusions, recommendations and decision making in accordance with the goal and scope definition. The life cycle interpretation is vaguer than other phases in LCA (Laurent *et al.,* 2020). Lack of comprehensive guidance for the interpretation phase is alarming since LCA is recognised by both private and public stakeholders as a key element for decision support. The interpretation phase need a critical assessment of the results of an LCA study, which encompasses LCI and LCIA according to the goal and scope definition. The interpretation phase is systematised. This is demonstrated by situations whereby LCA practitioners formulate conclusions and recommendations with lack of consistency underlying within the LCIA steps and across the goal and scope definition (Sala *et al.,* 2020).

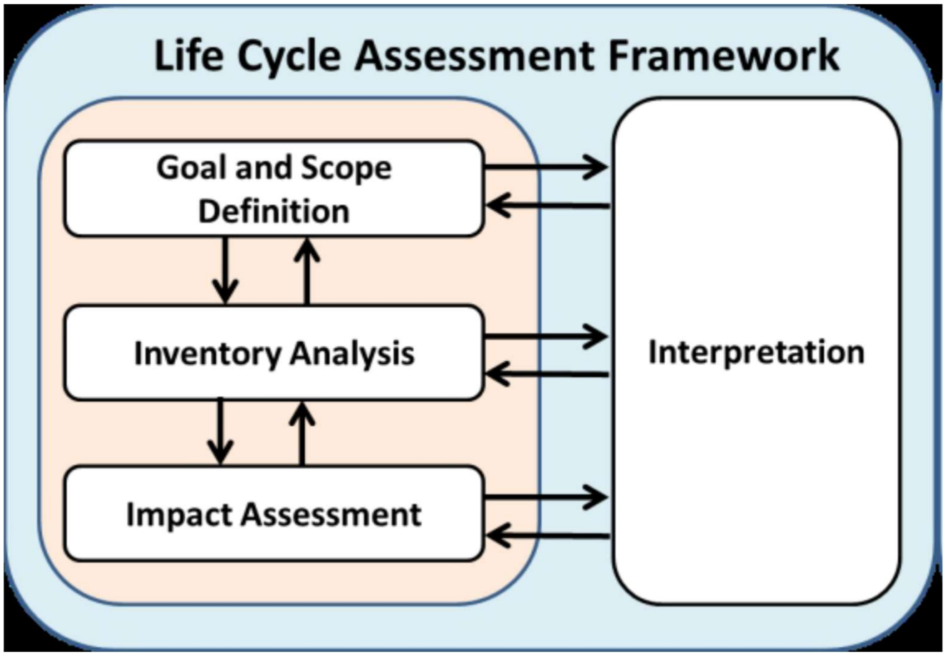

Figure 2.1. General LCA framework (ISO. 2006)

2.4 Stages of Pavement LCA

Pavement LCA includes material production, design, construction, use, maintenance and rehabilitation, and end of life stage. The need to protect the environment is increasing, and impacts that are associated with the production, use, and retirement of products, has generated interest to apply assessment methods in order to address those impacts. LCA is a tool that has been developed for such purpose (Harvey *et al.,* 2016). The Carbon emissions should be reduced in order to achieve sustainability. It is crucial to check the environmental indicators which influence road components. Vehicles generate emissions which involve the following air pollutants: hydrocarbon, carbon monoxide, nitrogen oxide, sulphur dioxide, carbon dioxide, particulates and lead. There are developments in the automobile industry. Electricity, hydrogen and biofuels are emerging as new sources of vehicles fuel. It has been identified that low-carbon biofuels used in hybrid electric vehicles would be the lowest emitting vehicle fuel combination. The hydrogen fuel cell and battery electric vehicles that are made from very low-carbon sources are likely to be lowest emitting (Nigro and Jiang, 2013). The electric vehicles that are powered by the present European electricity mix have good global warming potential over the conventional gasoline or diesel vehicle (Hawkins *et al.*, 2012).

2.4.1 Material Production

Material production stage requires that each material input to the pavement system be characterised by an LCA that includes the following processes: raw material acquisition, material production, mixing process and transportation of raw materials. Pavement construction requires a range of distinct materials to ensure the pavement structure is durable and in good shape to withstand heavy loads and traffic. Materials such as soil, aggregate, binder, filler are used to build roads.

Ecopave refers to the application of waste plastic in flexible pavement construction. This application has been known for the past 20 years. After the results of Graphene-Based Supermodifier research in 2014, waste plastic was combined with graphene. This process assisted to achieve the creation of a product for the dry modification of bituminous mixes for building safe and eco-sustainable pavements. Ecopave helps to improve performance of bituminous mixes and it has the potential to increase the pavement life span (Giustozzi and Nizamuddin, 2022). Shisalanga Construction is a South African-based asphalt manufacture. Part of the products they manufacture is eco-asphalt (recycled plastic). It is an asphalt paving mix that utilises a specialised binder that is manufactured with locally sourced plastic.

2.4.2 Pavement Design

Pavement design is the stage whereby pavement structure is designed. The following are taken into account: design parameters, geometry of the road, selection of materials for the layer works based on the standards, degree of compaction required, road marking and signs as per the standards. This stage is very critical since it is a prerequisite to the construction stage.

Pavement design takes into account design considerations, estimating design traffic, pavement investigation and structural capacity estimation. The purpose of structural design is to ensure a structurally balance pavement is achieved. Estimating design traffic describes methods of obtaining traffic data, and the procedures for estimating the cumulative design traffic for structural design period. The pavement investigation covers new and rehabilitation design, material availability, constructability, performance and maintainability. The structural capacity estimation is achieved through the use of South African Mechanistic-Empirical Design Method and the pavement number method for flexible pavements (Van der Walt and Bredenhann, 2013). The current revision of the SAMDM for flexible pavements is based on technology and models that were developed during the 1970s and 1980s. It is the appropriate time for the revision of SAMDM, due to the challenge to validate results from the method. Factors taken into consideration when applying SAMDM are load input, material characteristics, primary pavement response model and damage models (Theyse *et al.,* 2007).

2.4.3 Construction

The Council for Scientific Industrial Research is focused on sustainable approach to future road construction. This will be achieved by increasing job creation, increasing economic benefits, producing better performing roads and trying to resolve South Africa's environmental challenges (CSIR, 2021). LCA have proved to be an appropriate methodology in ensuring demand for sustainable solutions is met (Vandewalle, *et al.,* 2020). The modelling of this stage requires mobilisation and demobilisation of equipment, equipment used on site, transport of materials to site, energy used on site and changes to traffic flow be considered.

2.4.4 Use and Maintenance

It is the stage whereby the road is complete and motorists are starting to use it. During the use stage there are characteristics which have environmental effect. These factors are pavement roughness, micro texture and structural response affect vehicle fuel economy. Pavement surface texture and permeability affect noise generated from tyre pavement interaction. Permeability of pavement system influences stormwater run-off and surface friction. The albedo, heat capacity, and thermal conductivity of the pavement affect absorption of energy from the sun and the emissions of reflected and thermal energy from the pavement (Van Dam *et al.,* 2015). In the past the main criterion used to pavement design was to build at a low cost, provided that structural capacity and safety are ensured. However, currently the approach that will address economic, social and environmental impacts is required. Any construction activity related to pavement construction has a significant impact on the environment. This result from activity inherent in the construction, due to the consumption of energy and natural resources as well as the release of gaseous emissions to the atmosphere. However, the effects on the environment continue during the use phase (Araūjo, 2014). Poor maintenance of roads results in road deteriorating rapidly and this leads to premature rehabilitation. Roads should be built only if they can be maintained. Poor road conditions cause accidents that result in serious injuries and deaths. Roads require constant maintenance and periodic resurfacing to stay in good condition.

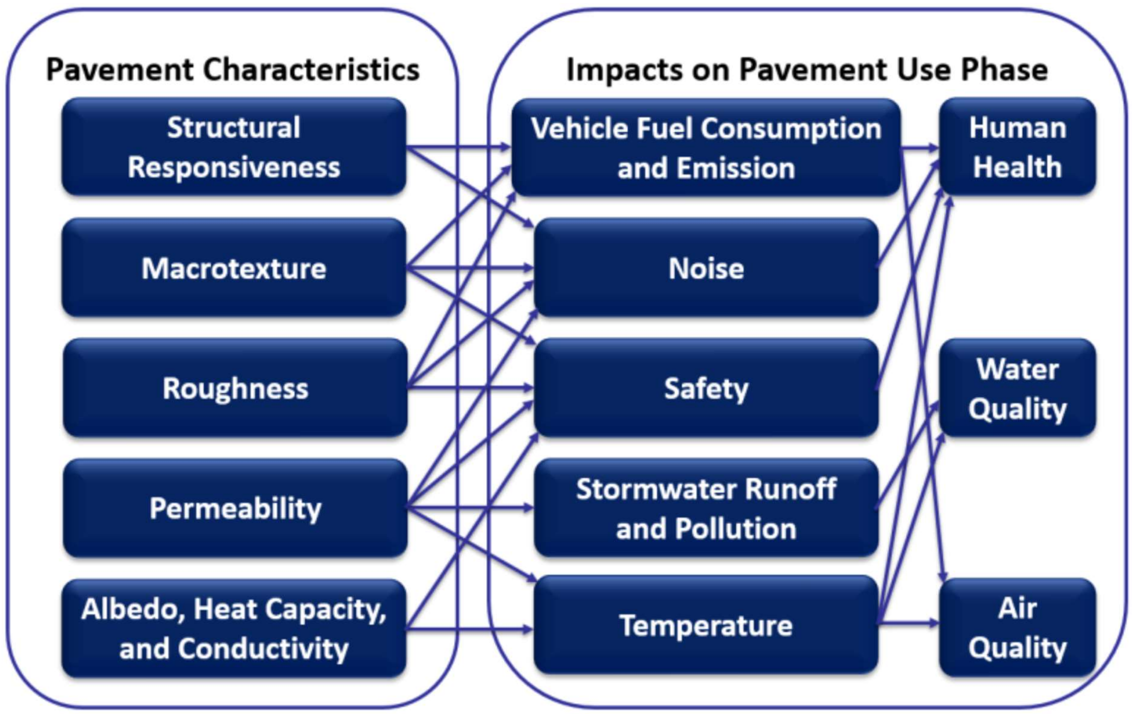

Figure 2.2. Pavement characteristics and influence on use stage objective (US DOT, 2014)

2.4.5 End of Life

When pavement reaches its end of life stage, it can be kept as the supporting structure for the new pavement or be removed and land filled. Both approaches have economic and environmental costs. End-of-life stage affects sustainability factors such as waste generation and disposition, air and water quality, and materials use. The ideal goal is to recycle the materials and create a long-lived and well performing pavement. This will assist to achieve a zero waste, reduce energy consumption, reduce greenhouse gas and eliminate the need for landfill disposal (Babashamsi *et al.*, 2016). During end-of-life stage the degree of deterioration increases and the pavement becomes unfriendly to use. This means traffic takes longer than it is expected and that comes with a negative impact on developmental progress.

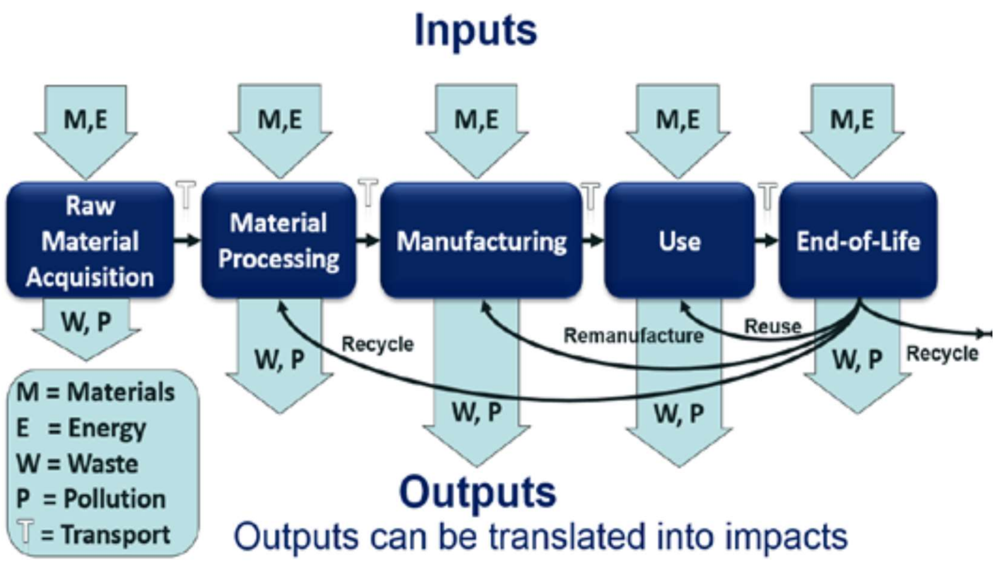

Figure 2.3. Generic life cycle of a production system for LCA (Kendall, 2012)

2.5 Consumptions

2.5.1 Material consumptions

Material used for all construction tasks are essential to the development of a modern economy. Aggregates are extracted from the ground through quarrying operations. Quarrying causes many adverse environmental impacts such as noise, dust, traffic, visual intrusion, loss of amenity, damage to biodiversity and the generation of derelict land.

Development needs to happen in a way which protects and enhances the environment in order to achieve sustainability. Roads are constructed through layer works which are compacted to a specified Mod AASHTO. The layer works increase quality of the road from layers to the surface. The materials used in each layer of the pavement are subjected to specification. The specification covers properties such as grading, particle strength and resistance to frost. Currently the techniques and choice of materials in pavement construction is dictated by the structural requirements and economic aspects. The ecological factors are considered important due to environmental considerations (Thiel *et al.,* 2014).

With the global increase of pavement system, there is a need for more sustainable pavement system development. Sustainable pavement system development requires a comprehensive evaluation framework that takes into account economic environmental and social indicators. An aggregated set of economic, environmental and social indicators are derived for the infrastructure system from material resource extraction to end-of-life management. The sustainability indicators can be applied to bring change in material design in order to optimise system performance (Bardeesi and Attallah, 2015). Pavement infrastructure is one of largest consumers of natural materials. In order to improve the environmental quality and sustainable development of pavement infrastructure, it is ideal to implement sustainable strategies in pavement construction and rehabilitation. The use of recycled material is a key element in generating sustainable pavement design, it helps to save natural resources, reduce energy, greenhouse gas emissions, and costs (Zhao *et al.,* 2021). Materials such as recycled asphalt shingles, recycled rubber tyres, recycled glass and reclaimed carbon from copier toner can be successfully incorporated into new pavements (Chan and Tighe, 2010). In the USA, 99% of generated RAP is reused and 460 million tons of crushed aggregate are used for paving works yearly. In Japan 99% of RAP is reused in new pavement construction. In Denmark and Sweden, 100% of RAP is reused. The incorporation of RAP as an alternative material in construction of asphalt base and sub-base offers reduction of 20% global warming, 16% energy consumption, 11% water consumption and 11% hazardous waste generation (Jamshidi and White, 2019).

2.5.2 Water consumptions

Water can be measured by meter pumping rate over time and other appropriate source dependent estimates. Water is used for different functions in pavement construction. It is used for concrete mix, dust control, concrete curing, construction equipment cleaning, geotechnical borings, compaction, site clean-up, pipe flushing and pressure testing (Muench *et al.,* 2011). It is ideal to use water sparingly during pavement construction and maintenance. This can be achieved by eliminating water wastage on site, improving efficiency of water using processes and offsetting use of mains water with alternative sources, such as rainwater harvesting and use of treated waste water (NSW Government, 2019). The implementation of permeable pavement and stormwater utilisation have provided great reductions in life cycle emissions such as CO_2, SO_2 and $PM_{2.5}$. The system proved to be an important strategy to reduce water and environmental stresses caused by centralised water utilities and traditional drainage system (Antunes *et al.,* 2020).

2.5.3 Energy consumptions

In pavement construction energy is used by machinery and materials used. The total construction energy is calculated by adding machinery energy and material energy. The fuel consumption and typical output per hour are measured for all activities of pavement construction. These activities are drainage, services, earthworks, pavement, road markings and structures. Each activity has a list of machinery used. The fuel consumption per unit of activity and then the energy per unit are calculated. Energy consumption in pavement construction remains poorly understood as a result of incomplete system boundaries of methodologies and inadequate databases for quantitative assessments. Preventive maintenance treatments and binder production procedures are suggested for energy consumption mitigation (Wang *et al.,* 2021). The use of recycled and low temperature materials are promising solution to reduce the environmental burden deriving from hot mix asphalt. The combined use of warm mix asphalt and recycled materials in bituminous mixtures entails lower energy consumption and environmental impacts due to reduction of virgin bitumen and aggregate consumption (Pratico *et al.,* 2020). Pavement construction has a negative impact towards climate change. It is responsible for about 28% of global energy consumption and approximately 22% of global equivalent CO_2 emissions. The energy required for Basic Oxygen Furnace production is 0.24 MJ/kg. The pavements with BOF can reduce up to 12% of emission compared to ordinary pavement (Xei *et al.,* 2021).

2.6 Environmental Indicators

2.6.1 Greenhouse effect indicator

Greenhouse gas emissions refer to the release of greenhouse gases to the atmosphere. Road projects typically results in emissions of CO_2, CH_4, N_2O and HFCs. Emission factors for all greenhouse gas emissions deemed typical for road projects have been provided in CO_2 equivalents (Renton, 2013). National pavement network which includes construction and maintenance, incurs the use of large amounts of energy and natural resources, and results in the emissions of significant quantities of greenhouse gases. The greenhouse gases are CO_2, CH_4, N_2O and fluorinated gases. CO_2 is produced anytime something is burned, CH_4 is produced by combustion processes, N_2O is a by-product of fertilizer production and fluorinated gases are created as replacement for ozone depleting refrigerants (Harvey, 2010).

2.6.2 Acidification potential

The release of gases such as NO and SO_2 lead to the potential acidification of soil and water. Acidification potential varies according to regional characteristic and atmospheric environments. Acidification is an environmental problem caused by acidified rivers/ streams and soil due to anthropogenic air pollutants such as SO_2, HNO_2 and NO. It increases mobilisation and leaching behaviour of heavy metals in soils and exerts adverse impacts on aquatic and terrestrial animals and plant by disturbing the food web (Kim and Chae, 2016).

2.6.3 Eutrophication indicator

This is an indicator of the enrichment of the aquatic ecosystem with the nutritional elements due to the emissions of nitrogen or phosphor containing compounds. Eutrophication refers to the process whereby water bodies grow more productive. The European Court of Justice defines it as "the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned, and therefore refers to the undesirable effects resulting from anthropogenic enrichment by nutrients" (Ferreira *et al.,* 2011). In the past 40 years, eutrophication has become an increasing threat to the usability of South Africa freshwater resources. Department of Water Affairs focused on monitoring areas affected by eutrophication through the Trophic Status Project. Eutrophication is a serious problem in South Africa (in a number of catchments). The root cause of the problem is nutrient enrichment in freshwater resources (Ginkel, 2011).

2.6.4 Indicator of the formation of tropospheric ozone

Tropospheric ozone is formed by interaction of sunlight, particularly ultraviolet light, with hydrocarbons and NO, which are emitted by automobile tailpipes. Tropospheric ozone is a concern worldwide due to its effect on human health, forest ecosystems and agriculture crops. Photolysis of ozone is the major source of the hydroxyl radical in the remote troposphere. As a result, increase in O_3 produces more OH which leads to decreased life times of trace species such as NH_4 and the hydro chlorofluorocarbons, which are important to the stratospheric (Finlayson-Pitts and Pitts Jr, 2012). The stratosphere consists about 90% of atmospheric ozone and the troposphere has only 10%. However, tropospheric ozone governs oxidation processes in the earth's atmosphere through the formation of OH (Lelieveld and Dentener, 2000).

2.6.5 Ecotoxicity indicator

Ecotoxicity refers to the potential for biological, chemical or physical stressors to affect ecosystems. Ecotoxicity impacts assessment of chemicals in LCA adhere to a number of underlying principles and boundary conditions which are: additive of toxicity, conservation of mass and mass balance, infinite time horizon, linearity of characterisation models and a large number of emitted substances to cover at least 100 000 potentially relevant elementary flows with current models covering about 2500 (Rosenbaum, 2015). In Ecorce M, vanadium often appears as the most important contributor in ecotoxicity and is also a significant contributor for toxicity. Missing values for this pollutant could therefore pose a problem. In Ecorce M, as in other streamlined LCA tools that do not allow sensitivity analysis with different LCIA models of ecotoxicity and toxicity indicators should be treated with caution (Tremblay and Jullien, 2014).

