Transportation Engineering 3 (2021) 100049

Contents lists available at ScienceDirect

Transportation Engineering

journal homepage: www.elsevier.com/locate/treng

Life Cycle Inventory for Pavements - A Case Study of South Africa

Sheldon A. Blaauw[a,b,*], James W. Maina[a]

[a] Department of Civil Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa
[b] Arup Group Limited, East West Building, 1 Tollhouse Hill, Nottingham, NG1 5AT, United Kingdom

ARTICLE INFO

Keywords:
Life cycle assessment
Life cycle inventory
Pavement sustainability
Carbon Dioxide equivalent
Pavement construction materials
Pavement construction processes

ABSTRACT

For many years, South African road authorities have taken measures to reduce costs of road construction, vehicle operating costs as well as road fatalities while enhancing road performance to improve the sustainability of pavement infrastructure. These efforts have commonly been realised through reducing economic costs evaluated using life cycle cost analyses (LCCAs). However, efforts to address sustainability are incomplete if environmental and social impacts are not considered. A life cycle assessment (LCA) is an approach which can quantify the environmental and social impacts of pavement infrastructure provision. At present, no such protocol is in place in most countries including South Africa. This paper proposes a framework for the development of an LCA model, by documenting the life cycle inventory (LCI) for common pavement materials and construction activities.

This LCI acts as a building block to the LCA by evaluating primary flows related to the supply chain of pavement materials and construction activities in South Africa. The primary flows are represented by indicators which quantify impacts, including key indicators for emissions to air and water, energy- and water-use. The LCI further provides indicators for novel and recycled materials which may greatly assist in evaluating the sustainability of pavement options. A worked example is provided to demonstrate implementation of the LCI.

The approach is envisioned to function as the first version of a living protocol that will be improved on through further research. Although the primary target audience is South African road authorities, the approach can be adapted for any country.

1. Introduction

Road pavements are constructed of bulk raw materials such as aggregate, cement, bitumen and water. The economic, environmental and social impacts of the materials and processes should be quantified and monitored towards the optimisation of the pavement design. At present, no such protocol is in place in most countries including South Africa. The need was identified to develop a holistic life cycle assessment (LCA) model of the effects of alternative pavement designs and technologies in terms of construction, maintenance and rehabilitation. A life cycle inventory (LCI) is the first step in the development of such an LCA.

The LCI analysis phase consists of the tracking of flows (inputs of materials, resources, energy, outputs of waste, pollution and co-products) which are represented by indicators for the system being studied [1]. For a typical asphalt plant, the indicators are listed in the inventory in terms of energy use, the use of materials such as aggregates, bitumen, cement and water and the production of various pollutants. These are referred to as the primary data sources for an LCI, which are to be traced back to their origin, known as the background data processes [1].

For pavement aggregates, the background data processes involve blasting and extraction processes whereas for energy, they may include delivering the aggregates to the place processing and crushing the aggregates. Due to the influence of the background data processes, it is important to develop inputs to an LCI regionally and consider the typical practices and available resources in that region. It is often challenging collecting reliable information for regions which do not voluntarily publish data regarding the processes or resources used to produce pavement materials. In these situations, published data sets (either commercial sources or from literature) are often utilised. The issues related to the use of default data were observed in the early years of development of pavement LCI [2] when studies were rapidly published and had numerous flaws. These flaws commonly manifested as poor-quality data, gaps in research being filled by default data and a general lack of consideration for location-specific evaluations.

Certain inventories are often viewed as ‘golden black boxes’ [3] and applied without much appreciation for inherent limitations in the inventories. Considering the widely cited Eurobitume inventory, originally published in 2012 [4] and revised in 2020 [5]. The inventory has vary-

---

[*] Corresponding author at: Department of Civil Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa.
E-mail address: sheldon.blaauw@arup.com (S.A. Blaauw).

https://doi.org/10.1016/j.treng.2021.100049
Received 13 October 2020; Received in revised form 29 December 2020; Accepted 14 January 2021

ing embodied Carbon Dioxide factors applied to certain elements of the inventory between the two data sets, with up to 50% differences in some instances. This highlights the impacts of the lack of quality data on predictions. An additional flaw present in LCI models is the inconsistency in selecting indicator categories; where energy and Carbon Dioxide emissions are typically focused on with other important indicators such as water use being omitted [6]. Focus on a holistic inventory which incorporates both environmental and social related indicators, as demonstrated by Bressi et al. [7], is required.