2.6.6 Toxicity indicator

Toxicity refers to the quality of being poisonous. It is the degree to which a chemical substance can damage an organism. Toxicity is based on same driving factors just like ecotoxicity which are: emitted quantity, mobility, persistence, exposure patterns and human toxicity. However, the mechanisms and parameters are certainly different from that of ecotoxicity and specific for human toxicity. Chemical exposure of humans can result from chemical ingredients in products released during their production, use or end of life treatment. The LCIA methods that cover human toxicity use the same fate model as for ecotoxicity. However, the exposure and effect models are different since they are specific for the targeted organism (Hauschild, 2017).

2.7 Perspective of LCA Worldwide

In France, Research shows that LCA is widespread; although it is still evolving, it is a systematic environmental management tool used for assessing the potential environmental impacts and resources consumed throughout a product's lifecycle from cradle to the 'cradle to grave' perspective i.e from raw material acquisition, via production and phases, to the end of life phase (Santos *et al.,* 2007).

In the United States of America; LCA studies include a selection of impact categories that are most relevant to the specific project goal and scope, and can range from narrowly focusing on energy and greenhouse gas emissions to a broader set of impact categories. The most commonly used selection of impact categories in the United State of America is the Traci impact assessment methodology developed by US EPA (Harvey *et al.*, 2014).

Pavement LCA is expanding; however it is still a limited research topic in the literature. The existing work exhibits methodological deficiencies and incompatibilities that create a barrier for effective use of pavement LCA by engineers and policy makers. The best approach of quantifying environmental impacts of pavement is through the use of LCA approach. It assesses a product from 'cradle to grave', it explores from upstream to recycling and disposal options when the product reaches its ultimate end of life. LCA is a methodology used to estimate and understand the environmental impacts of a product. There are three different approaches to conduct LCA and they are: Process LCA, input-output LCA and hybrid LCA. Process LCA aims to quantify the inputs and emissions of each discrete process within a life cycle system boundary. Input output LCA is a top-down method that include all economic sectors in the analysis. Hybrid LCA is a method that combines process LCA and input-output LCA methods such that it exploits their strengths and curtails their weaknesses (Santero *et al.*, 2010).

In Australia, life cycle assessment is a method of quantification of all stages of life. This method has been studied to explore all the environmental components of roads projects due to limitation of generic environmental assessment. The LCA ensures collection and assessment of the inputs and outputs relating to any potential environmental factor of any system throughout its life. However, absence of a defined system boundary covering all potential environmental components restricts the findings of the current LCA studies (Alam *et al.*, 2012).

In Canada, the LCA and life cycle cost analysis (LCCA) methods have been recognised by the Ministry of Transport as basic for choosing type of pavement. In that context, many studies have been published on various supports, aiming at comparing different technologies for construction and maintenance of pavements.

2.8 Perspective of LCA in South Africa

Pavements are constructed through the use of bulk raw materials such as aggregates, cement, bitumen and water. There is a need to quantify and monitor the environmental, social and economic impacts of the materials towards optimisation of the pavement design. Currently in South Africa there is no such protocol in place. There is a need for LCA models to address effects of alternative pavement designs and technologies in terms of construction, maintenance and rehabilitation. It is ideal to start with LCI when developing LCA model (Blaauw *et al.,* 2021). The LCI serves as a building block to the LCA through evaluating primary flows related to pavement materials and construction activities in South Africa (Blaauw and Maina, 2021).

LCA has been identified as a tool to be used to evaluate the environmental impacts of products and services. Research has increased on this topic in the past 20 years. However, this concept is new in South Africa even though there is research conducted on this topic in the continent. There is still a need for a LCI database for African countries. South Africa has published 43 articles, Egypt 23 articles and Tunisia 19 articles. According to United Nations projections, the African population is more than 1.2 billion people and it is expected to double by 2050. South Africa, Nigeria and Egypt might enter lists of the top 30 global economies by 2050. High population and economic growth may pose a challenge on environmental problems in Africa (Karkour *et al.*, 2021).

2.9 LCA Tools

Project Emission Estimator (PE2)

The Project Emission Estimator is a web-based tool. It can be used to implement the project-based life cycle framework. It can also be used to benchmark the CO_2 footprint of a highway construction projects. It allows the user to build their own emission inventories. The user can generate emissions reports using data and emission metrics developed by the Project Emission Estimator's Inventory Tool along with information obtained from Michigan DOT construction, rehabilitation, and maintenance projects investigated by researchers at Michigan Technological University. Three types of emission reports are; Material Use Emissions Report, Equipment Emissions Report and Pavement Life Cycle Report (Mukherjee *et al.,* 2013).

Economic Input-Output Life Cycle Assessment (EIO–LCA)

The Economic Input-Output Life Cycle Assessment method estimates the materials and energy resources required for the environmental emissions resulting from activities in our economy. It is one technique for performing a life cycle assessment, an evaluation of the environmental impacts of a product or process over its entire life cycle. The method uses information about industry transactions-purchases of materials by one industry from other industries, and the information about direct environmental emissions of industries, and estimate of the total emissions throughout the supply chain. This method is not used as widely for quantification of energy use and environmental impacts (Azari, 2019).

Palate

Palate is an excel-based tool for LCA of environmental and economic effects of roads. The tool takes user input for the design, initial construction, maintenance, equipment use, and costs for a roadway, and provides output for the life-cycle environmental effects and costs (Horvath *et al.,* 2007).

Road-Res

Road-Res is a LCA tool for road construction and disposal of municipal solid waste incineration residues. The road system and the landfills are the core systems in the model, and extraction of resources, upgrading of resources and residues, energy production and transport are upstream processes. These processes cause release of emissions and waste that contribute to different environmental impacts (Birgisdóttir, 2005).

Roadprint

Roadprint is an online pavement LCA tool designed to be used by pavement practitioners. It is able to perform pavement LCA (Muench *et al.,* 2014).

Athena Pavement LCA

Athena Pavement LCA is a free pavement LCA software that is used to assess roads for environmental effects in Canada and some regions in the United States. The software was made possible by the support from Cement Institute of Canada and Athena Institute members. The earlier software prototype was developed in association with transportation engineers at Morrison Hershfield, and was funded by Environment Canada (Ahammed *et al.,* 2016).

Ecorce M tool

The first developed Ecorce tool was Ecorce 1.0 and it was certified in 2009. It was certified by LCPC. The version of Ecorce 2.0 was finished in 2013 after it was reviewed for 6 months by Institute Des Routes des Reus et des Infrastructures pour la Mobilite (IDRRIM). The international version Ecorce M has been available since July 2014. The aim of Ecorce M tool is to reduce consumption of materials, water, and energy by means of evaluating impacts. It takes into account civil engineering practices and provides a set of dedicated data related to road materials, road works, and earthworks (Jullien *et al.,* 2015). Ecorce M tool is a process-based LCA tool with an extensive integrated default database that is used to complement the lifecycle inventory phase. The data used to populate the integrated database is taken from different sources. In cases whereby international consensus does not exist, the tool draws data from research conducted in France to populate values (Presti and DÁnglo, 2017). The selection of Ecorce M tool is based on the following advantages:

- The software allows for quick and easy comparison of multiple design options over a range of expected roadway lifespan.
- It takes into account the environmental impact of the following life cycle stages, material production, pavement design, construction and use (with or without Pavement Vehicle Interaction effects)

- It provides a life cycle inventory profile for a given three-dimensional roadway design.
- It calculates the total energy, including pre-combustion energy and the related emissions to air, water and land over the life cycle of the roadway.
- It can subsequently compare the life cycle operation and embodied energy and other environmental effects of various design options, allowing the user to better understand trade-offs.
- It enables decision makers to understand environmental effects.
- It allows easy change of input data (geometry, operations, materials, and haulage).
- Its output screens and tables offer several approaches to investigate environmental LCA results on roads.
- It can be used to assess initial construction and maintenance policies.
- Freely available and accessible
- It is based on full process of LCA
- User-friendly and in any case accompanied by a user manual
- It can perform a cradle to laid carbon foot printing of road pavement technologies.
- It performs a full pavement LCA
- It performs a cradle to grave analysis

2.10 Measures to minimise consumptions and regulate environmental indicators

The use of LCA assist to limit the environmental impacts associated with a boundless and crucial infrastructure system. The following measures can be taken to minimise consumptions and regulate environmental indicators. The improved comprehension of the effect of each phase and stage in respect to remained LCA and reconciliation of sensible maintenance timetables and activities. Considering uncertainty of LCA results based on data and modelling errors. Sensitivity analysis for testing of outcome to changes in variables. Coherent utilisation of data quality scoring methods that account for general quality as well as for regional and temporal applicability. Enhanced energy use and emission factors for materials, especially for bitumen and cement production. Consideration of distinctive electricity mixes, transportation distances, production variability, and other processes that vary between locations. Consideration of a functional unit framework that accounts for significant characteristics of the pavement, including function, location, and design descriptions of system boundaries. Enhanced unification of LCA modules and components. Coherent and accepted accounting strategies for feedstock energy (Babashamsi *et al.,* 2015).

2.11 Summary

This chapter defines LCA, explains LCA phases, pavement LCA stages, perspective of LCA worldwide and in South Africa. It explains various LCA tools and motivates why Ecorce M tool is selected to be used to achieve the outputs of this research. It further explains the origin of Ecorce M tool and how it is applied to achieve desired outcomes. The goal of the study defines what the study should achieve. The scope outlines the work that must be incorporated in order to achieve the outcomes defined by the goal. The LCI phase is a breakdown of processes considered in the research in order to achieve the outcomes defined by the goal. The LCIA translate the outcomes achieved by use of Ecorce M tool model into consumptions and impact indicators. The interpretation phase interprets the consumptions and environmental impact indicators.

CHAPTER 3

RESEARCH TOOLS AND METHODOLOGY

3.1 Quantitative Approach

Quantitative approach is selected as the methodology for this research. Quantitative research is explaining the phenomena by collecting numerical data that are analysed using mathematical based methods (Muijs, 2004). The purpose of this research is to calculate and analyse the consumption of materials, energy and water and to calculate and analyse environmental impact indicators. Ecorce M is the LCA tool used to achieve the desired outcomes. Data is gathered from rehabilitation of road; project that took place in Klerksdorp. Data is entered into the model as inputs. After running the software, the following results have been achieved, consumption of materials, energy and water, and values of environmental impact indicators which are: greenhouse effect indicator, eutrophication indicator, media acidification indicator, indicator of the formation of tropospheric ozone; and toxicity and ecotoxicity indicators.

3.2 LCA Methodology

LCA methodology starts with goal and scope definition according to ISO 14040 2006. The goal definition explains why the study is performed, which questions it must address and who is it performed for. Goal definition is also basis of the scope definition (Hauschild, 2018). Scope definition is where the assessment is framed in line with goal definition. It gives a quantitative description of the function which the assessment is performed for. It determines the reference flow of product that scales data collection in analysis phase. Scope definition helps to identify activities and processes which belong to the life cycle of the product which is studied. It helps to select the assessment parameters, geographical and temporal boundaries, settings of the study and level of technology relevant for the product system. Scope definition helps to identify the need to do critical review. It helps to decide relevant perspective to be applied to the study (Curran, 2017).

Goal and scope definition are crucial to consider when results of the study are interpreted. The reason behind this is that these definitions involve choices that determine the collection of data and the manner in which the system is modelled and assessed. They have influence on the validity of the conclusions and recommendations that are based on the results of the LCA.

Life cycle inventory is the outcome of inventory analysis. Inventory analysis collects information about physical flows in terms of input resources, and output emissions. All processes that belong to the product system are studied. Most product systems are comprehensive and as a result they rely on generic data. The outcome of inventory analysis is a list of quantified physical elementary flows for the function described by the functional unit.

The impact assessment translates the physical flows of the product system into impacts on the environment. The impact assessment consists of five elements. These elements are selection of impact categories, classification of elementary flows, characterisation, normalisation and weighting supports comparison. According to the ISO 14040 standards, the first three elements are mandatory.

Interpretation phase is whereby the results of the study are interpreted to answer question posed by goal definition. The interpretation phase takes into account the results of inventory analysis and impact assessment elements which are characterisation, normalisation and weighting. The scoping choices must be adhered to as they impose meaningful interpretation of the results.

3.3 Selection of Research Site

Patchwork, Rehabilitation and Reseal of Road P3/4 (N12) from Road R503 to Archbishop Desmont Tutu Street Phase 2 project is selected as study site. The project entails the following: Patchwork, Rehabilitation and Reseal of Road P3/4 (N12) from Road R503 to Archbishop Desmont Tutu Street Phase 2. This project is ideal for this research as it covers all LCA stages which are material production, construction (includes deconstruction and new construction, and rehabilitation), use, maintenance and end of life.

3.4 Data Collection Strategy

Inputs consist of data collected from project titled PWR 129/15: Patchwork, Rehabilitation and Reseal of Road P3/4 (N12) from Road R503 to Archbishop Desmont Tutu Street Phase 2 in Klerksdorp. Data collected is geometry of each layer, composition and mass density of the component layer material, hauling distances and unit consumption values for construction vehicles.

The layer works are as follows:

Table 3.1: Layer works

Subbase	Base	Surface
G 5 gravel material stabilized	G 1 gravel material	Asphalt

3.4.1 Geometry of each layer

It refers to thickness, length and width. Various types of excavations can also be input layer by layer to ensure the tool's functionality.

Table 3.2: Geometry of layers

Layer Type	Name of Layer	Year of Operation	Length (m)	Width (m)	Depth (mm)
Subbase	G5 (stabilised)	2018	7000	11.6	350
Base	G1	2018	7000	11.6	150
Surface	Asphalt	2018	7000	11.6	40

It shows measurements of the length, width and depth of each layer.

3.4.2 Composition and mass density of the component layer material

Ecorce M requests the composition and mass density of the target layer. These data mainly comprise of: Bituminous material mix design, concrete formulation, hydraulically bound material composition, concentration of asphalt surface treatment, concentration of tack coat, type and composition of unbound material and composition of the treated material.

3.4.2.1 Composition and mass density for the subbase

Table 3.3: Composition and mass density – Subbase

Maximum dry density	Optimum moisture content	Material classification	Grading modulus	UCS
2300 kg/m³	7.7%	C3	2.53	1265 KPa

It shows the maximum dry density, optimum moisture content, material classification as per COLTO, grading modulus and unconfined compression strength results. Mass density is a representation of the amount of mass of a substance in relation to the space it occupies.

3.4.2.2 Composition and mass density for the base

Table 3.4: Composition and mass density – Base

Maximum Dry Density	Optimum Moisture Content	Material Classification	Liquid Limit	Plastic Limit	Plasticity Index	Linear Shrinkage (mm)
2235kg/m³	5.9%	G1	23	0	0	0.8

It shows the maximum dry density, optimum moisture content, material classification as per COLTO, liquid limit and linear shrinkage

3.4.2.3 Composition and mass density for the surface

The requested mass densities are those of the material on-site following placement (i.e. the apparent density).

In-situ density = 2682 kg/m³

Asphalt mix design

Mix: ACTSF_a AC Medium with washed sand

Table 3.5: Asphalt mix design – binder A

Type	Pen@25 0oCP (0.1mm)	Softeni ng Point	RD of Bind er	Mixing Temp oC	Sourc e	Visc. @60oC (Pa.s)	Visc. @135o C (Pa.s)	Hot Flow	Compact ion Temp
50/70	61	50	1.021	155-	Sapref	189	0.36	N/A	138

				165					

It shows asphalt mix design which includes the softening point, mixing temperature, source and compaction temperature.

See Annexure A for the detailed results.

Mix : AC Medium-A-E2+0.03 zycotherm

Table 3. 6: Asphalt mix design – binder B

Type	**RD of Binder**	**Mixing Temp oC**	**Source**	**Compaction Temp**
A-E2+0.03 zycotherm	1.025	157-161	Engine	141-143

It shows asphalt mix design which includes mixing temperature, source and compaction temperature. See appendix A for the detailed results.

3.4.3 Hauling distances

Distance between worksite and mixing plant for materials produced at a mixing plant, hauling distance of raw materials, hauling distance of equipment and distance between extraction site and discharge site for excavated volumes.

The imported material was sourced commercially. The hauling distance is measured from the supplier to site and it is 10km.

3.4.4 Unit consumption values for construction vehicles

The consumption data on applicable worksite vehicles. The unit consumption rates of these vehicles may vary considerably depending on the type of engine, its age, maintenance frequency, as well as on external conditions (e.g. temperature, slope).

Table 3.7: Consumptions of the plant, hauling distance and operating times as received from the contractor.

Placement				
Machine	Operating Time (hrs)	Hourly Fuel Consumpti	Hourly Water Consumption (l/h)	Distance Hauled from Depot to Jobsite (KM)

		on (l/h)		
Contractor's Plant				
140H Grader	180	16	0	10
140H Grader	180	16	0	10
120 ton Roller	180	12	0	10
120 ton Roller	180	12	0	10
120 ton Roller	180	12	0	10
Diesel Bowser	28	15	0	10
10m³ Tipper Truck	180	6	0	10
18000 lt Water Cart	180	10	0	10
18000 lt Water Cart	180	10	0	10
18000 lt Water Cart	180	10	0	10
Bakkie	280	8	0	10
Bakkie	280	8	0	10
Bakkie	280	8	0	10
7 ton Flat-Back-Truck	140	4	0	10
7 ton Flat-Back-Truck	140	4	0	10
TLB	180	12	0	10
TLB	180	12	0	10
TLB	180	12	0	10
24m³ Tipper Truck	180	12	0	10
24m³ Tipper Truck	180	12	0	10
24m³ Tipper Truck	180	12	0	10
Loading Shovel	180	12	0	10
Demolition Hammer	180	12	0	10
Subcontractor's Plant				
Reclaimer	90	12	0	10
Milling Machine	180	13	0	10
Dozer	180	13	0	10
Pneumatic Roller	180	12	0	10

Pneumatic Roller	180	12	0	10
14m³ Tipper Truck	180	12	0	10
14 m³ Tipper Truck	180	12	0	10
24m³ Tipper Truck	180	12	0	10
24m³ Tipper Truck	180	12	0	10
Mechanical Broom	45	4	0	10
Flat Roller	180	12	0	10
Flat Roller	180	12	0	10
Paving Machine	90	13	0	10

3.5 Data Analysis

Ecorce M tool aim to reduce consumption of materials, water and energy by means of evaluating impacts. The environmental assessment is on the LCA framework established by ISO 14040 series of standards. There are several functional units that can be defined in order to compare pavement layers that have been designed to offer the same service. Ecorce M has been built by selecting the processes to be considered during the impact assessment. The selection relies on list of main processes, such as road materials, road equipment and material transport.
This tool has been built to specifically propose simple functionalities for road engineers and researchers, allow for quick case study implementation and display a user friendly interface. The tool also takes into account civil engineering practices and provides a set of dedicated data related to road materials, road works and earthworks.

This tool allows easy changing input data (geometry, operations, materials and transport distances). The output screens and tables offer several approaches to investigating environmental LCA results on roads. The tool makes it possible to compare not only the materials used in a given layer but also the pavement structures composed of several layers using various mixed materials. The results from Ecorce M indicate that the relative magnitude of impacts from each main process can be analysed for road design optimization. Ecorce M tool shows that pavement materials have more impact than other processes such as transport. LCA approach when applied to pavements it requires certain adaptations. Though end of life is crucial stage in LCA, it is limited to upper layers and again it does not correspond to complete removal of the entire pavement structure.

3.5.1 Inputs of the Surface

Table 3.8: Bituminous material formulation

Bituminous material formulation	
Distance from plant to construction site (km) :	10.0
In-situ density (kg/m3) :	2682.0
Type of coating :	Hot-mix asphalt plant using gas

It shows hauling distance, density of the surfacing material and type of coating.

Table 3.9: Composition and origin – Inputs of the surface

Composition and origin							
Components	Content	Road transport	Rail transport	Waterway transport	Maritime transport	Transport by Transport by dumper	Density
Bitumen (%)	5.0	10.0	0.0	0.0	0.0	0.0	0,0
Aggregates (%)	95.0	10.0	0.0	0.0	0.0	0.0	0.0

It shows percentage of bitumen and aggregates in relation to content and road transport.

Table 3.10: Laying – Inputs of the surface

Laying – Machine Used					
Type of machine	Brand / Model	Operating time (h)	Fuel (L/h)	Water (L/h)	Haul distance (km)
Other machine	Pneumatic Roller	180.0	12.0	0.0	10.0
Other machine	Reclaimer	90.0	12.0	0.0	10.0
Sweeper	Mechanical Broom	45.0	4.0	0.0	10.0

It shows operating time, consumption of fuel and hauling distance of machinery used during laying.

Table 3. 11: Deconstruction - Inputs of the surface

Deconstruction Machine used					
Type of machine	**Brand / Model**	**Operating time (h)**	**Fuel (L/h)**	**Water (L/h)**	**Haul distance (km)**
Demolition hammer	Demolition Hammer	180.0	12.0	0.0	10.0
Loading shovel	Loading Shovel	180.0	12.0	0.0	10.0
Tipper truck (dumper)	Nissan	180.0	12.0	0.0	10.0

It shows operating time, fuel consumption and hauling distance of machinery used during deconstruction of the surface.

3.5.2 Inputs of the base

Table 3.12: "as dug" gravel formulation – Inputs of the base

"as dug" gravel formulation	
Distance from plant to construction site (km) :	0.0
In-situ density (kg/m3) :	2235.0
Type of "as dug" gravel :	A (G1)

It shows hauling distance for transportation of base material, density of the base material and type of gravel.

Table 3.13: Composition and origin – Inputs of the base

Composition and origin							
Components	**Content**	**Road transport**	**Rail transport**	**Waterway transport**	**Maritime transport**	**Transport by dumper**	**Density**
Aggregates (%)	100.0	10.0	0.0	0.0	0.0	0.0	2235.0

It shows percentage of aggregates in relation to content, road transport and density.

Table 3.14: Laying – Inputs of the base

Laying Machine used					
Type of machine	**Brand / Model**	**Operating time (h)**	**Fuel (L/h)**	**Water (L/h)**	**Haul distance (km)**
Tipper truck (dumper)	Nissan	180.0	12.0	0.0	10.0
Water tank tractor	Mercedes	180.0	10.0	0.0	10.0
Compactor	None	180.0	12.0	0.0	10.0
Other machine	None	180.0	16.0	0.0	10.0
Other machine	None	180.0	12.0	0.0	10.0
Van for personal use	Isuzu	280.0	8.0	0.0	10.0

It shows operating time, fuel consumption and hauling distance of machinery used during laying.

Table 3.15: Deconstruction Inputs of the base

Deconstruction Machine used					
Type of machine	**Brand / Model**	**Operating time (h)**	**Fuel (L/h)**	**Water (L/h)**	**Haul distance (km)**
Tipper truck (dumper)	Nissan	180.0	12.0	0.0	10.0
Loading shovel	Loading Shovel	180.0	12.0	0.0	10.0
Demolition hammer	Demolition Hammer	180.0	12.0	0.0	10.0

It shows type of machine, operating time, consumption of fuel and hauling distance of machinery used during deconstruction of the base.

3.5.3 Sub-base

Table 3.16: “as dug” gravel formulation - Inputs of the subbase

"as dug" gravel formulation	
Distance from plant to construction site (km) :	10.0
In-situ density (kg/m3) :	2300.0
Type of "as dug" gravel :	B (Stabilized G5; C3)

It shows density of the sub-base layer, type of gravel and haulage distance during transportation of subbase material.

Table 3.17: Composition and origin – Inputs of the subbase

Composition and origin							
Components	**Content**	**Road transport**	**Rail transport**	**Waterway transport**	**Maritime transport**	**Transport by dumper**	**Density**
Aggregates (%)	100.0	10.0	0.0	0.0	0.0	0.0	2300.0

It shows percentage of aggregates in relation to content, road transport and density.

Table 3.18: Laying – Inputs of the sub-base

Laying - Machine used					
Type of machine	**Brand / Model**	**Operating time (h)**	**Fuel (L/h)**	**Water (L/h)**	**Haul distance (km)**
Tipper truck (dumper)	Nissan	180.0	12.0	0.0	10.0
Water tank tractor	Mercedes	180.0	10.0	0.0	10.0
Compactor	None	180.0	12.0	0.0	10.0
Other machine	None	180.0	16.0	0.0	10.0
Other machine	None	180.0	12.0	0.0	10.0
Van for personal use	Isuzu	28.0	8.0	0.0	10.0

It shows operating time, fuel consumption and hauling distance of machinery used during laying.

Table 3.19: Deconstruction – Inputs of the sub-base

Deconstruction - Machine used					
Type of machine	**Brand / Model**	**Operating time (h)**	**Fuel (L/h)**	**Water (L/h)**	**Haul distance (km)**
Tipper truck (dumper)	Nissan	180.0	12.0	0.0	10.0
Loading shovel	None	180.0	12.0	0.0	10.0
Demolition hammer	None	180.0	12.0	0.0	10.0

It shows type of machine, operating time, fuel consumption and hauling distance of machinery used during deconstruction of the subbase.

3.6 Trustworthiness

Methods used to establish trustworthiness are internal validity, external validity, reliability and objectivity (Malakoff, 2012).

3.7 Internal validity

This refers to the degree of confidence that the causal relationship being tested is trustworthy and not influenced by other factors or variables. It is used to establish trustworthiness by analysing data using statistical test measures. It is supported when changes in the dependent variable from only the independent variable, not from other confounding variables (Streefkerk, 2021).

3.8 External validity

It refers to how well the results of a given study generalise. It is used to generalise from research sample to the larger population. It is also used in the form of such things as statistical confident limits to make reasonably accurate statements (Bauman *et al.,* 2014).

3.9 Reliability

It refers to the consistency of a measure. It is important for quantitative research because it is basis for validity. It measures whether or not a study obtains same results each time (Chiang *et al.,* 2015).

3.10 Objectivity

It is described as freedom from bias. This refers to reliable knowledge, checked and controlled, undistorted by personal bias and prejudice. It is used through methodology of measurement, data collection, and data analysis through which reliability and validity are established (Green, 2004).

3.11 Summary

This chapter explains quantitative research approach and why it is selected. It also explains research design, research methodology and gives overview of the research structure. This research is conducted following LCA phases which are goal and scope definition, LCI, LCIA and interpretation phase. It also follows pavement LCA stages which are material production, pavement design, use stage, maintenance and end-of-life stage. It shows all inputs incorporated in order to reach the desired outputs. The inputs include geometry of all layer works, haulage and composition of layer works. Deconstruction activities are included as inputs.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Analysing consumption of materials, energy and water

Sustainable way of constructing roads can be defined as the optimal use of natural and man-made resources during road construction causing negligible damage to the environment. The use of roadway materials efficiently to reduce waste and minimizing the amount of energy consumed during construction are two means of improving the sustainability of roadways. For asphalt pavements the majority of energy is consumed during asphalt mixing, drying of aggregates, and the production of bitumen. With regard to material waste, the extraction and production of aggregates produce the majority of waste.

4.1.1 Materials consumption

Aggregates are the bulk material used for different construction tasks. They are essential to the development of a modern economy. Aggregates are extracted from the ground via quarrying. As a result, in South Africa the majority of aggregate materials for construction applications are obtained from primary such as crushed rock, sand and gravel. Material extraction result in adverse environmental impacts. This is because quarrying causes many adverse environmental impacts such as noise, dust, visual intrusion, loss of amenity, damage to biodiversity and the generation of derelict land. The use of alternative materials in pavement construction reduces the consumption of scarce natural aggregates. Table 4.1 shows materials consumed per layer, mainly in tons, except for water, concrete and excavated volumes (expressed in m³).

Table 4.1: Material results

Name	Opera-tion	Bitumen	Stabil-isation plant	Hot-mix asphalt plant using gas	Construct-ion machine	Decons-truction machine	Aggre-gate	Road transport
Asphalt	2017	435,5568	0	8711,136	122955,84	232968,96	8275,5792	13174,704
G1	2017	0	0	0	481756,8	232968,96	27222,3	20578,725
G5 Stabilised	2017	0	65366	0	409277,568	232968,96	65366	98211

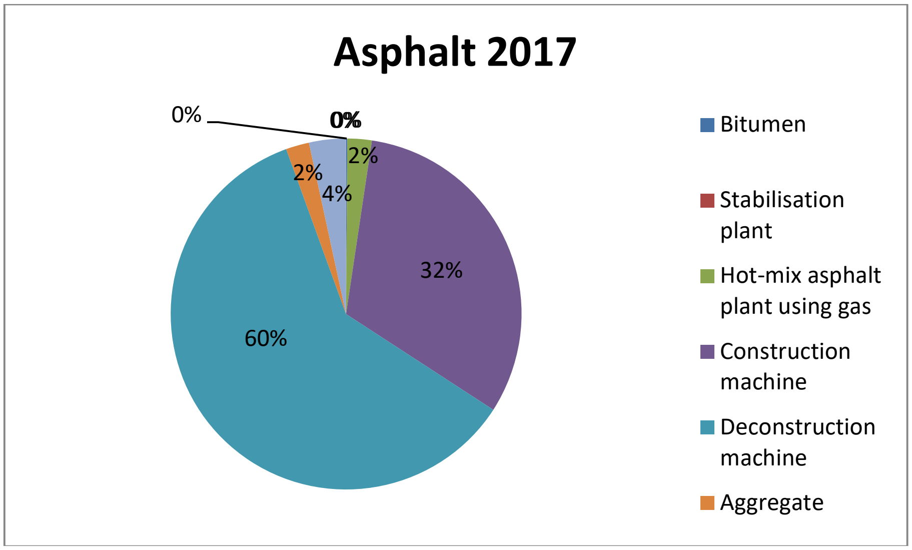

Figure 4.1. Pie chart showing material consumptions

Figure 4.1 is a graphical representation of Table 4.1. It shows that most of the material consumption occurs during use of deconstruction machine with 60%. This is the stage whereby the existing pavement layers are demolished. It is ideal to recycle this material and reuse it. Recycling is beneficial towards the environment since it eliminates waste to be transported to the landfill site and create air pollution. It is followed by construction machines used to process layer works with 32%. During construction of new pavement layers through the use of construction machines one third of materials is consumed. Then follows aggregate with 2%, hot mix asphalt plant using gas is 2% and road transport is 4%. Most of the consumption occurs during use of machines and it adds up to 92%. This shows majority of consumption occur during demolition of pavement layers and construction of new pavement layers of material.

The use of reclaimed and marginal materials can help to achieve environmental benefits and conserve primary aggregates. Recycled and secondary materials can be more variable than primary aggregates. However, it is crucial to perform frequent testing in order to enable confidence in their reuse in pavement construction. It is ideal to develop methods in pavement construction that will lead to cost savings, improvements in performance and risk mitigation. Use of recycling techniques in road rehabilitation projects especially in-place recycling. The use of cold asphalt mixes instead of hot asphalt mixes. Replacement of non-renewable natural aggregates by recycled aggregates and in particular secondary aggregates obtained from industrial wastes and by products. The structural capacity of South African roads is carried by the layer works under the surface, unlike in developed countries. In developed countries the structural capacity of the road is carried by the surface. It is important for government to identify areas where borrow pits can be established prior to construction. This will reduce the costs of sourcing material commercially. The money that is saved can be used to build new roads and increase South African road network of surfaced roads. The government should ensure that only SANAS accredited civil engineering laboratories are used for soil testing. Laboratories which are not SANAS accredited must work under the umbrella of laboratories that are SANAS accredited. This will help to ensure that results for material classification, compaction tests and mix design are in accordance with the specification. Therefore, the amount of waste will be reduced since the quantity of improper material will be minimised as the material will be correctly classified since results will be obtained from accredited laboratory. Government should invest in research of alternative methods of recycling, for example in Japan they do on site recycling which involves crushing the existing asphalt and mixing it with a granular base material and a stabilising agent (e.g. cement) and then compact this to form a base course.

4.1.2 Energy consumption

Energy consumption does not only refer to burning gasoline in our cars. Due to environmental health and high fuel prices, automobile manufacturers are seeking ways to make driving more energy efficient. Roadway construction makes up a small part of the energy consumption through its life span. The majority of energy consumption results from traffic on the roadway. A study of a roadway projects across Europe estimated that roadway traffic is 18 times more energy intensive than construction. Energy consumption is important, apart from energy and fuel used during pavement construction, energy is required to produce and refine materials, transport materials and equipment, and to dispose of the roadway.

According to pavement interactive it is important to look into embodied energy when considering the total energy consumption of a construction process. For a given product, the embodied energy represents the total sum of energy inputs for each process in the production chain. This process includes extraction of raw materials, processing materials, transportation, disposal and any other treatments that require energy. Energy that is required to extract, produce and refine paving materials is a huge contributor to the energy required for pavement construction. The "Reference vector" table lists the energy consumption value, expressed in MJ, for each type of production process from Table 4.2 to Table 4.4.

Table 4.2: Layer energy

Type of layer	Bitumen (MJ/t)	Stabilisation plant (MJ/t)	Hot-mix asphalt plant using gas (MJ/t)	Construction machine (MJ/MJ)	Deconstruction machine (MJ/MJ)	Aggregate (MJ/t)	Road transport (MJ/km)	Total
Wearing course	1261497,074	0	2442476,805	131663,349	249467,3982	401376,682	192736,1835	4679217,5
Road base layer	0	0	0	515873,9407	249467,3982	1320318,033	301051,5391	2386710,9
Road base layer_2	0	2524217,033	0	438261,8612	249467,3982	3170338,602	1436754,352	7819039,2

Table 4.3: Operations energy

Operation name or year:	Bitumen (MJ/t)	Stabilisation plant (MJ/t)	Hot-mix asphalt plant using gas (MJ/t)	Construction machine (MJ/MJ)	Deconstruction machine (MJ/MJ)	Aggregate (MJ/t)	Road transport (MJ/km)	Total
2017	1261497,074	2524217,033	2442476,805	1085799,151	748402,1945	4892033,317	1930542,075	14884967,65

Table 4.4: Total energy

Bitumen (MJ/t)	Stabilisation plant (MJ/t)	Hot-mix asphalt plant using gas (MJ/t)	Construction machine (MJ/MJ)	Deconstruction machine (MJ/MJ)	Aggregate (MJ/t)	Road transport (MJ/km)	Total
1261497	2524217,033	2442476,805	1085799,151	748402,1945	4892033,317	1930542,075	14884968

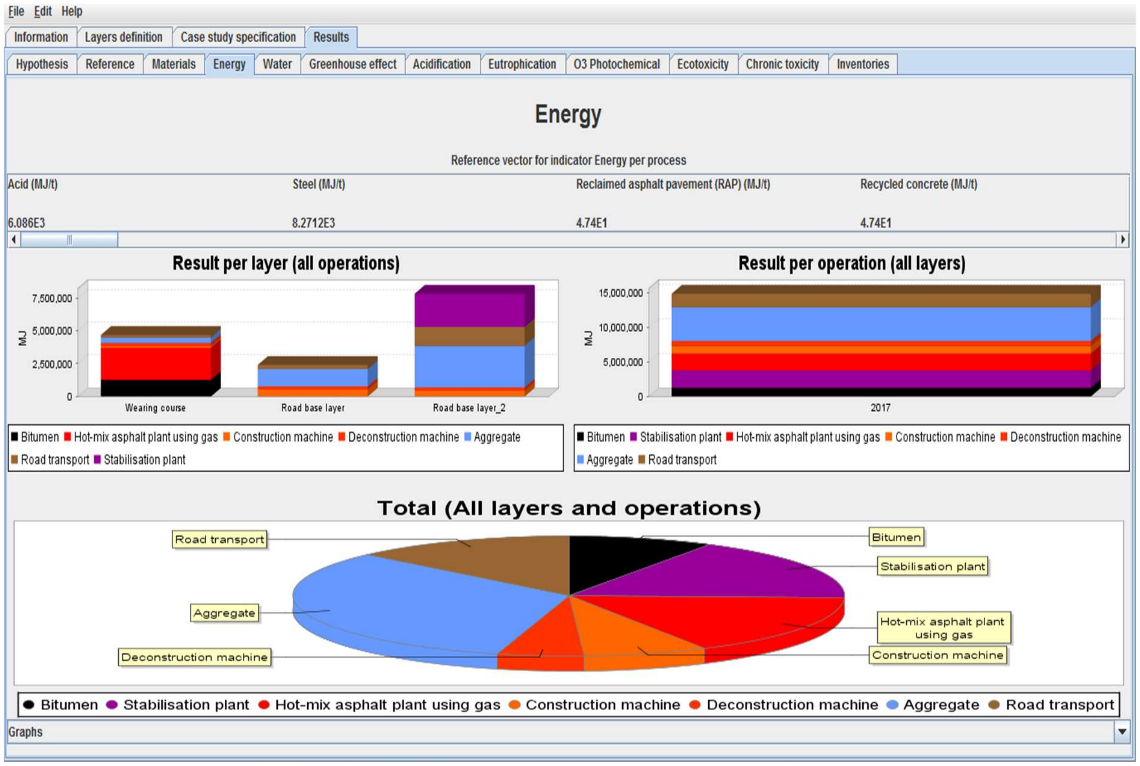

Figure 4.2. Reference vector for indicator energy per process

The results for all layers and operations are as follows:

In Figure 4.2 the bar graph which illustrates results per layer is a graphical representation of Table 4.2, the bar graph which illustrates results per operation is a graphical representation of Table 4.3 and the pie chart which illustrates total for all layers and all operations is a graphical representation of Table 4.4. The pie chart shows that most of the energy is consumed by machinery used and it amounts to 59%. The 59% is divided into: stabilisation plant 17%, hot mix asphalt plant using gas 16%, road transport 13%, construction machines 7%, and deconstruction machine 6%. The materials used consume less energy as compared to machinery used and it amounts to 41%. The 41% is divided into aggregates at 33% and followed by bitumen with 8%. Energy is consumed during processing of aggregates which refers to construction of pavement layers and mixing of the surface layer material.

In Africa, South Africa produces the highest CO_2 emissions and has one of the highest CO_2 emissions per GDP in the world (CSIR 2010). Government gazette issued on the 23rd December 2016 shows improvement in energy intensity in the transportation sector. It was 14% in 2012 and dropped to 9% in 2015. It further indicates that the energy consumption is dominated by the following sectors; mining 35%, transport 29% and residential 25%. The Department of Transport has developed a fuel reduction strategy and a GHG emissions reduction strategy to help reduce consumption of energy. For asphalt pavements the majority of energy is consumed during asphalt mixing, processing of aggregates, and the production of bitumen. The transportation engineering specialist in collaboration with the government should determine methods that can be implemented and safe energy during asphalt mixing, processing of aggregates and production of bitumen. Reduction in energy will help to reduce amount of emissions emitted to the atmosphere.

4.1.3 Water consumption

Water consumption during the construction process is associated primarily with the compaction of pavement layer works to meet minimum quality requirements. The requirement is estimated to be 50 litres per cube (Chakane, 2014). Dust suppression and cleaning are some of main activities of water in pavement construction. The 'Reference vector' Table provides the water consumption value in m^3, for each type of production process from Table 4.5 to Table 4.7.