Supporting the need to quantify these indicators, Giunta et al. [8] demonstrates the contributions of various pavement life cycle phases (excluding the use phase emissions related to road users) to the total energy and carbon footprint estimates for a typical pavement project. Giunta et al. [8] found that the production phase generally accounted for more than 50% of the total energy and emissions related to pavement development, with bitumen production being the leading contributor.

1.1. Relevance to international audience

The inventory detailed in this study is specific to South Africa, but the approach presented can be customised to any country. This approach follows the notion that sustainability is spatially dependent and influenced by local boundaries [9]. The research highlights the typical processes during production of materials and construction of road pavements and the common constraints experienced in the development of an LCI for these processes. The need to develop country-specific inventories is demonstrated through data validation and sensitivity analyses, to highlight key factors affecting estimates and support conclusions and recommendations.

The research details the LCI for various materials and construction activities (i.e. inventory items) required to construct and maintain road pavements in South Africa. This inventory uses the energy requirements to either produce the materials or carry out the construction activities as the key indicator input. The secondary indicators, discussed in later sections, are then calculated using South African specific electricity generation and fuel consumption data. The developed approach is then easily adaptable to any country by introducing country specific electricity generation as well as energy requirements and fuel consumption data. Furthermore, the results presented in this paper may also act as default data for any country specific inventories where certain key input variables are not available.

2. Methodological framework

The methodological framework implemented in this study is that specified by the International Organisation for Standardisation (ISO) standard 14040 [10] for the development of an LCA. As this study only aims to develop an LCI, certain steps of ISO 14040 [10] are omitted. Fig. 1 shows the ISO 14040 [10] framework, with the steps which are implemented in this study highlighted in blue (steps 1 to 5), and the steps omitted highlighted in grey (steps 6 to 8). Further details regarding each step are provided in subsequent sections.

2.1. Objective and scope

The objective of this study is to provide an LCI for leading materials used in the provision of road pavement infrastructure in South Africa. ISO 14040 [10] was used as a guide in the development of the LCI. The LCI is intended to act as a building block for the development a holistic LCA model for road pavement infrastructure in South Africa.

The scope of the study considers a ‘cradle-to-grave’ scenario but exclude the use phase emissions related to road users, for the development of any road pavement in South Africa. The LCI provides indicators for emissions, energy- and water-use. Certain uncommon alternative materials, such as the use of nano-modifiers (organosilanes) are introduced in this study to demonstrate how the implementation of these alternative materials may improve the sustainability of road pavements in South Africa.

2.2. Functional unit and system boundaries

The functional unit (FU), representing the reference unit used to quantify performance of the indicators, is one-tonne of product depending on the relevant pavement layer considered. For construction, maintenance and demolition activities, the FU is either one square- or cubic-meter, or one tonne-km transported. This study comprises all the processes and activities related to raw material sourcing, material production, construction activities, maintenance and end-of-life of a pavement for a cradle-to-grave approach. The system boundaries include the following steps, shown in Fig. 2:

1. Raw material extraction.
2. Material processing and production.
3. Construction.
4. Maintenance.
5. Recycling; and
6. Transportation between phases.

Allocation procedures specified in ISO 14040 [10] are not performed in this study.

2.3. Indicators

For this study, the following indicators are used:

- Energy use (MJ/t) – Key input variable
- Carbon Dioxide emissions (kg CO_2e/t)
- Water use (l/t)
- Emissions to water (kg PAHs/t)
- Sulphur Dioxide emissions (kg SO_2/t)
- Nitrogen oxides emissions (kg NOx/t)
- Particulate Matter emissions (kg PM_{10}/t)
- Volatile Organic Compounds emissions (kg VOC/t)

This inventory focuses on the main construction materials used in South Africa. These materials cover most indicator factors for many pavement construction and maintenance projects in South Africa.