Table 4.5: Layers Water

Type of layer	Bitumen (m3/t)	Stabilisation plant (m3/t)	Hot-mix asphalt plant using gas (m3/t)	Construction machine (m3/MJ)	Deconstruction machine (m3/MJ)	Aggregate (m3/t)	Road transport (m3/km)	Total
Wearing course	62,2846224	0	51,62575216	12,09158908	22,91037932	62,97147577	17,70034523	229,584164
Road base layer	0	0	0	47,37640167	22,91037932	207,1430124	27,64772073	305,0775141
Road base layer_2	0	2723,583333	0	40,24872811	22,91037932	497,3903803	131,9474506	3416,080272

Table 4.6: Operations Water

Operation name or year:	Bitumen (m3/t)	Stabilisation plant (m3/t)	Hot-mix asphalt plant using gas (m3/t)	Construction machine (m3/MJ)	Deconstruction machine (m3/MJ)	Aggregate (m3/t)	Road transport (m3/km)	Total
2017	62,2846224	2723,583333	51,62575216	99,71671886	68,73113795	767,5048685	177,2955166	3950,74

Table 4.7: Total Water

Bitumen (m3/t)	Stabilisation plant (m3/t)	Hot-mix asphalt plant using gas (m3/t)	Construction machine (m3/MJ)	Deconstruction machine (m3/MJ)	Aggregate (m3/t)	Road transport (m3/km)	Total
62,2846224	2723,583333	51,62575216	99,71671886	68,73113795	767,5048685	177,2955166	3950,742

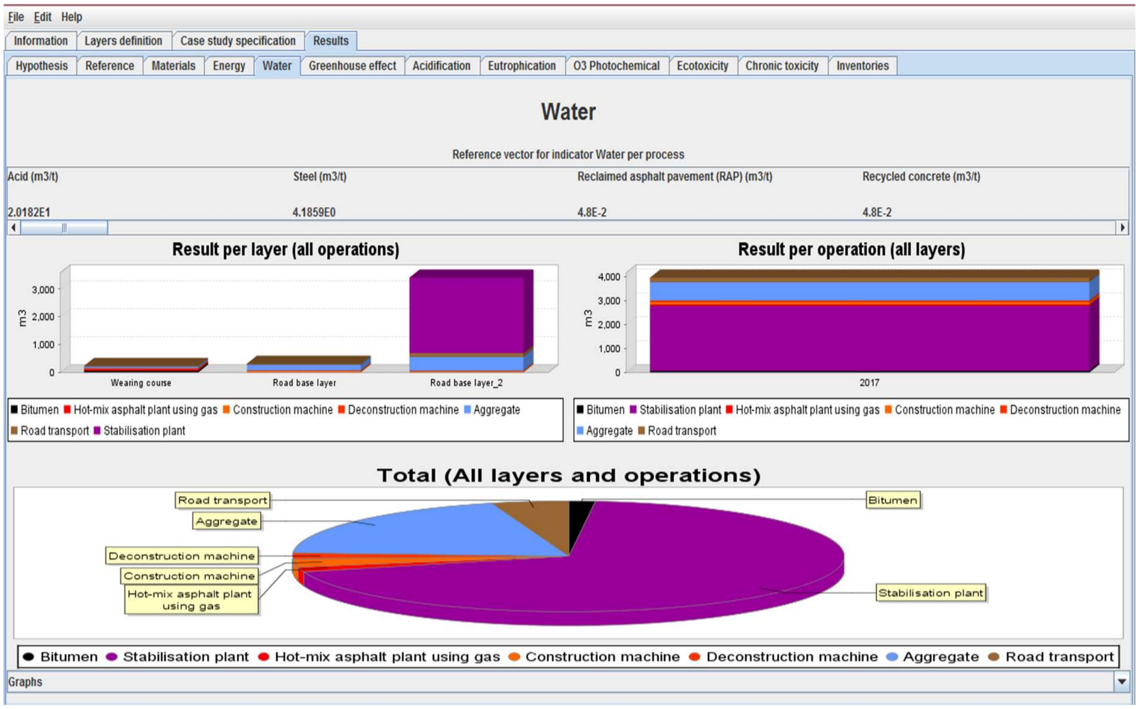

Figure 4. 3. Reference vector for indicator water per process

The results for all layers and operations are as follows:

In Figure 4.3 the bar graph which illustrates results per layer is a graphical representation of Table 4.5, the bar graph which illustrates results per operation is a graphical representation of Table 4.6 and the pie chart which illustrate the total for all layers and all operations is a graphical representation of Table 4.7. The pie chart shows that most of the water consumption results from machinery used and it amounts to 79%. The 79% is divided into stabilising plant 69%, road transport 4%, construction machines 3% and deconstruction machines with 3%. The amount of water consumed by materials used is less as compared to machinery used and it amounts to 21%. The 21% is divided into aggregates 19% and bitumen with 2%. The high consumption resulting from stabilising plant is due to the sub-base layer, it is stabilised in order to increase soil compressibility, strength, durability, stiffness and reduction in soil plasticity and swelling. Without water the reaction of soil, water and cement will not occur. Water is a strong polar molecule and it has strong affinity to soil materials. Too much water on the mixture makes it weak and less water makes it dryer and strong. Hence it is important for soil to be at its optimum moisture content during compaction. The stage where a maximum dry unit weight can be achieved after compaction, a maximum dry unit weight with no voids in the soil. It is ideal to encourage a greater level of water efficiency across a project life cycle. This will require measurement, monitoring and reporting water use to be the norm. Pavement construction agencies should be encouraged to use water more efficiently and innovatively. Monitoring water consumption needs to improve in order for the construction sector to achieve reduction in their water consumption.

4.2 Analysing Environmental Indicators

The environmental impact indicators can be divided into direct, indirect and operational emissions. The direct emissions are defined as the emissions that are directly related to on-site construction processes. Indirect emissions are emissions that are produced in off-site construction processes. Operational emissions refer to emissions that are produced during daily operation of the facility after being constructed till the end of its remaining life cycle (Alam, 2016).

4.2.1 Greenhouse effect indicator

Many greenhouse gases are naturally present in the atmosphere and they contribute to the natural gas effect. The main contributors to greenhouse effect are CO_2, CH_4, N_2O, water vapour and O_3. The presence of water vapour is a function of atmospheric temperature. CO_2, CH_4 and N_2O contribute to increase the greenhouse effect beyond its natural state. Greenhouse effect is a natural process that warms the earth's surface. When the sun's energy reaches the earth's atmosphere, some of it is reflected back to space and the rest is absorbed and re-radiated by greenhouse gases. During pavement construction, greenhouse gases are released into the environment. These emissions affect weather, including temperature and rainfall.

The indicator selected for this category is the Global Warming Potential (GWP), as defined by the GIEC organisation in 2007. The GWP of a substance is determined by taking the integral, over a given time period of the radiative forcing (increase or decrease in the level of energy exchange by radiation) generated by 1 kg of this gas instantaneously injected into the atmosphere. GWP is expressed in terms of CO_2. The resulting coefficient is then multiplied by the flow of target substances, yielding a final value expressed in kg equivalent to CO_2. The GPWi values assume an integral calculation performed over a 100-year period, which corresponds to the life cycle of a CO_2 molecule in the atmosphere. Table 4.8 to Table 4.10 show the GPWi values for each type of production process.

Table 4.8: Layers Greenhouse Effect

Type of layer	Bitumen (kg eq.CO2/t)	Stabilisation plant (kg eq.CO2/t)	Hot-mix asphalt plant using gas (kg eq.CO2/t)	Construction machine (kg eq.CO2/MJ)	Deconstruction machine (kg eq.CO2/MJ)	Aggregate (kg eq.CO2/t)	Road transport (kg eq.CO2/km)	Total
Wearing course	83355,84625	0	131138,5612	10407,36592	19719,21964	18139,40326	15436,68918	278197,0854
Road base layer	0	0	0	40777,39864	19719,21964	59669,08969	24111,91792	144277,6259
Road base layer_2	0	107458,4443	0	34642,53031	19719,21964	143277,0088	115072,9975	420170,2006

Table 4.9: Operations Greenhouse Effect

Operation name or year:	Bitumen (kg eq.CO2/t)	Stabilisation plant (kg eq.CO2/t)	Hot-mix asphalt plant using gas (kg eq.CO2/t)	Construction machine (kg eq.CO2/MJ)	Deconstruction machine (kg eq.CO2/MJ)	Aggregate (kg eq.CO2/t)	Road transport (kg eq.CO2/km)	Total
2017	83355,84625	107458,4443	131138,5612	85827,29488	59157,65893	221085,5017	154621,6046	842644,9

Table 4.10: Total Greenhouse Effect

Bitumen (kg eq.CO2/t)	Stabilisation plant (kg eq.CO2/t)	Hot-mix asphalt plant using gas (kg eq.CO2/t)	Construction machine (kg eq.CO2/MJ)	Deconstruction machine (kg eq.CO2/MJ)	Aggregate (kg eq.CO2/t)	Road transport (kg eq.CO2/km)	Total
83355,84625	107458,4443	131138,5612	85827,29488	59157,65893	221085,5017	154621,6046	842644,9

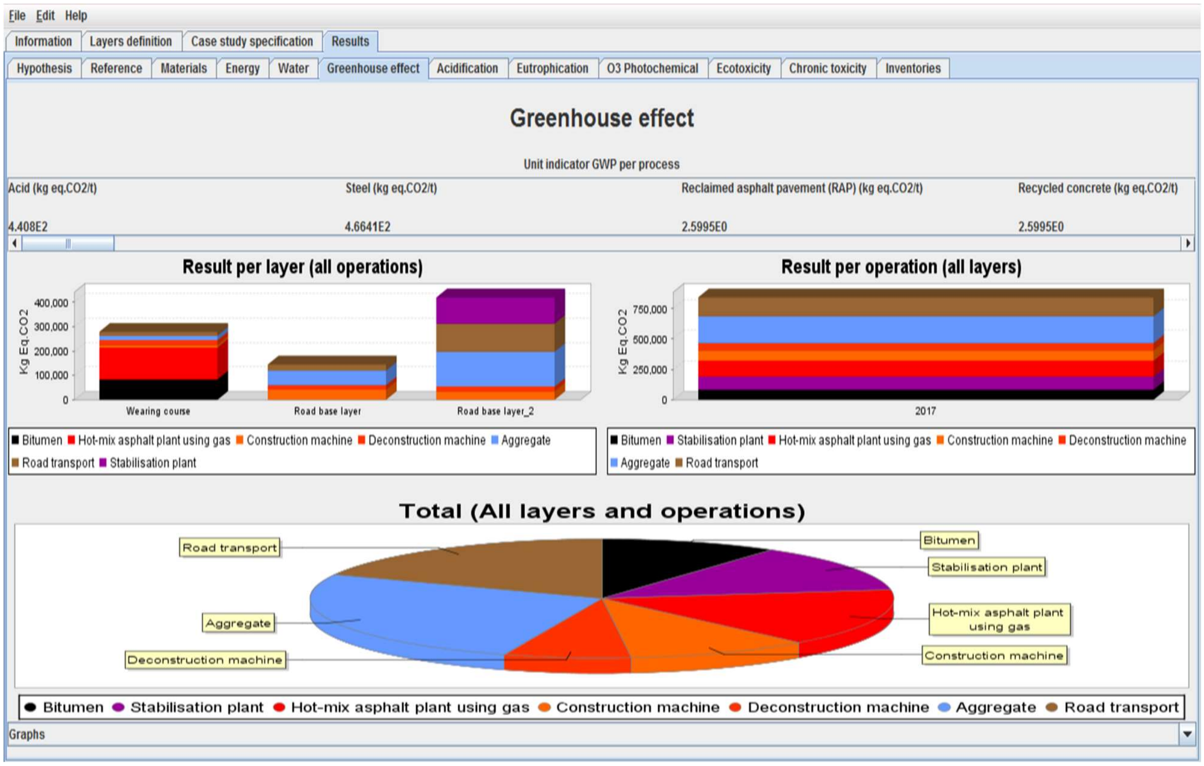

Figure 4.4. Unit indicator GWP per process

The percentages for all layers and operations are as follows:

In Figure 4.4 the bar graph which illustrates results per layer is a graphical representation of Table 4.8, the bar graph which illustrates results per operation is a graphical representation of Table 4.9 and the pie chart which illustrates the total for all layers and all operations is a graphical representation of Table 4.10. The unit indicator global warming potential per process indicates that machinery used have more environmental impact contribution which amount to 64%. The 64% is divided into road transport 18%, hot mix asphalt plant using gas 16%, stabilisation plant 13%, construction machines 10% and deconstruction machine 7%. Transportation of materials and processing them lead to the production of more greenhouse gases to the atmosphere. Materials used have less environmental impact contribution which amount to 36%. The 36% percent is divided into aggregates 26% and bitumen 10%. The greenhouse pollutants are CO_2, CH_4, N_2O and HFCs. The values in Table 4.8 to Table 4.10 are expressed in kg equivalent to CO_2. Pavement construction generates carbon emissions from direct and indirect sources. Activities that create carbon emissions are land preparation, embodied carbon in asphalt and raw materials used, and emissions from construction vehicles. CH_4 is produced during combustion process. N_2O is a by product of fuel consumption in mobile sources. When any fossil fuel is burnt, part of the nitrogen that is in the fuel and surrounding air gets oxidized creating nitrous oxide emissions. Mobile emissions are caused by machinery used on site.

These impacts can be reduced by identifying nearby borrow pits which will reduce the hauling distance. The less the machinery travels, the fewer pollutants will be emitted into the atmosphere. The application of recycled materials is not only economical; it also reduces pollutants emitted since it requires less time to process as compared to virgin materials. Furthermore, studies show reusing reclaimed asphalt can reduce CO_2 emissions more than warm mix asphalt, increasing the amount of construction equipment operating with natural gas, rather than diesel. By applying this strategy, the amount of environmental impacts will be lessened. CO_2 can also be reduced by limiting the use of carbon-intensive equipment during pavement maintenance, incorporating emissions standards into contracts with suppliers and planting trees for capturing carbon near major projects. The other on site method involves heating the existing asphalt mixture, scarifying it to loosen the materials and then adding new asphalt or rejuvenators, if necessary. The reuse of material from deteriorating flexible road pavements through cement stabilisation should be considered. The advantage of this process is that it requires very little material to be removed from site, reducing the greenhouse gas emissions associated with the transport of unwanted materials. The use of recycled asphalt pavement (RAP) can help to reduce global warming potential, energy consumption, waste generation and the life cycle costs.

4.2.2 Layers Acidification

Acidification can be defined as an impact which leads to a fall in the system's acid neutralising capacity that is a reduction in the quantity of substances in the system which have capacity to neutralise hydrogen ions added to the system. Acidification occurs naturally over time. However, it is greatly increased by man-made input. The main source of it is air-borne emissions of gases that release hydrogen when they are degraded in the atmosphere. One of the methods to describe the sensitivity of an ecosystem towards acidification is by its critical load. In regions like the Mediterranean, critical loads are found to be high in calcareous and low in granite rock regions. The most contributor to acidification are man-made emissions which are SO_2 and NO (Dincer and Bicer, 2018).

What goes up (emissions of acid-precursor gases) must come down (as acidifying deposition). Acidification potential is a consequence of acids being emitted to the atmosphere and subsequently deposited in surface soils and waters. Acidification potential classification factors are mainly based on the contributions SO_2, NO, HCl, NH_3 and HF and expressed as SO_2 equivalent (Biopolymers and Biotech Admixtures for Eco-Efficient Construction Materials, 2016). Table 4.11 to Table 4.13 show acidification potential values expressed as SO_2 equivalents for each type of production process.

Table 4. 11: Layers Acidification

Type of layer	Bitumen (kg eq.SO2/t)	Stabilisation plant (kg eq.SO2/t)	Hot-mix asphalt plant using gas (kg eq.SO2/t)	Construction machine (kg eq.SO2/MJ)	Deconstructio n machine (kg eq.SO2/MJ)	Aggregate (kg eq.SO2/t)	Road transport (kg eq.SO2/km)	Total
Wearing course	191,9244452	0	54,01252462	6,867730896	13,01254275	82,0626161	30,80185367	378,6817133
Road base layer	0	0	0	26,90865322	13,01254275	269,9428161	48,11211516	357,9761272
Road base layer_2	0	179,1337073	0	22,86030659	13,01254275	648,1848381	229,6128133	1092,804208

Table 4. 12: Operations Acidification

Operation name or year:	Bitumen (kg eq.SO2/t)	Stabilisation plant (kg eq.SO2/t)	Hot-mix asphalt plant using gas (kg eq.SO2/t)	Constructio n machine (kg eq.SO2/MJ)	Deconstruction machine (kg eq.SO2/MJ)	Aggregate (kg eq.SO2/t)	Road transport (kg eq.SO2/km)	Total
2017	191,9244452	179,1337073	54,01252462	56,6366907	39,03762825	1000,19027	308,5267822	1829,462049

Table 4. 13: Total Acidification

Bitumen (kg eq.SO2/t)	Stabilisation plant (kg eq.SO2/t)	Hot-mix asphalt plant using gas (kg eq.SO2/t)	Construction machine (kg eq.SO2/MJ)	Deconstruction machine (kg eq.SO2/MJ)	Aggregate (kg eq.SO2/t)	Road transport (kg eq.SO2/km)	Total
191,924445	179,1337073	54,01252462	56,6366907	39,03762825	1000,19027	308,5267822	1829,462049

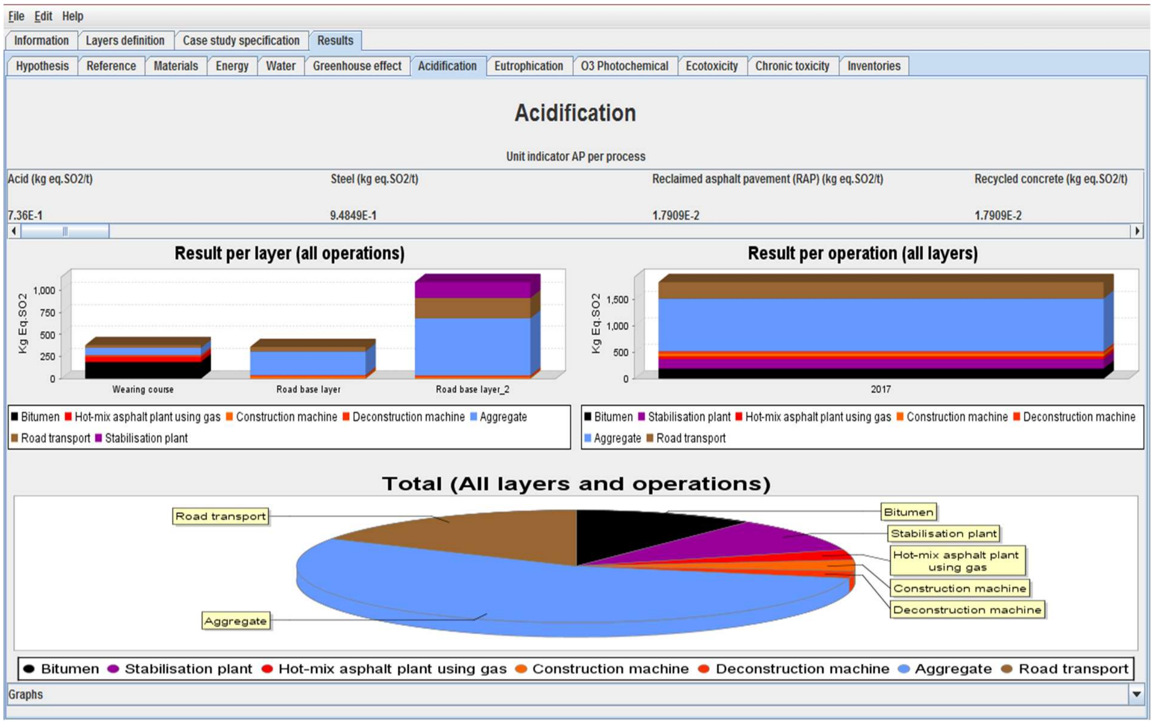

Figure 4. 5. Unit indicator AP per process

In Figure 4.5 the bar graph which illustrates results per layer is a graphical representation of Table 4.11, the bar graph which illustrates results per operation is a graphical representation of Table 4.12 and the pie chart which illustrates the total for all layers and all operations is a graphical representation of Table 4.13. The unit indicator AP per process shows that materials used have more environmental impact contribution, which amounts to 65%. The 65% is divided into aggregates 55% and bitumen 10%. The materials used emit more pollutants to the atmosphere. Machinery used has less environmental impact contribution as compared to material used and it amounts to 35%. The 35% is divided into road transport 17%, stabilisation plant 10%, construction machines with 3%, hot mix asphalt plant using gas 3% and deconstruction with 2%. The values in Table 4.11 to Table 4.13 are expressed as SO_2 equivalent. The main gases emitted are SO_2 and NO, HCl, NH_3 and HF.

The impact of acidification potential can cause respiratory diseases; it can also make the diseases worse if it already exists. It has negative impact on the ecology resulting from acid rain in aquatic environments. Acidification potential emissions have negative impact on the health of civilians. The damage caused by acidifying deposition from the atmosphere can be solved by reducing the emissions of acid forming gases. However, the issue of emissions reduction is a challenge. For instance, it is ideal to coordinate emissions reduction. However, it is going to be a problem if government of another country with large emissions do not regard acidifying deposition to be a problem when a neighbouring country does. Bitumen is one of the major components of urban smog, it is ideal to look for other products that are able to perform the role of the aggregate binder (bitumen) in the asphalt layer of pavement. This product must be more prevalent and economical. Some of this product is liquid rosin, is a viscous yellow–black odorous liquid obtained as a by-product of wood pulp manufacture. It is a mixture of fatty acids and resins. It can be employed as a bitumen substitute often in combination with other bio-materials.

4.2.3 Eutrophication indicator

Eutrophication means poor conditions, low in O_2 and limited ability to support life. Nutrients are a fundamental precondition for the existence of life and they occur naturally in the environment. When a changed availability of nutrients affects the ecosystems, the ecosystem adopts to a new balance with its surroundings. Eutrophication is the process by which water bodies grow more productive. This indicator corresponds to the sum of all eutrophication precursors, through multiplying the measured mass by its equivalent factor, with these precursors being expressed in the form of phosphate equivalents. Table 4.14 to Table 4.16 show the eutrophication precursors values expressed in the form of phosphate equivalents for each type of production process.