In sourcing data, this study has focused only on energy requirements for processes and activities related to pavement materials. The reason being energy generation in South Africa is typically accepted to be more environmentally damaging than many other countries. The Cape Town-based Centre for Environmental Rights [11] states that the emissions generated by Eskom, which is the state-owned utility company in South Africa, during electricity production are often multiples of those recommended by the World Health Organisation [12]. As such, energy requirements are used to derive factors for other environmental and social impact categories in this study to allow indicators to be more representative of South Africa.

Data quality indicators (DQIs) are used in this study to assess the quality of data collected according to the applicable ISO 14040 [10] guidance. To do this, a relevant data quality matrix [13] is used and applied to all data in this study. The data quality matrix utilised together with the scores of each inventory item (i.e. material or construction activity) listed in this paper are presented in the supplementary information. DQI scores, for items where multiple DQIs are used, are calculated as the average of the various DQIs assigned to that inventory item. For instance, the DQI score for organosilanes (DQI = 76%) is calculated as the average of the DQI scores for Eskom [20] (DQI = 80%) and Silicones Europe (DQI = 72%). Reference to the DQIs used for each item is provided at the end of each inventory item throughout this paper, using the corresponding Roman numeral numbers as listed in the supplementary information.

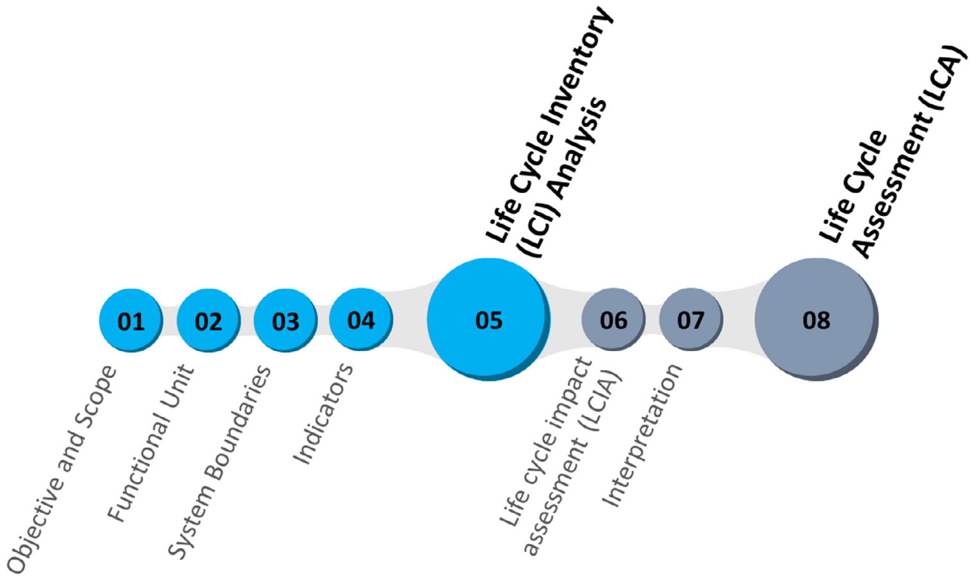

Fig. 1. Methodological framework for LCI development in South Africa.