Table 4. 14: Layers Eutrophication

Type of layer	Bitumen (kg eq.PO4/t)	Stabilisation plant (kg eq.PO4/t)	Hot-mix asphalt plant using gas (kg eq.PO4/t)	Construction machine (kg eq.PO4/MJ)	Deconstruction machine (kg eq.PO4/MJ)	Aggregate (kg eq.PO4/t)	Road transport (kg eq.PO4/km)	Total
Wearing course	25,27442696	0	4,811489206	2,010230422	3,808857642	23,07036533	8,337293857	67,31266341
Road base layer	0	0	0	7,87634142	3,808857642	75,88935964	13,02275008	100,5973088
Road base layer_2	0	41,78262446	0	6,691363487	3,808857642	182,2250097	62,15046403	296,6583193

Table 4. 15: Operations Eutrophication

Operation name or year:	Bitumen (kg eq.PO4/t)	Stabilisation plant (kg eq.PO4/t)	Hot-mix asphalt plant using gas (kg eq.PO4/t)	Construction machine (kg eq.PO4/MJ)	Deconstruction machine (kg eq.PO4/MJ)	Aggregate (kg eq.PO4/t)	Road transport (kg eq.PO4/km)	Total
2017	25,27442696	41,78262446	4,811489206	16,57793533	11,42657293	281,1847347	83,51050796	464,5682915

Table 4. 16: Total Eutrophication

Bitumen (kg eq.PO4/t)	Stabilisation plant (kg eq.PO4/t)	Hot-mix asphalt plant using gas (kg eq.PO4/t)	Construction machine (kg eq.PO4/MJ)	Deconstruction machine (kg eq.PO4/MJ)	Aggregate (kg eq.PO4/t)	Road transport (kg eq.PO4/km)	Total
25,27442696	41,78262446	4,811489206	16,57793533	11,42657293	281,1847347	83,51050796	464,5682915

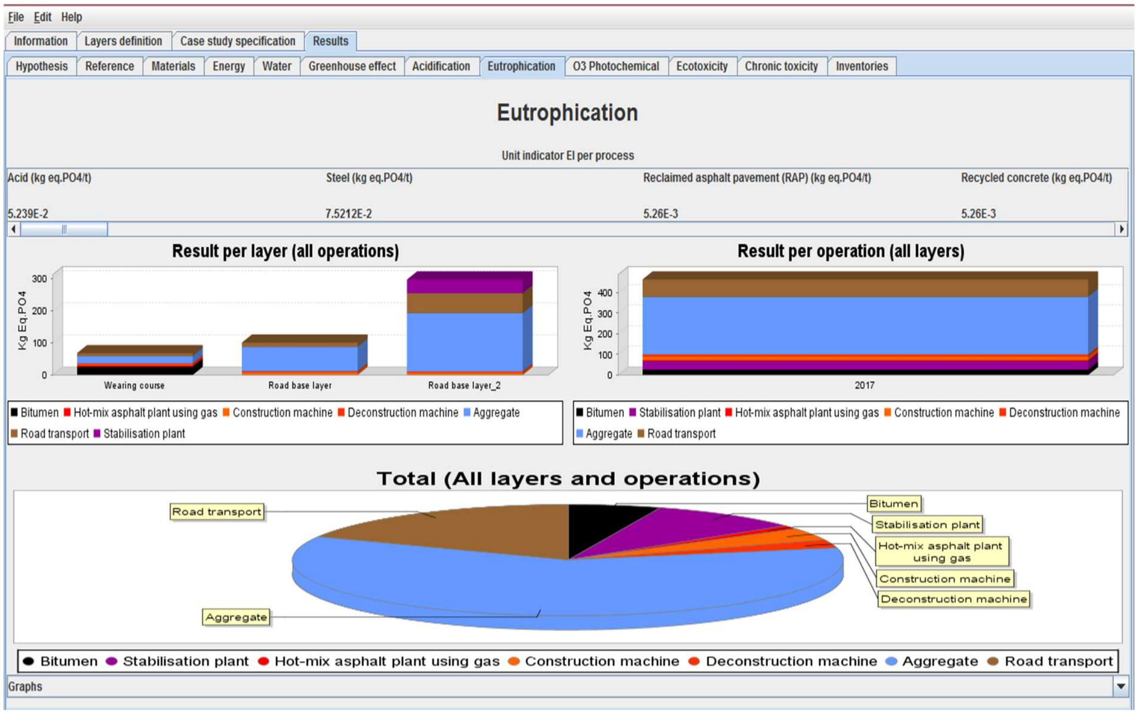

Figure 4. 6. Unit indicator EI per process

In Figure 4.6 the bar graph which illustrates results per layer is a graphical representation of Table 4.14, the bar graph which illustrates results per operation is a graphical representation of Table 4.15, and the pie chart which illustrates the total for all layers and all operations is a graphical representation of Table 4.16. The unit indicator eutrophication indicator per process shows that materials used have more environmental impact contribution and it amounts to 66%. This 66% is divided into aggregate 61% and bitumen 5%. The machinery used have less environmental impact contribution and it amounts to 34%. The 34% is divided into road transport 18%, stabilising plant 9%, construction machines 4%, deconstruction 2% and hot mix asphalt plant using gas 1%. Atmospheric deposition of nitrogen results from combustion gases. Atmospheric deposition refers to the process whereby particles and gases move from the atmosphere to the earth’s surface. Contaminants emitted from used materials are washed from roads and roadsides when it is raining. A large amount of this run-off pollution is carried directly to water bodies. Contaminants in run-off pollution from roads include sediment, oil and grease and heavy metals. Sediment occurs when soil particles are eroded from the land and transported to surface water. Oil and grease are leaked onto the road surfaces from transporting machinery engines and when it is raining these pollutants move to the surface waters. Heavy metals are toxic and have potential to contaminate ground water.

The following measures can help to minimise eutrophication: clean water act, national pollution discharge elimination system, coastal zone management act and reauthorization and intermodal surface transportation efficiency act. There are other products that can be used to replace bitumen, they are vegecol from Colas and Ecopave. Vegocol is a clear bitumen replacement. Ecopave refers to the use recycled plastic combined with graphene. It significantly improves the durability and sustainability of asphalt pavement surfaces. It helps asphalt to have good elasticity and strength. It also has the potential to increase pavement life span. It will be ideal for asphalt manufactures in South Africa to follow in the footsteps of Shisalanga Construction (Pty) Ltd and use recycled plastic in order to enhance binder properties and build safe and eco-sustainable pavements.

4.2.4 Indicator of the formation of tropospheric ozone

Ozone is a trace gas of the troposphere. It is also an important constituent of the stratosphere, where the ozone layer exists. According to United States Environmental Protect Energy, ozone is a gas composed of the three atoms of oxygen (O_3). It occurs in the earth's upper atmosphere and ground level. In the upper atmosphere it forms a protective layer that shields us from the sun's harmful ultraviolet rays. O_3 is partially destroyed by man-made chemicals, causing hole in the O_3. The O_3 at ground level is a harmful air pollutant. It is harmful to human and ecosystem health. It is also a major component of urban smog. The O_3 affects sensitive vegetation and ecosystems, including forests, parks, wildlife refuges and wilderness areas.

The O_3 is a reactive gas that exists in two layers of the atmosphere: the stratosphere (upper layer) and the troposphere (at ground level and up to 15km). Tropospheric O_3 is a short-lived climate pollutant with an atmospheric lifetime of hours to weeks. It does not have any direct emissions sources, rather it is a secondary gas formed by the interaction of sunlight with hydrocarbons – including CH_4 and NO, which are emitted by vehicles, fossil fuel power plants, and other man-made sources.

The indicator Photochemical O_3 Creation Potential (POCP) is the most widely used value in Europe for describing this phenomenon; it corresponds to the maximum quantity of O_3 formed for each volatile organic compound taken individually, spanning the five days following its release, compared to the level of O_3 produced for the same quantity of ethylene released.

Table 4. 17: Layers Tropospheric Ozone

Type of layer	Bitumen (kg eq.éthylène/t)	Stabilisation plant (kg eq.éthylène/t)	Hot-mix asphalt plant using gas (kg eq.éthylène/t)	Construction machine (kg eq.éthylène/MJ)	Deconstruction machine (kg eq.éthylène/MJ)	Aggregate (kg eq.éthylène/t)	Road transport (kg eq.éthylène/km)	Total
Wearing course	79,66969611	0	135,7339122	10,78920335	20,44270109	37,86972541	23,49126772	307,9965059
Road base layer	0	0	0	42,27348681	20,44270109	124,5714652	36,69307017	223,9807232
Road base layer_2	0	38,41397921	0	35,91353536	20,44270109	299,1201476	175,1159566	569,0063198

Table 4. 18: Operations Tropospheric Ozone

Operation name or year:	Bitumen (kg eq.éthylène/t)	Stabilisation plant (kg eq.éthylène/t)	Hot-mix asphalt plant using gas (kg eq.éthylène/t)	Construction machine (kg eq.éthylène/MJ)	Deconstruction machine (kg eq.éthylène/MJ)	Aggregate (kg eq.éthylène/t)	Road transport (kg eq.éthylène/km)	Total
2017	79,66969611	38,41397921	135,7339122	88,97622553	61,32810326	461,5613381	235,3002945	1100,983549

Table 4. 19: Total Tropospheric Ozone

Bitumen (kg eq.éthylène/t)	Stabilisation plant (kg eq.éthylène/t)	Hot-mix asphalt plant using gas (kg eq.éthylène/t)	Construction machine (kg eq.éthylène/MJ)	Deconstruction machine (kg eq.éthylène/MJ)	Aggregate (kg eq.éthylène/t)	Road transport (kg eq.éthylène/km)	Total
79,66969611	38,41397921	135,7339122	88,97622553	61,32810326	461,5613381	235,3002945	1100,983549

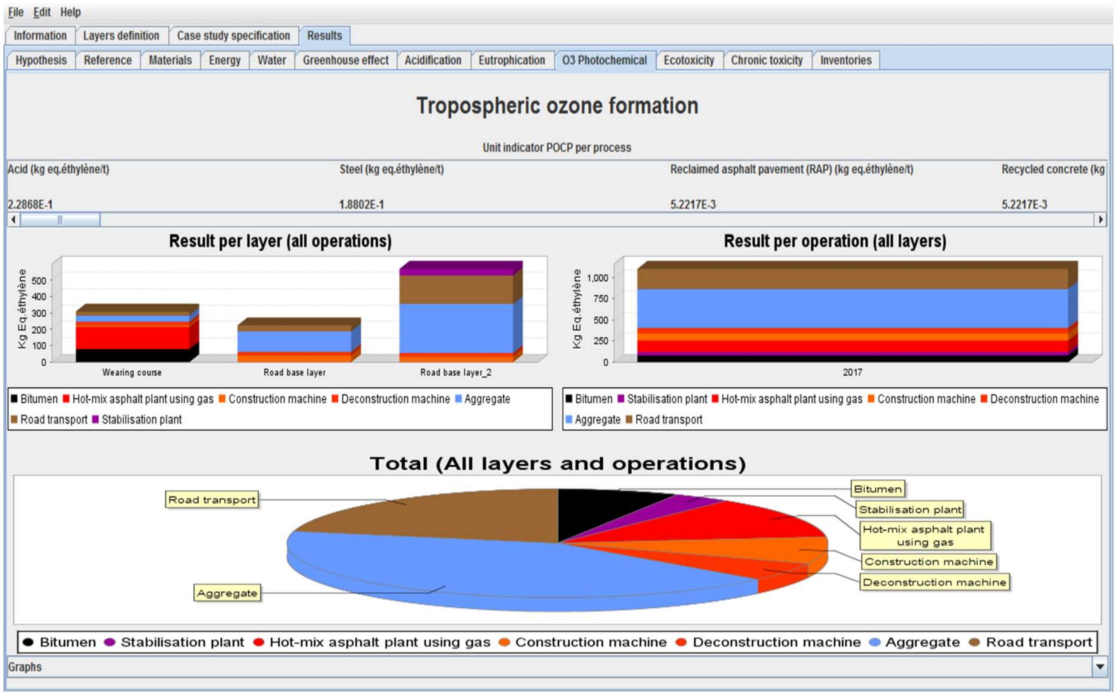

Figure 4. 7. Unit indicator POCP per process

In Figure 4.7 the bar graph which illustrates results per layer is a graphical representation of Table 4.17, the bar graph which illustrates results per operation is a graphical representation of Table 4.18, and the pie chart which illustrates the total for all layers and all operations is a graphical representation of Table 4.19. The unit indicator POCP per process shows that environmental impact contribution of both materials used and machinery used is balanced and it amounts to 50% respectively. The 50% of materials used is divided into aggregates 43% and 7% bitumen. The 50% of machinery used is divided into road transport with 21%, hot mix asphalt plant using gas produce 12%, construction machines 8%, deconstruction machine 6% and stabilisation 3%. Construction is one pollution source that needs to be examined; it has impact on the formation of ground level O_3. Road traffic have a substantial impact on the concentration of tropospheric O_3 and nitrogen are emitted from combustion processes in transport. Tropospheric O_3 is not directly emitted to the air, it is created by chemical reactions between oxides of nitrogen and volatile organic compounds. This results due to pollutants emitted by cars, chemical plants and other sources chemically react in the presence of sunlight. CO is emitted from combustion processes with insufficient oxygen supply in road traffic. Strategies to prevent the formation of tropospheric O_3 are primarily based on CH_4 reductions and cutting the levels of atmospheric pollution arising from man-made sources, such as fossil fuel production and distribution.

4.2.5 Ecotoxicity indicators

Ecotoxicity refers to the potential for biological, chemical or physical stressors to affect ecosystem. This impact results from emissions of toxic substances to air, water and soil. Ecotoxicity has three aspects: freshwater aquatic ecotoxicity, marine ecotoxicity and terrestrial ecotoxicity.

Table 4. 20: Layers Chronic Ecotoxicity

Type of layer	Bitumen (kg eq. 1,4DCB/t)	Stabilisation plant (kg eq. 1,4DCB/t)	Hot-mix asphalt plant using gas (kg eq. 1,4DCB/t)	Construction machine (kg eq. 1,4DCB/MJ)	Deconstruction machine (kg eq. 1,4DCB/MJ)	Aggregate (kg eq. 1,4DCB/t)	Road transport (kg eq. 1,4DCB/km)	Total
Wearing course	8787044,318	0	320670,941	230390,5861	436529,5316	403744,5549	337258,6419	10515638,57
Road base layer	0	0	0	902699,9574	436529,5316	1328107,089	526793,835	3194130,413
Road base layer_2	0	245,0397031	0	766890,7698	436529,5316	3189041,63	2514098,873	6906805,843

Table 4. 21: Operations Chronic Ecotoxicity

Operation name or year:	Bitumen (kg eq. 1,4DCB/t)	Stabilisation plant (kg eq. 1,4DCB/t)	Hot-mix asphalt plant using gas (kg eq. 1,4DCB/t)	Constructio n machine (kg eq. 1,4DCB/MJ)	Deconstruction machine (kg eq. 1,4DCB/MJ)	Aggregate (kg eq. 1,4DCB/t)	Road transport (kg eq. 1,4DCB/km)	Total
2017	8787044,318	245,0397031	320670,941	1899981,31	1309588,595	4920893,273	3378151,35	20616574,83

Table 4. 22: Total Chronic Ecotoxicity

Bitumen (kg eq. 1,4DCB/t)	Stabilisation plant (kg eq. 1,4DCB/t)	Hot-mix asphalt plant using gas (kg eq. 1,4DCB/t)	Construction machine (kg eq. 1,4DCB/MJ)	Deconstruction machine (kg eq. 1,4DCB/MJ)	Aggregate (kg eq. 1,4DCB/t)	Road transport (kg eq. 1,4DCB/km)	Total
8787044,318	245,0397031	320670,941	1899981,313	1309588,595	4920893,273	3378151,35	20616574,83

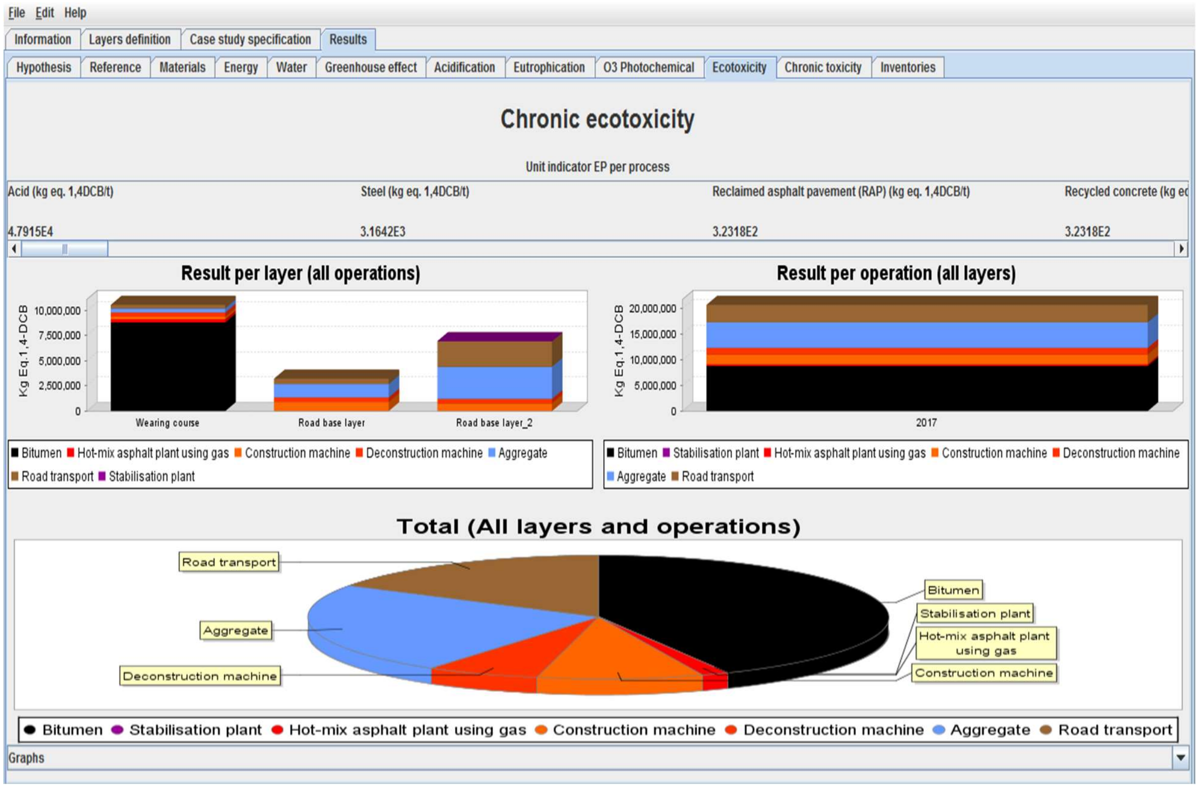

Figure 4. 8. Unit indicator EP per process

In Figure 4.8 the bar graph which illustrates results per layer is a graphical representation of Table 4.20, the bar graph which illustrates results per operation is a graphical representation of Table 4.21, and the pie chart which illustrates the total for all layers and all operations is a graphical representation of Table 4.22. The unit indicator EP per process shows that materials used have more environmental impact contribution and it amounts to 67%. The 67% is divided into bitumen 43% and aggregates 24% respectively. Bitumen is intimately mixed with graded aggregates and it is compacted on the road. During this process CO_2 gas is released and it contaminates the air. This contaminant has a toxic effect on terrestrial organisms, and ultimately on humans. The machinery used have less environmental impact contribution and it amounts to 33%. The 33% is divided into road transport 12%, construction machines 9%, deconstruction machine 6%, hot mix asphalt plant using gas 3% and stabilising plant 3%. The government should educate pavement construction projects participants about the importance of environmental impact indicators management and its drawbacks on the environment and the health of civilians. The government should consider reusing asphalt as a recycled material and incorporation with road materials alternatives.

4.2.6 Toxicity Indicators

Toxicity refers to how poisonous a substance is. A considerable amount of work on modelling toxicity and ecotoxicity has been carried out over the past 20 years, revealing not only the importance ascribed by society to environmental effects on human health, but also the difficulty of faithfully representing these impacts by means of simple indicators.