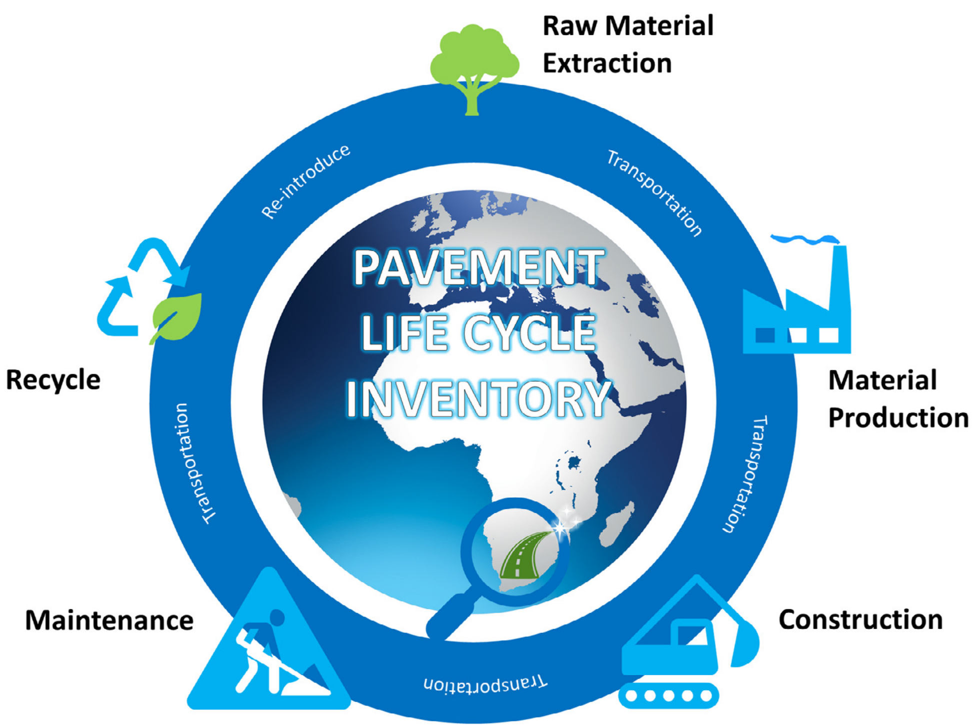

Fig. 2. System boundaries of the assessed system.

2.4. Emissions

This study focuses on two separate types of emissions, namely environmental and social emissions. Environmental emissions are “greenhouse” gasses (GHGs) affecting climate, covered under the Kyoto protocol, such as Carbon Dioxide and methane [14]. Emissions to water are also covered under environmental emissions. Social emissions are those that predominantly affect human health such as Sulphur Dioxide (SO_2), Nitrogen Oxides (NO_x), Particulate Matter (PM) and Volatile Organic Compounds (VOCs) [12].

2.4.1. Environmental emissions

To measure the environmental impact of pavement infrastructure provision, it is important to understand the various terms used to define it and its effect on the environment, such as “GHG”, “CO_2”, “CO_2e”, and “carbon” as these terms may often be used interchangeably, and their meaning may become confusing [15].

A GHG is any gas in the atmosphere which adds to the greenhouse effect by absorbing and re-emitting heat, increasing the temperature of the planet above what it would normally be. CO_2 is the most common GHG emitted from human activities in terms of quantity and total global warming potential (GWP). The GWP indicates the amount of warming a gas causes over several years (typically 100 years). CO_2e is a term used to describe the collection of GHGs in a common unit. For any quantity or type of GHG, CO_2e signifies its equivalent CO_2 and the GWP impact on the atmosphere. Embodied carbon refers to the CO_2e associated with the non-operational phase of the project. This includes the emissions caused by the extraction, manufacturing and production of material, transportation, construction, maintenance, rehabilitation, deconstruction, disposal and end of life aspects which make up the materials of a road pavement. The whole life carbon of road pavement infrastructure is both the embodied carbon and the CO_2e associated with the use (i.e. operational) phase of the pavement [14,15].

An additional source of pollution as a result of the provision of road pavement infrastructure is emissions to water. Emissions to water include diesel and oil, harmful chemicals, paints, solvents and cleaners, construction debris and dirt, and polycyclic aromatic hydrocarbons (PAHs). These emissions are caused by, among others, material extraction, production and construction processes and activities. Surface water run-off is a leading pathway for these pollutants with receptors typically including lakes, rivers, streams, groundwater and bays [16]. When the pollutants enter water sources, they poison the water life as well as any animal or human which drinks from them. This study focuses on PAHs and Nitrogen (represented by NOx in this study) as indicators of the emissions to water.

PAHs are produced by the burning of crude oil-based products (diesel or heating oil in this study). When diesel or heating oil is burned, a certain number of PAHs are released into the atmosphere which eventually return to the Earth's surface and can contaminate water sources. The impacts of PAHs on water sources include lung, bladder as well as skin cancer. Nitrogen can also find its way back into water sources, but in this study, it is categorised as a social emission because of its direct impact on human health. Nitrogen in water sources often leads to a process of eutrophication with the result being hypoxia of the water source [17].

Specific site contamination as a result of sediment or debris runoff, for instance, is difficult to quantify and it depends, predominantly, on the quality of contamination management practices of the specific site. As such, this study does not focus on these types of contaminations, but their importance is acknowledged and highlighted.

2.4.2. Social emissions

Emissions from the provision of road pavement infrastructure, which predominantly affect human health, include SO_2, NO_x, PM and VOCs. When these emissions are breathed in, they may cause nose, throat and airways problems, exacerbate asthma and in some cases cause cancer [12].

2.4.3. Legislation governing emissions in South Africa

The main legislation which governs these emissions in South Africa is the National Environmental Management: Air Quality Act (AQA) [18]. The act forms the framework for the control of air pollution and sets the limits on the air emissions for specific activities and processes. According to section 29 of the AQA, any production process with over 0.1 Megatonnes of CO_2e emissions annually is required to provide a pollution prevention plan to the Minister for approval. The processing of crude oil at a refinery requires an Atmospheric Emission License. Defined emission limits (taken as daily averages) are provided for refineries in South Africa under the AQA. These emission limits are 20 tonne/day for SO_2, 4 tonne/day for NO_x and 1 tonne/day for PM.

2.5. Energy

This study considers two sources of energy in the production of materials as well as construction, maintenance and demolition of the road pavement infrastructure. These sources are electricity and diesel.

South Africa obtains its electricity from Eskom, which uses a variety of methods to produce electricity, of which coal is the predominant source. Renewable energy is used to supplement electricity supply and occasionally diesel generators are required when the utility company cannot provide enough electricity or when maintenance is required on old infrastructure with large backlogs [11]. As a result of these factors, among others, Eskom is not considered to be an environmentally friendly provider of electricity to the nation and as such, the indicator factors for electricity production in South Africa are often higher than most other countries.

The diesel fuel and engines used in South Africa are assumed to generally conform to the requirements of Euro V diesel [19] and indicator factors utilised in this study are those of Euro V using typical corresponding calorific values. The indicator factors for electricity production [20] and diesel combustion [19,21] are shown in Table 1.

2.6. Water

Water use may be classified as a non-renewable material [22] and is primarily needed during material extraction and compaction of pavement layers, especially granular layers. The quality of the water used for both processes generally needs to be of a near potable or 'drinkable' quality [23,24], as contaminated water may lead to accelerated weathering of aggregate, among other concerns.

'Drinkable' quality water in South Africa is arguably rare, and its availability for use in road pavement construction, especially in rural areas, is a serious challenge. The recent Blue Drop report released by the Department of Water and Sanitation of South Africa [25] reported that only 44 out of 1036 municipal drinking water systems complied with Blue Drop standards. This is a notable decline from the previous Blue Drop report. Verlicchi and Grillini [26] state that South African rural populations typically do not have access to safely managed water, with the situation predicted to greatly worsen in coming years. It has become common practice for these populations to rely on untreated surface and groundwater sources.

Given the state of water availability and quality in South Africa, the use of treated water in road pavement construction is an unjustifiable requirement. Having recognised this, the updated Committee of Transport Officials [27] standard water quality requirements for pavement construction have been considerably relaxed, with key specifications reproduced in Table 2.

A review of recent dam, lakes and river water quality data, consisting of over 70,000 samples taken for the period 1999–2012 by the Department of Water Affairs in South Africa [28], shows that the quality of raw water found across South Africa conforms to the water quality requirements [27] for earthworks and pavement layer construction. The results are summarised in Table 3.

Given that most raw (i.e. untreated) surface water in South Africa conforms to the requirements for use in pavement construction, treated water is essentially only required to produce bitumen emulsion and concrete.

Energy requirements for water treatment in South Africa were reported by Swartz et al. [29], with an average of 0.4 MJ/t water required. Other indicator factors, including the water required for electricity generation, are obtained from Eskom [20]. Indicator factors for water treatment to a near potable quality in South Africa are shown in Table 4.