Table 4. 23: Layers Chronic Toxicity

Type of layer	Bitumen (kg eq. 1,4DCB/t)	Stabilisation plant (kg eq. 1,4DCB/t)	Hot-mix asphalt plant using gas (kg eq. 1,4DCB/t)	Construction machine (kg eq. 1,4DCB/MJ)	Deconstruction machine (kg eq. 1,4DCB/MJ)	Aggregate (kg eq. 1,4DCB/t)	Road transport (kg eq. 1,4DCB/km)	Total
Wearing course	5102,704747	0	2212,623641	1288,376242	2441,133931	1773,924466	1935,793655	14754,55668
Road base layer	0	0	0	5048,023871	2441,133931	5835,277849	3023,68579	16348,12144
Road base layer_2	0	410,7682545	0	4288,559981	2441,133931	14011,62914	14430,39863	35582,48994

Table 4. 24: Operations Chronic Toxicity

Operation name or year:	Bitumen (kg eq. 1,4DCB/t)	Stabilisation plant (kg eq. 1,4DCB/t)	Hot-mix asphalt plant using gas (kg eq. 1,4DCB/t)	Construction machine (kg eq. 1,4DCB/MJ)	Deconstruction machine (kg eq. 1,4DCB/MJ)	Aggregate (kg eq. 1,4DCB/t)	Road transport (kg eq. 1,4DCB/km)	Total
2017	5102,704747	410,7682545	2212,623641	10624,96009	7323,401794	21620,83145	19389,87808	66685,16806

Table 4. 25: Total Chronic Toxicity

Bitumen (kg eq. 1,4DCB/t)	Stabilisation plant (kg eq. 1,4DCB/t)	Hot-mix asphalt plant using gas (kg eq. 1,4DCB/t)	Construction machine (kg eq. 1,4DCB/MJ)	Deconstruction machine (kg eq. 1,4DCB/MJ)	Aggregate (kg eq. 1,4DCB/t)	Road transport (kg eq. 1,4DCB/km)	Total
5102,704747	410,7682545	2212,623641	10624,96009	7323,401794	21620,83145	19389,87808	66685,16806

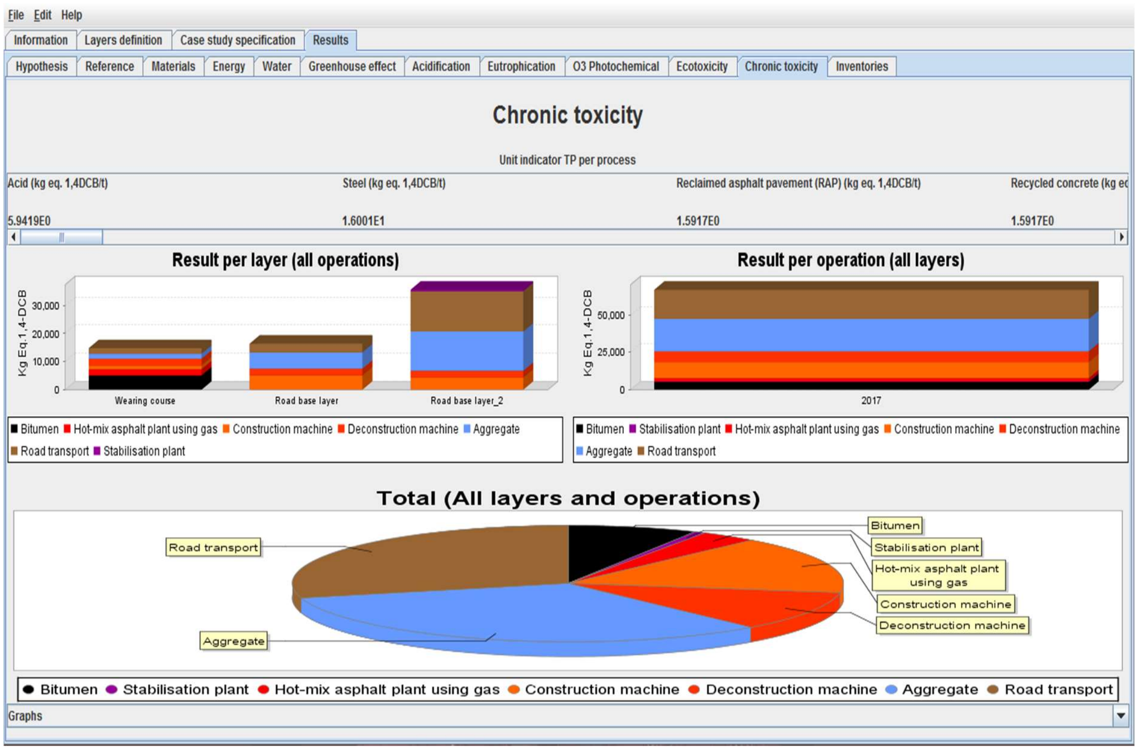

Figure 4. 9. Unit indicator TP per process

In Figure 4.9 the bar graph which illustrates results per layer is a graphical representation of Table 4.23, the bar graph which illustrates results per operation is a graphical representation of Table 4.24, and the pie chart which illustrates the total for all layers and all operations is a graphical representation of Table 4.25. The unit indicator TP per process shows that machinery used have more environmental impact contribution and it amounts to 60%. The 60% is divided into road transport 29%, construction machine 16%, deconstruction machine 11%, hot mix asphalt plant using gas 3% and stabilisation plant 1%. The class of road used in this research is national road. National roads have carried heavy vehicular traffic historically. As a result, the soil still carries chemical elements such as lead. Lead came as a result of leaded gasoline. Leaded gasoline was stopped and unleaded gasoline was introduced which helped to reduce emissions in the air but not in the soil where traffic was heavy during the use of leaded gasoline. Lead is a heavy metal. Other heavy metals that contribute to toxicity are zinc, cadmium, nickel and polycyclic aromatic hydrocarbons. Polycyclic aromatic hydrocarbons are combustion by product of gasoline and fossil fuels. The materials used have less environmental impact contribution and it amounts to 40%. The 40% is divided into aggregate 32% and bitumen 8%.

Since the price of oil continually increases, the government must adopt legislation that encourages the expansion of biofuel and decreases the amount of equipment operating with diesel. The contractors should adopt international standards, such as the environmental management systems (EMS), which allow the company to identify opportunities for reducing the environmental impact indicators of its day-to-day operations.

4.3 Summary

This chapter shows the levels of consumption produced during pavement deconstruction and construction. The consumptions of materials, water and energy. It further analyses the results achieved on consumptions. The results show that most of materials consumption occurs during material extraction. Most of the energy is consumed during processing of aggregates and most of water consumption occurs during mixing and processing of pavement layer works. It also outlines the environmental impact contribution of both materials used and machinery used. Most of the environmental impact indicators result from materials used with 54% on average and machinery used is 46% on average. This is based on the six indicators which are: greenhouse effect indicator, acidification indicator, eutrophication indicator, tropospheric ozone, ecotoxicity and toxicity indicator. The gases emitted to the atmosphere are CO_2, CO, SO_2, CH_4, N_2O and NO which lead to contamination of the atmosphere and have a negative impact towards pavement sustainability.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

After concluding this research, it is evident that research regarding LCA in South Africa is limited. The government should invest in conducting more research on this topic to close research gaps. The research shows that South Africa need to develop a guideline to use LCA method in the roads and transport industry in order to enhance sustainability in South African road network. Furthermore, it will be ideal to develop our own LCA tools as a country. After evaluating the consumption of water, energy and materials during pavement construction and evaluating the environmental impact indicators, it is crucial for the government to implement measures that will help to reduce the consumption of materials, energy and water and reduce the impact of environmental impact indicators. By reducing consumptions of water, energy and materials, less material consumption will allow more sustainable roads to be built with the money saved from buying material, less energy consumption will lead to less emissions produced to pollute the environment and less water use will save more water for the government. Water is a scarce resource in South Africa. The outcomes achieved show that materials used contributes more environmental impacts with 54% on average. As it is indicated in the research for asphalt pavements, the majority of energy is consumed during asphalt mixing, drying of aggregates, and the production of bitumen. The use of roadway materials efficiently to reduce waste and minimizing the amount of energy consumed during construction can be two means of improving the sustainability of roadways in South Africa.

5.2 Recommendations

Having discussed all the problems that are faced by South African roads and the effect of environmental indicators, there has to be a way of addressing them in order to do away with long term problems in the future, as such, below are recommended solutions which will help the country to resolve consumption of materials, energy and water and to minimise the impact brought by environmental indicators.

- Government and the construction industry should give incentives to innovations in sustainable pavement construction practices.
- Government should provide funding for research and development of sustainable roads.
- It is ideal for South Africa to develop a guideline to apply LCA approach in the pavement industry.
- In order to build sustainable roads in South Africa the government should introduce measures to reduce consumption of materials, energy and water during pavement construction and rehabilitation.
- Tools such as the Ecorce M should be adopted and implemented for future use in order to address pavement problems.
- Through the results obtained from Ecorce M tool, it is evident that there is high consumption of materials, energy and water during construction. High consumption of materials occurs due to high amount of waste material. High amount of waste material results due to improper material used during construction stage. It is ideal to make provision in the budget to be used by consultants to conduct their own tests and compare them with the tests submitted by the contractor.
- Currently the retention period is one year after practical completion. After retention period the engineer issues a defects list and once the contractor has attended all items on the defects list, the engineer releases his final claim and do final completion. Once the contractor is issued with final completion certificates he is no longer responsible for maintenance of the road. The government takes over maintenance of the road, which cost more money that can be saved to build new roads. It would be ideal for the government to introduce the law whereby they sign agreement with the construction company and the consulting engineering firm that if the road deteriorates before it reaches its life span, the party at fault is responsible to fix the road at their own costs. Roads that deteriorate before their life span compromises the goal of creating a sustainable road network.

- The extraction and production of aggregates produce the majority of material wastes. It is ideal to implement alternative approved methods of extraction and production of aggregates to help reduce material wastes.
- The engineers should evaluate and determine the alternative methods of extraction and production of aggregates. This will assist to reduce material consumption and help to build sustainable roads.
- The focus of government should be to build sustainable roads instead of building roads that deteriorate before they reach their life span. Roads that deteriorate before they reach their life span force government to spend more money on maintenance.
- Building sustainable roads will help government to save money and extend South African road network by building new roads. The government should find approved alternative methods to maintain roads that deteriorate before they reach their life span. Techniques of patching potholes should be well implemented so that they can help the road reach its life span. If it is not done correctly, it provides temporary solution. When it rains patches of the surface become detached and the pothole develops again.
- Government should consider reusing previous pavement layers as a resource material rather than virgin quarries and use scrap tyres and plastic bags as an alternative durable wearing surface.
- The ability to use asphalt repeatedly confirms its place as viable and useful asphalt aggregate substitute.
- In-situ stabilisation or the process of stabilising natural earth to strengthen and allow it to function as a pavement layer, is a technique that drastically reduces the amount of aggregates needed.
- The government should consider the use of stabilising aids such as in countries like Australia. These stabilising aids strengthen the subgrade of the pavement. The use of stabilising aids can help to reduce the cost of building the road and save cost of ongoing road maintenance.
- South Africa should promote the use of stabilising aids like in the United States, in states such as California and New York and by governments of Kazakhstan, Romania, Morocco, Venezuela and Thailand.
- The research shows that there is high amount of energy consumption during construction. It is vital for transport engineering specialists to develop

methods that will help to reduce energy consumption. This can be achieved through the funding assistance from the government.

- A new concept of building sustainable roads has emerged through both academia and industry: it is defined to be a road that is:
  - constructed to reduce environment impacts;
  - designed to optimise the alignment (vertical and horizontal including considerations of ecological constraints and operational use by vehicles);
  - resilient to future environmental and economic pressures (e.g climate change and resource scarcity);
  - adaptable to changing uses including increased travel volumes, greater demand for public use and activities (cycling and walking transport); and
  - able to harvest the energy to power itself.
- There is a need for investigation into commissioning and testing water consumption.
- Ensuring how much water is used in each site can help to promote a more water efficient culture.
- The construction companies must adopt the latest environmental technologies in order to reduce the amount of environmental impact indicators, such as those proposed in environmental technology policies like the Environmental Protection Agency (EPA). The EPA program provides the verification process for the performance of innovative environmental technologies in a particular application. In the construction sector, the EPA program has largely been concerned with the technologies for emission reductions, such as after-treatment technologies, use of cleaner fuel, and emission-reducing fuel additives. The EPA rules for off-road diesel engines are the regulations with the biggest impact on emissions from construction equipment. Thus, equipment manufacturers are required to ensure their products comply with these regulations with a standardised certification test for their products.
- Environmental impact indicators incentives should be granted to construction companies that adopt best practices; these incentives include: grant programs, which provide direct funding to equipment owners to replace old equipment with new and cleaner equipment, and tax incentives, which offer

tax exemptions, tax deduction, or tax credits to adopt the usage of technologies for reducing emissions.

- Tropospheric O_3 can be minimised by limiting driving.
- Conserving energy also help to reduce tropospheric O_3.

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APPENDIX A

ASPHALT MIX DESIGN

ACTSF_1 AC Medium with washed sand	Prepared and designed by: WHCES Pty Ltd Date: 7/12/2016	ASPHALT MIX DESIGN		D3

Contract	MAKALI
Route	N12 - KLERKSDORP
Section	
Layer	Asphalt Overlays
Mix	ACTSF_1 AC Medium with washed sand

SAMPLE CODE	MATERIAL	TYPE	SOURCE
Sample A	14mm	quartzite	C& C Crushers Skag #5 @ Stilfontein
Sample B	10mm	quartzite	C& C Crushers Skag #5@ Stilfontein
Sample C	7mm	quartzite	C& C Crushers Skag #5@ Stilfontein
Sample D	Dust #4	quartzite	C& C Crushers Skag #4@ Stilfontein
Sample E	washed sand	quartzite	C& C Crushers @ Stilfontein

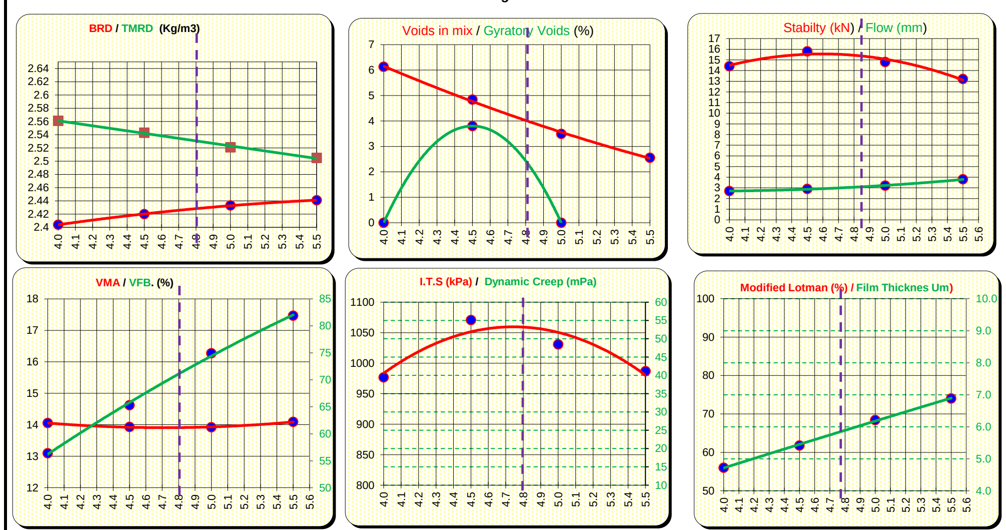
Notes:

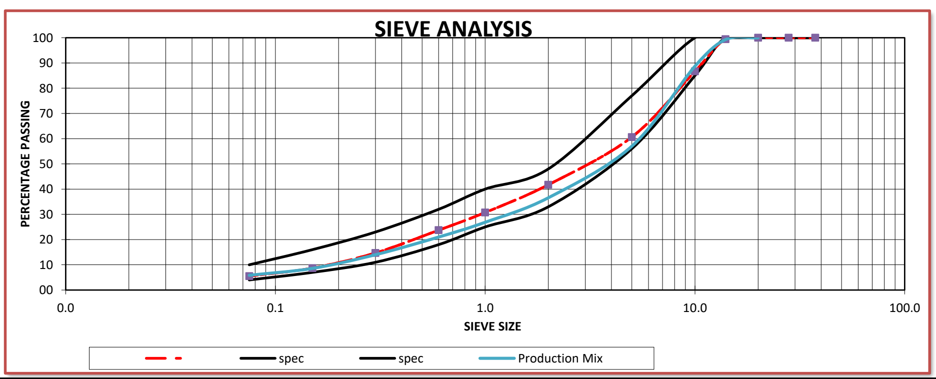
Binder			
Type:	50/70	Source:	Sapref
Pen@25oC (0.1 mm)	61	Visc.@60oC(Pa.s)	189
Softening point	50	Visc.@135oC(Pa.s)	0.36
RD of Binder	1.021	Hot Flow	n/a
Mixing Temp. oC	155-165	Compaction Temp.	138

SAMPLE NO :	1	2	3	4	5	6	MF	Blend 1	Blend 2	Blend 3	Pzroduction Mix	SPECIFICATION Min	Max
% IN MIX - Lab blend (1)													
% IN MIX - Lab blend (2)													
% IN MIX - Lab blend (3)	12%	18%	10%	40%	20.0%								
Sieve Analysis 37.5	100	100	100	100	100					100	100	100	100
28	100	100	100	100	100					100	100	100	100
20	100	100	100	100	100					100	100	100	100
14	95	100	100	100	100					99	99	100	100
10	10	86	100	100	100					87	89	85	100
5	0.7	8	3	97	100					61	57	56	77
2	0.6	2	1	62	82					42	37	33	48
1	0.6	2	1	43	65					31	27	25	40
0.6	0.6	2	1	33	50					24	21	18	32
0.3	0.5	2	0.9	21	29					15	14	11	23
0.15	0.4	2	0.9	14	13					09	9	7	16
0.075	0.3	1.5	0.9	10.30	5					5.5	5.8	4	10

	1	2	3	4	5	6	MF	DESIGN				Min	Max
BRD	2.691	2.683	2.685	2.686	2.682			2.685					
Sand eqv.				50	74			Filler				50	
Water absorp.	0.6	0.6	0.8	0.5	0.6		0.588	Blend no.	Type		% in mix	n/a	1
ACV	12.4							1	none			n/a	25
10 % FACT / Wet/Dry Rato (%)	303 / 67							2	none			160/75	n/a
Flak. Index	11.3	11.8	13.5					3	none			n/a	25
PSV	59											50	n/a
Methylene Blue Value	0.25											n/a	2

Design Curves





Property	B1	B2	B3	Lab Design				Lab design proposal	Job Mix Target based on 3 days production mixes	Spec Min	Max
BINDER % Total Added			4.5	4	4.5	5	5.5	4.7	4.8		
BINDER % Total Recovered			n/a	n/a	n/a	n/a	n/a				
BRD Kg/m^3			2.420	2.404	2.420	2.433	2.441	2.426	2.410		
TMRD(rice) Kg/m3			2.543	2.561	2.543	2.521	2.505	2.533	2.518		
VOIDS IN MIX (%)			4.8	6.1	4.8	3.5	2.6	4.2	4.6	3	6
STABILITY (Kn)			15.8	14.4	15.8	14.8	13.2	15.5	13.2	8	18
FLOW (mm)			2.9	2.7	2.9	3.2	3.8	3.0	3.5	2	6
STABILITY FLOW RATIO			5.4	5.3	5.4	4.6	3.5	5.2	3.7	2.5	n/a
ITS (kPa)			1071	977	1071	1031	987	1058.0	1197	1000	n/a
VMA (%)			13.9	14.1	13.93	13.92	14.1	13.9	14.6	15	n/a
VFB (%)			64	56	65	75	82	69.0	70.4	65	75
CREEP Dyn/~~Stat~~ (Mpa)			60.7	.	60.7	.	.	61.0		20	n/a
AIR PERMEABILITY			0.42	.	0.42	.	.	0.4			1
MODIFIED LOTTMAN (TSR)			0.94	.	0.94	.	.	0.94		0.8	n/a
RESILLIENT MODULUS (Mpa)											n/a
FILLER/BITUMEN RATIO			1.5	1.4	1.2	1.1	1.0	1.2	1.2	1	1.5
BINDER ABSORPTION (%)			0.8	0.65	0.68	0.64	0.69	0.65	0.5	n/a	0.5
FILM THICKNESS (microns)			5.2	4.7	5.4	6.2	6.9	5.6	7.6	5.5	8
GYRATORY VOIDS@ 300 (%)			3.80	.	3.80	.	.	3.8		2	

Notes:

Designed By: WHCES Pty Ltd
Signature:
Designer Name: Wim Hofsink
Date: 7/12/2016

Consultant Approval
Signature: Date
Name:
PROF REG NO:

PROJECT MANAGER: Date

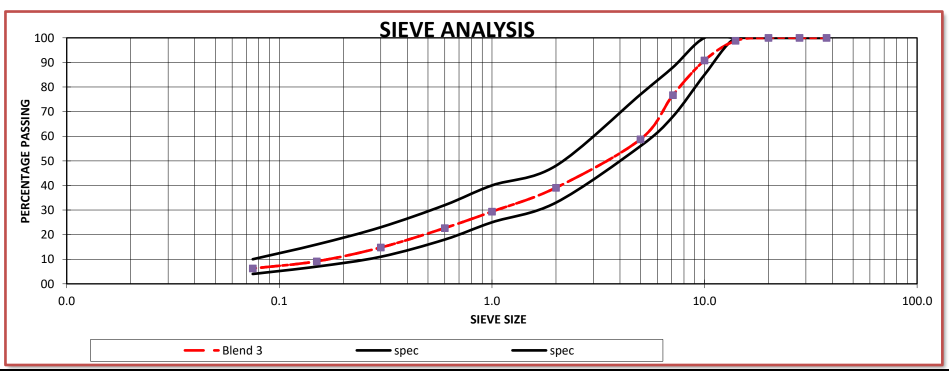
PROJEC MATERIAL SPECIALIST Date

AC MEDIUM - A-E2 + 0.03 zycotherm	**Prepared by:** WHCES Pty Ltd Date: 20-Sep-17	**ASPH GN** Central University of Technology, Free State	**Contract** MAKALI **Route** N12 KLERKSDORP **Section** **Layer** Surfacing **Mix** AC MEDIUM - A-E2 + 0.03 zycotherm **Revision**	**D3**