The energy required and associated indicator factors for collecting and distributing raw water during construction are presented in Table 16 later in this paper. These factors per tonne raw water are relatively low compared to treated water and other activities required to construct or maintain a pavement. As such, this study does not provide indicator factors for raw water, but rather focuses on the volume of water used during construction and provides practical methods to reduce consumption. As stated by Steyn and Paige-Green [22], a layer kilometre generally requires between 150 and 200 thousand litres of water for compaction, equating to between 20.83 and 27.79 l/m^2 per compacted layer in South Africa. Although much of this water will evaporate and return to the Earth's surface in the form of precipitation or form part of the surface or groundwater flows, it is a long process and local depletion of water can occur rapidly; especially in water scarce areas and areas under threat of becoming drier due to climate change. Injudicious water use for construction may effectively reduce the natural capital of an area and as such, it is difficult to justify the use of both treated and untreated water in relatively arid areas, where the local population struggle to meet their own daily water needs [22].

Table 1
Indicator factors for generation of one megajoule of energy in South Africa.

Indicator	Unit	Electricity	Diesel
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/MJ	0.297	0.075
Water Use	l/MJ	0.41	0.00
Emissions to Water	kg PAHs/MJ	0.00	1.86E−09
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/MJ	2.52E−03	3.59E−05
Nitrogen Oxides Emissions	kg NOx/MJ	1.21E−03	6.78E−04
Particulate Matter Emissions	kg PM_{10}/MJ	1.00E−04	7.93E−04
Volatile Organic Compounds Emissions	kg VOC/MJ	0.00	4.56E−05
DQI		80%	92%
DQI Reference		IV	III, V

Table 2
Construction water for earthworks and pavement layers in South Africa (Table A4.1.5-19) [27].

Purpose	Electric Conductivity at 25°C (maximum)	Total Dissolved Solids (TDS) (maximum)	pH range at 25°C
Crushed stone base layer compaction and slush - compaction	170 mS/m	1200 mg/l	5.0–9.7
Chemical stabilization compaction and curing	170 mS/m	1200 mg/l	5.0–9.7
Bituminous stabilization	170 mS/m	1200 mg/l	5.0–9.7
Other layers and materials	370 mS/m	2400 mg/l	4.0–10.0

Table 3
Average raw water quality for dams, lakes and rivers in South Africa (1999-2012) [28].

	Electric Conductivity at 25 °C	Total Dissolved Solids (TDS)	pH range at 25 °C
Dams and lakes	38.5 mS/m	251.5 mg/l	8.0
Rivers	74.6 mS/m	487 mg/l	7.9

Table 4
Indicator factors for treatment of one-tonne water in South Africa.

Indicator	Unit	Treated water
Environmental Related Indicators		
Carbon Dioxide Emissions	kg CO_2e/t	0.12
Energy Use	MJ/t	0.4
Water Use	l/t	1000.16
Emissions to Water	kg PAHs/t	0.00
Social Related Indicators		
Sulphur Dioxide Emissions	kg SO_2/t	1.01E−03
Nitrogen Oxides Emissions	kg NOx/t	4.84E−04
Particulate Matter Emissions	kg PM_{10}/t	4.00E−05
Volatile Organic Compounds Emissions	kg VOC/t	0.00
DQI		80%
DQI Reference		IV, VI

Table 5
Water requirements for granular layer compaction in South Africa.

Layer	Unit	Water requirement
Crushed stone G1 base	l/m^2	27.79
All other layers	l/m^2	20.83

This study makes a conservative assumption that the higher threshold value is equivalent to the water requirements for the slush-compaction process of a crushed stone G1 base layer, and that the lower threshold value is equivalent to the water requirements for all other granular pavement layers, as summarised in Table 5.

It is important to note that both the use of water for, and the contamination of water as a result of, provision of road pavement infrastructure, should be a leading concern to road authorities both in South Africa and globally. Practical methods to reduce consumption and contamination should be sought.