SAMPLE CODE	MATERIAL	TYPE	SOURCE
1	13.2mm	Stilfontein	CNC Crushers (Stilfontein)
2	9.5mm	Stilfontein	CNC Crushers (Stilfontein)
3	6.7mm	Stilfontein	CNC Crushers (Stilfontein)
4	Crusher Dust	Stilfontein	CNC Crushers (Stilfontein)
5	Crusher Sand	Stilfontein	CNC Crushers (Stilfontein)
6			
7			

Notes:

SAMPLE NO :	1	2	3	4	5	6	7	Blend 1	Blend 2	Blend 3	PLANT MIX	SPECIFICATION Min	SPECIFICATION Max
% IN MIX - Lab blend (1)													
% IN MIX - Lab blend (2)													
% IN MIX - Lab blend (3)	10%	18%	18%	36%	18%								
Sieve Analysis (mm) 37.5	100	100	100	100	100					100		100	100
28	100	100	100	100	100					100		100	100
20	100	100	100	100	100					100		100	100
14	88	100	100	100	100					99		100	100
10	19	94	100	100	100					91		85	100
7.1	2	27	98	100	100					77		68	88
5	1	2	34	95	100					59		56	77
2	0.4	0.8	2	68	78					39		33	48
1	0.4	0.8	2	51	58					29		25	40
0.6	0.4	0.8	2	40	43					23		18	32
0.3	0.4	0.8	1	27	26					15		11	23
0.15	0.3	0.7	1	18	13					09		7	16
0.075	0.3	0.6	1.0	13.10	6.7					6.2		4	10
BRD	2691	2688	2681	2674	2672			2,679					
Sand eqv.								Filler				50	
Water absorp.	0.3	0.4	0.6	1	1			Blend no.	Type	% in mix			1
ACV	13.2							1	none				
10 % FACT / Wet/Dry Rato (%)	325/0.7							2	none			160	
Flak. Index								3	none			20	
PSV													
Methylene Blue Value													

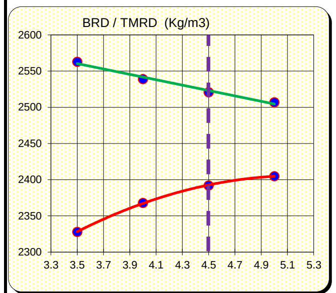


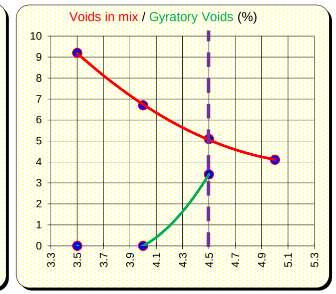
Notes:

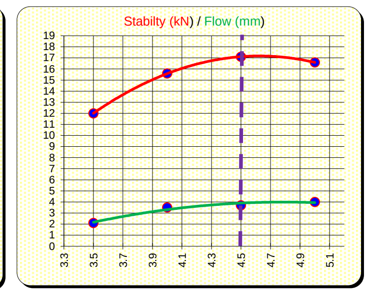
Binder

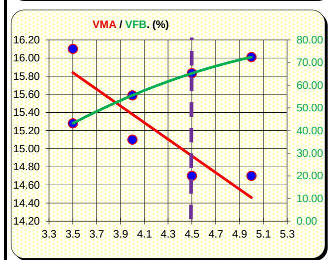
Type:	A-E2 + 0.03 zycotherm	Source:	Engen
Pen@25oC (0.1 mm)	-	Visc.@60oC(Pa.s)	-
Softening point	-	Visc.@135oC(Pa.s)	-
RD of Binder	1.025	Hot Flow	-
Mixing Temp. oC	157 - 161	Compaction Temp.	141-143

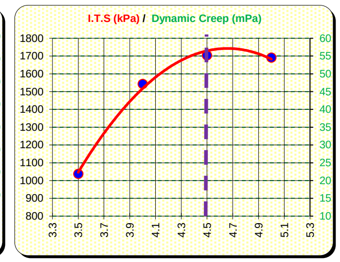
Design Curves

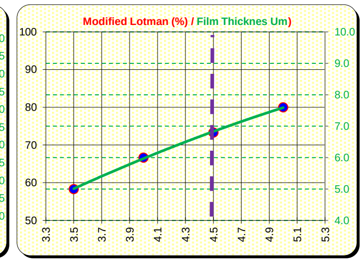












Property	Plant Mix	B1	B2	B3	Lab Design				Proposal	Spec Min	Spec Max
BINDER % Total Added					3.5	4	4.5	5	4.5		
EFFECTIVE BINDER (%)					3.1	3.63	4.1	4.52	4.1		
BRD Kg/m^3					2328	2368	2392	2405	2395		
TMRD(rice) Kg/m3					2563	2539	2521	2507	2521		
VOIDS IN MIX (%)					9.2	6.7	5.1	4.1	5.0	4	6
STABILITY (Kn)					12	15.6	17.1	16.6	17.1	8	n/a
FLOW (mm)					2.1	3.5	3.7	4	3.8	2	4
STABILITY FLOW RATIO					5.7	4.5	4.6	4.2	4.5		
ITS (kPa)					1038	1543	1704	1691	1710	1000	n/a
VMA (%)					16.1	15.1	14.7	14.7	14.9	14	n/a
VFB (%)					43	56	65	72	65.0	65	78
CREEP Dyn/Stat (Mpa)					-	-	-	-	-	15	n/a
AIR PERMEABILITY					-	-	0.35	-	0.4		1
MODIFIED LOTTMAN (TSR)					-	-	0.84	-	0.84	0.8	n/a
RESILLIENT MODULUS (Mpa)					-	-	-	-	-		n/a
FILLER/BITUMEN RATIO					1.8	1.6	1.4	1.2	1.4	1	1.5
BINDER ABSORBTION (%)					0.4	0.4	0.4	0.5	0.40		
FILM THICKNESS (microns)					5.0	6.0	6.8	7.6	6.9	6	n/a
GYRATORY VOIDS@ 300 (%)					-	-	3.41	-	3.4	2	

Designed By: WHCES Pty Ltd
Signature:
Designer Name: Wim Hofsink
Date: 20-Sep-17

Consultant Approval
Signature: Date
Name:
PROF REG NO:

PROJECT MANAGER: Date
PROJEC MATERIAL SPECIALIST Date

APPENDIX B

G1 MATERIAL CLASSIFICATION (BASE LAYER)

G1 MATERIAL CLASSIFICATI[ON RES]ULTS

STRATALAB

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P O BOX 2334 KLERKSDORP 2570
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FAX: 018 462 6655
Email address: stratalab@yahoo.com
VAT No: 4620161093

Summary of test results

Client: Makali Plant & Construction

Date: 11-08-2017

Ref No: 2017080061

Project: N12 - Klerksdorp - Walk Way / Main Road

	MDD A.A.S.H.T.O & OMC	CORRECTED C.B.R at 2.54mm/13.344 Kn 100 / 95 / 93 / 90	U.C.S (kPa) @ 100% 100 / 90	I.T.S. (kPa) @ 100% 100 / 90	PI	GM	TRH 14 1987
Imported Crusher Run	2235	125.0/72.0/57.0/38.0			0		G 1
	5.9						

Technical Signatory: D van Vreden

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MOD A.A.S.H.T.O./Std PROCTOR/MOISTURE DENSITY/C.B.R. or U.C.S. DATA

TMH 1: A7; A8; A9 & A14

CLIENT:	Makali Plant & Construction N12 - Klerksdorp - Walk Way / Main Road	DATE: ORD/JOB No:	11-08-2017 2017080061

MOISTURE DENSITY RELATIONSHIP

COMPACTIVE EFFORT:	55 * 5	DESCRIPTION:	Crusher Run
MOD A.A.S.H.T.O./Std PROCTOR:	MOD A.A.S.H.T.O.		

Tin no.	87	94	63	82	62
Wet soil + Mass of Tin (g)	730.0	799.0	814.5	747.0	743.3
Dry soil + Mass of Tin (g)	714.1	773.8	782.7	714.1	705.4
Water (g)	15.9	25.2	31.8	32.9	37.9
Mass of Tin only (g)	195.8	186.4	192.0	187.1	189.7
Moisture content %	3.1	4.3	5.4	6.2	7.3
MASS gms: =					
1) Mass of Mould + Wet Soil	9963	10107	10240	10275	10195
2) Mass of Mould:	4750	4750	4750	4750	4750
3) Wet soil:	5213	5357	5490	5525	5445
4) Dry soil:	5058	5137	5210	5200	5072
M Volume (l) = 2.345 Dry Density(kg/m³)	2157	2190	2222	2218	2163

MAX D.D. (kg/m³) = 2235 OPTIMUM MOISTURE (%) = 5.9

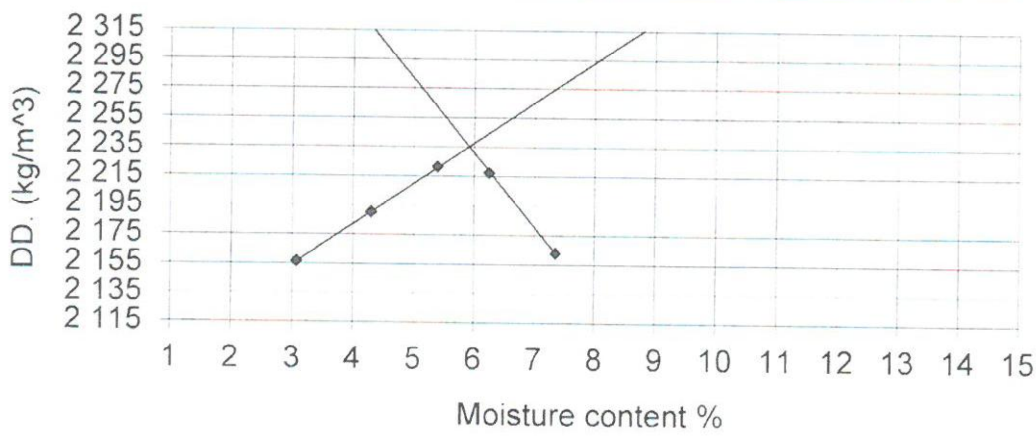
CORRECTED C.B.R at 2.54mm/13.344 kN

100% = 125.0 95% = 72.0 93% = 57.0 90% = 38.0

Percentage Swell

Mod = 0.00 N.R.B. = 0.00 Proc = 0.00

U. C. S. (kPa) @ 100% = n.a 90% = n.a
I. T. S. (kPa) @ 100% = n.a 90% = n.a



Remarks: G1 - N2H 14

Technical Signatory: D van Vreden

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VAT NR: 462016093

CBR/UCS CURVES

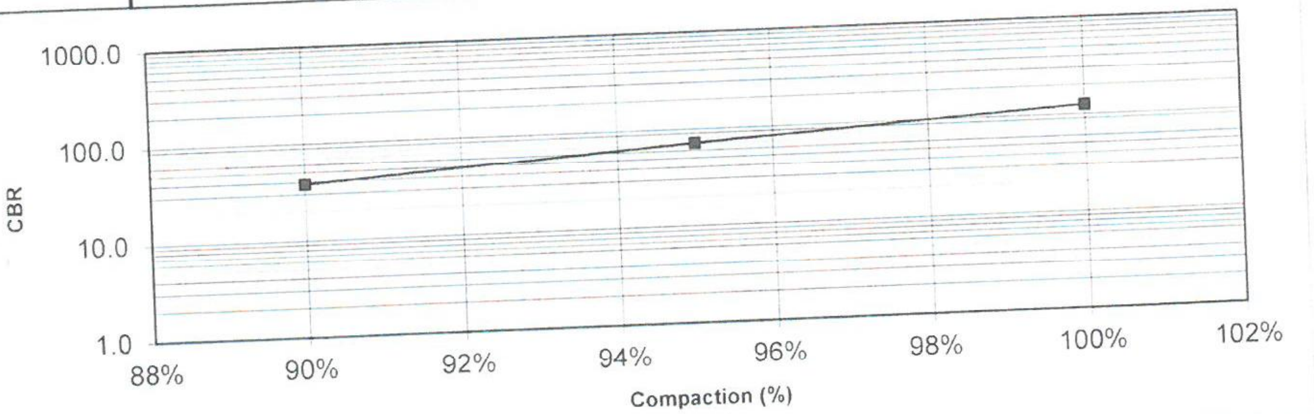
CLIENT: Makali Plant & Construction
PROJECT: N 12 - klerksdorp - Walk Way / Main Road

DATE: 11-08-2017
ORD/JOB No: 2017080061

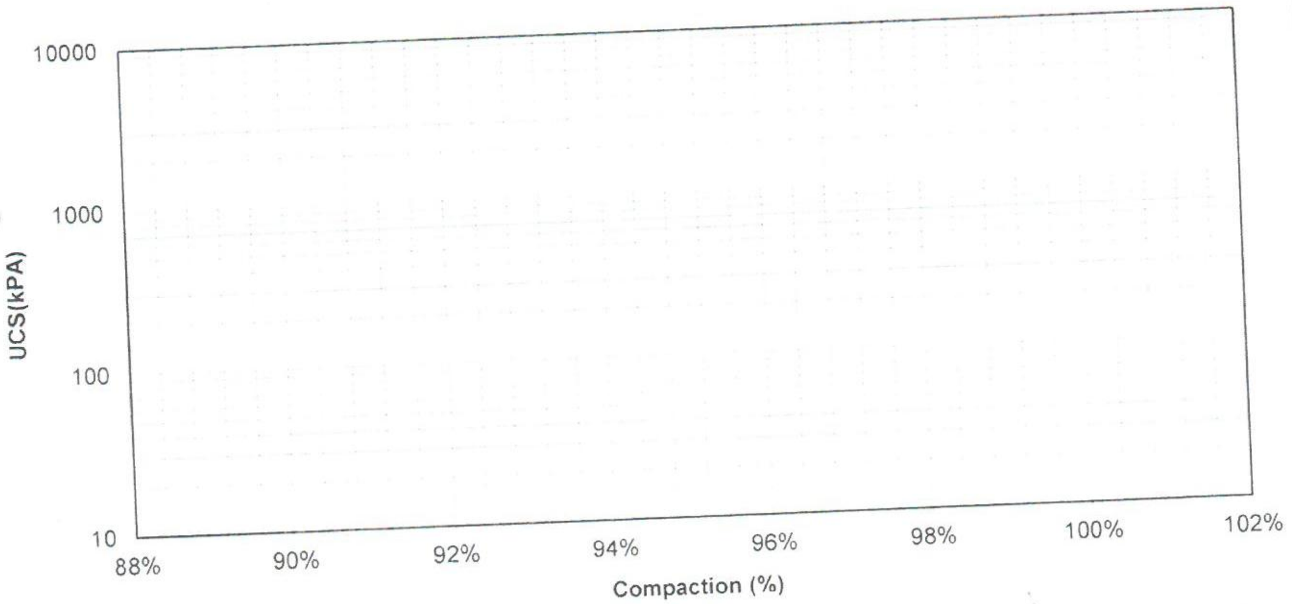
DESCRIPTION: Crusher Run

CBR = natural

DATA:	COMPACTION %	100%	95%	90%
	CBR	125.0	72.0	38.0



DATA:	COMPACTION %	100%	90%
	UCS(kPa)		



Technical Signatory: D van Vreden

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Email address: stratalab@yahoo.com

VAT No: 4620161093

ATTERBERG CONSTANTS
TMH 1 A3

CLIENT: Makali Plant & Construction
PROJECT: N 12 - Klerksdorp - Walk Way / Main Road

DATE: 11-08-2017
REF:
JOB No: 2017080061

Delivery Description:

Sample Description: Crusher Run

Depth of sample :

ATTERBERG LIMITS:	LIQUID LIMIT		*	PLASTIC LIMIT	
Mass (g) :	* Test 1	Test 2	*	Test 1	Test 2
Bottle+wet sample .... A *	130.79	130.34			
Bottle+dry sample .... B	130.22	129.85			
Bottle C	127.72	127.74			
Water .... D	0.57	0.49	*	0.00	0.00
Dry sample /................b-c=e	2.50	2.11	*	0.00	0.00
MEAN VALUE....	22.8	23.2	*	0.0	0.0
PLASTICITY INDEX	0.0			NP	

LINEAR SHRINKAGE	Test 1	*	Test 2
Length of wet soil bar	150 mm	*	150 mm
Contraction when dry	1.2 mm	*	1.2 mm
Linear shrinkage	0.8		0.8
MEAN VALUE		0.8	

Remarks: ______________________

Technical Signatory: D van Vreden

STRATA LAB
MATERIALS LABORATORY
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TEL: 018 462 2089
FAX: 018 462 6655
EMAIL: stratalab@yahoo.com
VAT No: 4620161093

Grading Analysis - TMH 1 B4 & B13

SABS 1083 / 1090 - 1976

CLIENT: Makalie Plant & Construction

DATE: 11-08-2017

PROJECT: Klerksdorp - N12 / Walk way - Main Road

JOB No: 2017080061

DESCRIPTION: Imported Crusher Run

DERIVED FROM: Mechanica X | Natural:

SAMPLED BY: Client: | Lab: X

GRADING

Sieve (mm)	Mass retained	% Retained	Cum % Retained	Cum % Passing	Colto Spec. G 1 & G 2
53.000	0.0	0.00	0.00	100.0	
37.500	0.0	0.00	0.00	100.0	100
26.500	743.0	16.19	16.19	83.8	84 - 94
19.000	511.5	11.15	27.34	72.7	71 - 84
13.200	551.5	12.02	39.36	60.6	59 - 75
9.500	499.0	10.87	50.23	49.8	
6.700	349.0	7.61	57.84	42.2	
4.750	214.0	4.66	62.50	37.5	36 - 53
2.000	465.0	10.13	72.64	27.4	23 - 40
1.180	144.0	3.14	75.77	24.2	
0.600	163.9	3.57	79.35	20.7	
0.425	67.0	1.46	80.81	19.2	11 - 24
0.300	57.5	1.25	82.06	17.9	
0.150	82.0	1.79	83.85	16.2	
0.075	46.0	1.00	84.85		
<0.075					

Fineness Modulus	4.56
Fines content	19.2
Dust (wash+dry)< 4-12	5.2

Total weight before wash 4588.6 g

Weight after wash (Sieve 0.075 mm) 4350.0 g

Technical signatory- D van Vreden

STRATALAB

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EMAIL: stratalab@yahoo.com
VAT No: 4620161093

Client: Makali Plant & Construction

Date: 11-08-2017

Project: Klerksdorp - N12 / Walk way - Main

Job no: 2017080061

Ref no:

Summary of test results

Source		CNC Crusher					
Description		Imported Crusher Run					
Sieve Analysis		% Cum Passing					
%	53.0	100					
	37.5	100					
P	26.5	83.8					
A	19.0	72.7					
S	13.2	60.6					
S	9.5	49.8					
I	6.7	42.2					
N	4.75	37.5					
G	2.0	27.4					
	1.18	24.2					
	0.600	20.7					
	0.425	19.2					
	0.300	17.9					
	0.150	16.2					
Fines Content (< 0.425mm)	< 0.425	19.2					
pH		8.15					
A.C.V. [%] (Dry)		16.8					
A.C.V. [%] (Wet)							
10% Fact [Dry] (kN)		275					
10% Fact [Wet] (kN) {% of Dry}							
Flakiness [%]		25.3					
Average Least Dimension (mm)							
Apparent Relative Density [kg/m³]		2686					
Bulk Relative Censity [kg/m³]							
Loose Bulk Denstiy [kg/m³]							
Compacted Bulk Density [kg/m³]							

Technical Signatory: D van Vreden

Central University of Technology, Free State

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AGGREGATE CRUSHING VALUE

TMH 1 METHOD B1

CLIENT: Makali Plant & Construction

DATE: 11-08-2017

SITE: Klerksdorp - N12 / Walk way - Main Road

JOB No: 2017080061

DESCRIPTION: Crusher Run

SAMPLED BY: Client: | Lab: X

DRY: X

WET:

A = MASS OF SAMPLE BEFORE TEST: 3599

B = MASS OF SAMPLES PASSING SIEVE: (' 2.36): 607

= B/A * 100 16.8 %

Technical Signatory: D van Vreden

Central University of Technology, Free State

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FLAKINESS INDEX OF A COARSE AGGREGATE
TMH 1 - METHOD B3

CLIENT:	Makali Plant & Construction	DATE:	11-08-2017
SITE:	Klerksdorp - N12 / Walk way - Main Road	JOB No:	2017080061
DESCRIPTION:	Crusher Run		

SAMPLED BY:

Client:		Lab:	X

1	2	3	4	5
Size of fraction to be gauged (Sieve sizes mm)		Mass Retained (g)	Width of Slots (mm)	Mass Passing Slot (g)
Passing	Retained			
75.0	63.0		37.5	
63.0	53.0		31.5	
53.0	37.5		26.5	
37.5	26.5		18.75	
26.5	19.0		13.25	
19.0	13.2	1998	9.5	505
13.2	9.5		6.6	
9.5	6.7		4.75	
6.70	4.75		3.35	
TOTAL		1893		112

$$\text{Flakiness Index} = \frac{\text{Total mass of sample passing}}{\text{Total mass of sample}} \times 100$$

$$= 25.3\%$$

Remarks:

Technical Signatory D van Vreden

Central University of Technology, Free State

STRATALAB

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EMAIL: stratalab@yahoo.com
VAT No: 4620161093

FLAKINESS INDEX OF A COARSE AGGREGATE
TMH 1 - METHOD B3

CLIENT: Makali Plant & Construction *DATE:* 11-08-2017

SITE: Klerksdorp - N12 / Walk way - Main Road *JOB No:* 2017080061

DESCRIPTION: Crusher Run

SAMPLED BY: Client: [ ] Lab: X

1	2	3	4	5
Size of fraction to be gauged (Sieve sizes mm)		Mass Retained (g)	Width of Slots (mm)	Mass Passing Slot (g)
Passing	Retained			
75.0	63.0		37.5	
63.0	53.0		31.5	
53.0	37.5		26.5	
37.5	26.5		18.75	
26.5	19.0		13.25	
19.0	13.2	1998	9.5	505
13.2	9.5		6.6	
9.5	6.7		4.75	
6.70	4.75		3.35	
TOTAL		1893		112

$$\text{Flakiness Index} = \frac{\text{Total mass of sample passing}}{\text{Total mass of sample}} \times 100$$

$= 25.3\%$

Remarks:

Technical Signatory D van Vreden

Central University of Technology, Free State

STRATALAB

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VAT No: 4620161093

APPARENT RELATIVE DENSITY (A.R.D.)
TMH 1 B14, B15

Client: Makali Plant & Construction — **Job No:** 2017080061

Project: Klerksdorp - N12 / Walk way - Main Road — **Date:** 11-08-2017

Layer:

Chainage	Crusher Run		
Mass Bottle + Glassplate (a)	760		
Mass Bottle + Glassplate + Material (b)	2130		
Mass Bottle + Glassplate + Material + Water ©	2650		
Mass Bottle + Glassplate + Water (d)	1790		
B - A =	1370	0	0
D - A =	1030	0	0
C - B =	520	0	0
A.R.D. of Material = (B - A) / ((D - A) - (C - B)) = E	1370 510	0 0	0 0
A.R.D. Kg/m	**2.686**	**#DIV/0!**	**#DIV/0!**

Chainage			
Mass Bottle + Glassplate (a)			
Mass Bottle + Glassplate + Material (b)			
Mass Bottle + Glassplate + Material + Water ©			
Mass Bottle + Glassplate + Water (d)			
B - A =	0	0	0
D - A =	0	0	0
C - B =	0	0	0
A.R.D. of Material = (B - A) / ((D - A) - (C - B)) = E	0 0	0 0	0 0
A.R.D. Kg/m	**#DIV/0!**	**#DIV/0!**	**#DIV/0!**

Remarks :

Technical Signatory: D van Vreden

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Client: Makali Plant & Construction

Project: Klerksdorp - N12 / Walk way - Main Road

Date: 11-08-2017

Job No: 2017080061

PH CONTENT

Test done according to TMH 1 method A20

	PH CONTENT	BOTTLE NUMBER
Crusher Run	8.15	47

Remarks:

Technical Signatory: D van Vreden

APPENDIX C

G5 MATERIAL CLASSIFICATION (SUB BASE LAYER - STABILISED)

Central University of Technology, Free State

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Unconfined Compressive Strength TMH 1 A 14 and Indirect Tensile Strength TMH 1 A 16 T

Client: Makali Plant & Construction

Project: N12 - Klerksdorp - Walk Way / Main Road

Date: 20/11/2017

Ref : Main Road

Job No: 20170110112

Sampled by:	Client :	Lab : X

Bag Type :	Plastic : x	Polythene :	Cement :
Curing :	Rapid (24 hrs) : x	7 Days :	11 days :
Stabilizer :	Cement : x	Lime :	Slag :

Position / Chainage (m)	Layer	MDD (kg/m³)	% OMC	% Moisture	% Comp	UCS (kPa)	ITS (kPA)	Colto Class.
CH ± 5 220m	Sub Base	2265	8.0	8.0	100 97 95 93 90	1580 1420 1260 1080 985	295 255 220 195 175	C3
CH ± 5 340m	Sub Base	2300	7.7	7.5	100 97 95 93 90	1620 1480 1320 1130 1020	310 280 245 205 180	C3
					100 97 95 93 90			

Remarks:

Technical Signatory: D van Vreden

S T R A T A L A B
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MOD A.A.S.H.T.O./Std PROCTOR/MOISTURE DENSITY/C.B.R. or U.C.S. DATA

TMH 1: A7; A8; A9 & A14

CLIENT:	Makali Plant & Construction	**DATE:**	20/11/2017
PROJECT:	Klerksdorp N12 Walkway / Main Road	**ORD/JOB No:**	20170110112

MOISTURE DENSITY RELATIONSHIP

COMPACTIVE EFFORT:	55 * 5	DESCRIPTION:	CH + 5.220m
MOD A.A.S.H.T.O./Std PROCTOR:	MOD A.A.S.H.T.O		Sub-Base

Tin no.	13	111	17	25	36
Wet soil + Mass of Tin (g)	832.8	919.0	887.6	919.0	920.0
Dry soil + Mass of Tin (g)	804.0	884.9	850.6	876.5	866.4
Water (g)	28.8	34.1	37.0	42.5	53.6
Mass of Tin only (g)	333.2	414.5	409.9	419.6	351.6
Moisture content %	6.1	7.2	8.4	9.3	10.4
MASS gms: =					
1) Mass of Mould + Wet Soil	10250	10380	10467	10460	10450
2) Mass of Mould:	4735	4735	4735	4735	4735
3) Wet soil:	5515	5645	5732	5725	5715
4) Dry soil:	5197	5263	5288	5238	5176
M Volume (l) = 2.345 Dry Density(kg/m³)	2216	2245	2255	2234	2207

MAX D.D. (kg/m³) = 2265 **OPTIMUM MOISTURE (%) =** 8.0

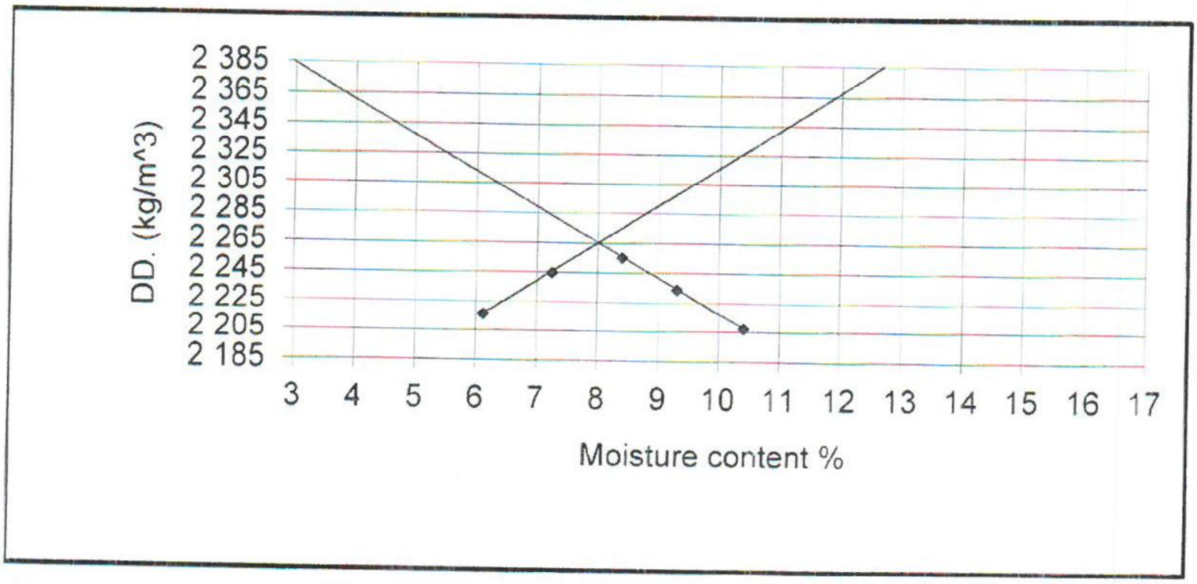
CORRECTED C.B.R at 2.54mm/13.344 kN

100% = n.a **95% =** n.a **93% =** n.a **90% =** n.a

Percentage Swell

Mod = n.a **N.R.B. =** n.a **Proc =** n.a

U. C. S. (kPa) @ 100% = n.a **90% =** n.a
I. T. S. (kPa) @ 100% = n.a **90% =** n.a



Remarks:

Technical Signatory: D van Vreden

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ATTERBERG CONSTANTS
TMH 1 A3

CLIENT: Makali Plant & Construction
PROJECT: Klerksdorp N12 Walkway / Main Road

DATE: 20/11/2017
REF:
JOB No: 20170110112

Delivery Description:

Sample Description: CH ± 5 220m

Depth of sample : Sub-base

ATTERBERG LIMITS:	LIQUID LIMIT		*	PLASTIC LIMIT	
Mass (g) :	* Test 1	Test 2	*	Test 1	Test 2
Bottle+wet sample .... A *	86.91	88.65			
Bottle+dry sample .... B	86.20	87.97			
Bottle C	83.40	85.27			
Water .... D	0.71	0.68	*	0.00	0.00
Dry sample /................b-c=e	2.80	2.70	*	0.00	0.00
MEAN VALUE....	25.4	25.2	*	0.0	0.0
PLASTICITY INDEX	0			NP	

LINEAR SHRINKAGE	Test 1	*	Test 2
Length of wet soil bar	150 mm	*	150 mm
Contraction when dry	0.9 mm	*	0.9 mm
Linear shrinkage	0.6		0.6
MEAN VALUE		0.6	

Remarks:

Technical Signatory: D van Vreden

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CLIENT:	Makali Plant & Construction		
PROJECT:	Klerksdorp - Walkway / Main Road	SAMPLE NO:	N/A
DESCRIPTION:	CH ± 5220m	DEPTH:	Sub-base
JOB NO:	20170110112	DATE:	20/11/2017
REMARKS:	N/A	REF:	N/A

SOIL MORTAR ANALYSIS
TMH 1 A1(A) A5

% Fines Content	18

	(g) Ret.	% pass
0.25 mm	29.0	15.3
0.15 mm	17.0	9.0
0.075 mm	14.5	7.7

Coarse sand	47
Fine sand	32
Silt & clay<0.075mm	21

SIEVE ANALYSIS

1. DETERMINATION OF AGGREGATE LARGER THAN 19.0 mm	Sieve Aperture	(g) Mass Retained	% Retained	% Passing	% Passing
	-	-	-	-	-
Total mass of dry sample	75.0				
	53.0				
	37.5				
	26.5				
	19.0				

2. FINAL SIEVE ANALYSIS		Sieve Aperture	(g) Mass Retained	% Retained	% Passing	% Passing
		-	-	-	-	-
Total mass		63.0		0.0	100.0	100
of Dry sample (g) :	3124.5	53.0		0.0	100.0	100
Mass retained on 0.425		37.5	470.0	15.0	85.0	85
after wash (g) :	2595.0	26.5	319.0	10.2	74.7	75
Mass passed thru 0.425		19.0	415.0	13.3	61.5	61
sieve (g) :	432.5	13.2	187.0	6.0	55.5	55
Passed thru 0.425 sieve		4.75	446.0	14.3	41.2	41
after sift process(g) :	25.5	2.0	238.5	7.6	33.6	34
Total passed thru 0.425		0.425	494.0	15.8	17.8	18
sieve + wash (g) :	529.5	0.075				7

G.M. = 2.41

Technical Signatory: D van Vreden

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MOD A.A.S.H.T.O./Std PROCTOR/MOISTURE DENSITY/C.B.R. or U.C.S. DATA

TMH 1: A7; A8; A9 & A14

CLIENT:	Makali Plant & Construction	DATE:	20/11/2017
PROJECT:	Klerksdorp N12 Walkway / Main Road	ORD/JOB No:	20170110112

MOISTURE DENSITY RELATIONSHIP

COMPACTIVE EFFORT:	55 * 5	DESCRIPTION:	CH ± 5 340m
MOD A.A.S.H.T.O./Std PROCTOR:	MOD A.A.S.H.T.O.		Sub-Base

Tin no.	47	31	35	25	36
Wet soil + Mass of Tin (g)	920.0	904.0	932.6	914.6	915.0
Dry soil + Mass of Tin (g)	894.9	868.1	897.9	876.5	866.4
Water (g)	25.1	35.9	34.7	38.1	48.6
Mass of Tin only (g)	413.8	296.0	408.7	419.6	351.6
Moisture content %	5.2	6.3	7.1	8.3	9.4
MASS gms: =					
1) Mass of Mould + Wet Soil	10280	10389	10479	10533	10500
2) Mass of Mould:	4735	4735	4735	4735	4735
3) Wet soil:	5545	5654	5744	5798	5765
4) Dry soil:	5270	5320	5364	5352	5268
M Volume (l) = 2.345 Dry Density (kg/m³)	2247	2269	2287	2282	2246

MAX D.D. (kg/m³) = 2300 OPTIMUM MOISTURE (%) = 7.7

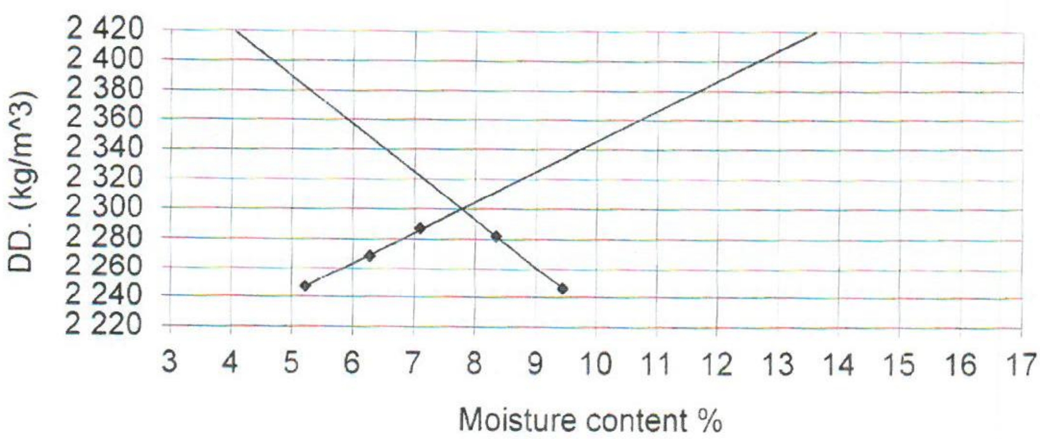
CORRECTED C.B.R at 2.54mm/13.344 kN

100% = n.a 95% = n.a 93% = n.a 90% = n.a

Percentage Swell

Mod = n.a N.R.B. = n.a Proc = n.a

U. C. S. (kPa) @ 100% = n.a 90% = n.a
I. T. S. (kPa) @ 100% = n.a 90% = n.a



Remarks:

Technical Signatory: D van Vreden

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ATTERBERG CONSTANTS
TMH 1 A3

CLIENT: Makali Plant & Construction
PROJECT: Klerksdorp N12 Walkway / Main Road

DATE: 20/11/2017
REF:
JOB No: 20170110112

Delivery Description:

Sample Description: CH ± 5 340m

Depth of sample : Sub-base

ATTERBERG LIMITS:	LIQUID LIMIT		PLASTIC LIMIT	
Mass (g) :	Test 1	Test 2	Test 1	Test 2
Bottle+wet sample .... A	70.09	71.55		
Bottle+dry sample .... B	69.11	70.66		
Bottle C	53.26	67.11		
Water .... D	0.98	0.89	0.00	0.00
Dry sample /................b-c=e	15.85	3.55	0.00	0.00
MEAN VALUE....	6.2	25.1	0.0	0.0
PLASTICITY INDEX	0		NP	

LINEAR SHRINKAGE	Test 1	Test 2
Length of wet soil bar	150 mm	150 mm
Contraction when dry	- mm	- mm
Linear shrinkage	0.0	0.0
MEAN VALUE	0.0	

Remarks: ______________________

Technical Signatory: D van Vreden

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CLIENT:	Makali Plant & Construction		
PROJECT:	Klerksdorp - Walkway / Main Road	**SAMPLE NO:**	N/A
DESCRIPTION:	CH ± 5 340 m	**DEPTH:**	Sub-base
JOB NO:	20170110112	**DATE:**	20/11/2017
REMARKS:	N/A	**REF:**	N/A

SOIL MORTAR ANALYSIS
TMH 1 A1(A) A5

% Fines Content	15

	(g) Ret.	% pass
0.25 mm	36.5	20.5
0.15 mm	15.0	8.4
0.075 mm	14.0	7.9

Coarse sand	44
Fine sand	33
Silt & clay<0.075mm	23

SIEVE ANALYSIS

1. DETERMINATION OF AGGREGATE LARGER THAN 19.0 mm		Sieve Aperture	(g) Mass Retained	% Retained	% Passing	% Passing
		-	-	-	-	-
Total mass of dry sample		75.0				
		53.0				
		37.5				
		26.5				
		19.0				

2. FINAL SIEVE ANALYSIS		Sieve Aperture	(g) Mass Retained	% Retained	% Passing	% Passing
		-	-	-	-	-
Total mass		63.0		0.0	100.0	100
of Dry sample (g) :	3192.0	53.0		0.0	100.0	100
Mass retained on 0.425		37.5	297.5	9.3	90.7	91
after wash (g) :	2740.5	26.5	768.5	24.1	66.6	67
Mass passed thru 0.425		19.0	372.0	11.7	54.9	55
sieve (g) :	364.5	13.2	316.0	9.9	45.1	45
Passed thru 0.425 sieve		4.75	412.0	12.9	32.1	32
after sift process(g) :	15.0	2.0	195.5	6.1	26.0	26
Total passed thru 0.425		0.425	364.0	11.4	14.6	15
sieve + wash (g) :	447.5	0.075				6

G.M. = 2.53

REPORT END

Technical Signatory: D van Vreden

Central University of Technology, Free State

APPENDIX D

PLANT USED

	ANNEXURE 12 : PLANT ON SITE	REHABILITATION OF ROAD P3/4(N12) FROM R503CTO ARCHBISHOP DESMOND DUDU STREET

de Bruin and associates

CONTRACTOR : MAKALI PLANT AND CONSTRUCTION (Pty) Ltd

No.	DESCRIPTION	Number of Month Ending						REMARKS
		1-Jun-17	1-Jul-17	1-Aug-17	1-Sep-17	1-Oct-17	1-Nov-17	
1	**MAKALI PLANT**							
2	140H Grader	1	2	2	2	2	2	
3	12 ton Roller	1	3	3	3	3	3	
4	Diesel Bowser	1	1	1	1	1	1	
5	10m3 Tipper Truck	1	1	1	1	1	1	
6	18 000lt Water Cart	0	2	3	3	3	3	
7	Bakkie	2	3	3	3	3	3	
8	7ton Flat-back-truck	1	2	2	2	2	2	
9	TLB's	1	2	3	3	1	2	
10	24 m3 Tipper truck					1	3	
11								
12								
	SUB CONTRACTOR'S PLANT							
1	Reclaimer	0	1	1	1	1	1	
2	Milling Machine	0	1	0	1	0	0	
3	Dozer	0	1	0	0	0	0	
4	Pnematic Roller	0	0	1	1	2	2	
5	14m3 Tipper	0	0	1	1	2	2	
6	24m3 Tipper trucks	0	0	8	8	2	2	
7	Prime Distributor	0	0	0	1	1	1	
8	Mechanical Broom	0	0	0	1	1	1	
9	Flat Roller					2	2	
10	Paving Machine					1	1	