2.7. Organosilane

One of these practical methods is presented by Steyn and Paige-Green [22], where water use can be considerably reduced using nano-silanes, referred to as organosilanes in this study. The main aim of the organosilane is to redirect the energy produced during the salt crystallization process to nurture new bonds (similar to cement bonds) rather than having their natural destructive forces accelerate the deterioration of aggregates.

A new generation of organosilanes has been developed and successfully trialled in South Africa [30] that interact with the free energy surrounding the natural material molecules. This interaction rearranges the surface atom arrangements of the aggregate and helps to drastically reduce the susceptibility of the aggregates to water and make the aggregates water-repellent.

Working with the Council for Scientific and Industrial Research (CSIR), Jordaan et al. [31] further studied the use of organosilanes in South Africa. The study looked at the impacts of organosilane modified emulsions in improving the material properties of lower quality locally available aggregates (as compared to sourcing high quality commercially sourced crushed stone). The study found that the organosilanes successfully improved the strength characteristics of the lower quality aggregates and reduced the susceptibility of the aggregates to moisture-induced deterioration; allowing for the use of locally available material to meet the same strength requirements as sourced crushed stone.

A further study [32] considered the use of organosilanes as a stabilising agent on dolomite, a material known as a 'problem' soil in South Africa due to its susceptibility to weathering in the presence of water. The study showed that the organosilane stabiliser improved the properties of the dolomite, reduced the Plasticity Index, and in doing so the moisture in the material acted as a lubricant, reducing the required compaction effort and overall reduced the moisture sensitivity of the dolomitic material. The before mentioned research has already helped alleviate the effect of water use on the environment and society and increased the sustainability of pavements in South Africa.

Table 6
Indicator factors to produce one-tonne organosilane in South Africa.

Indicator	Unit	Organosilane
Environmental Related Indicators		
Carbon Dioxide Emissions	kg CO_2e/t	1260.82
Energy Use	MJ/t	6,398.34
Water Use	l/t	1442.83
Emissions to Water	kg PAHs/t	5.36E−06
Social Related Indicators		
Sulphur Dioxide Emissions	kg SO_2/t	8.97
Nitrogen Oxides Emissions	kg NOx/t	6.21
Particulate Matter Emissions	kg PM_{10}/t	0.35
Volatile Organic Compounds Emissions	kg VOC/t	0.00
DQI		76%
DQI Reference		IV, VII

Table 7
Indicator factors to produce one-tonne bitumen in South Africa.

Indicator	Unit	Bitumen[a]
Environmental Related Indicators		
Carbon Dioxide Emissions	kg CO_2e/t	221.89 (233.36)
Energy Use	MJ/t	2201.4 (2240.00)
Water Use	l/t	681.61 (688.68)
Emissions to Water	kg PAHs/t	2.61E−07 (2.61E−07)
Social Related Indicators		
Sulphur Dioxide Emissions	kg SO_2/t	1.13 (1.23)
Nitrogen Oxides Emissions	kg NOx/t	2.51 (2.56)
Particulate Matter Emissions	kg PM_{10}/t	0.03 (0.03)
Volatile Organic Compounds Emissions	kg VOC/t	0.68 (0.68)
DQI		80%
DQI Reference		II

[a] Values in brackets represent inland scenario, with remaining values representing coastal scenario.

To determine the indicator factors for a typical organosilane used in gravel stabilisation, a conservative approach was followed. Production energy requirement data produced by Silicones Europe [33] for a similar organosilane-based stabiliser was utilised, with an average energy requirement of 6398 MJ/t. Other indicator factors, including the water required for electricity generation, are obtained from Eskom [20]. The indicator factors to produce a one-tonne organosilane are shown in Table 6.

2.8. Bitumen products

For bitumen, four products are considered in this study, namely:

- Paving-grade bitumen - baseline data obtained from Blaauw et al. [13].
- Polymer modified bitumen (PMB).
- Cut back bitumen; and
- Bitumen emulsion.

Indicator factors for typical paving-grade bitumen used in South Africa are sourced from Blaauw et al. [13], shown in Table 7. Using these estimates, inventories for other materials in which paving-grade bitumen is used can be produced.

2.9. Polymer modified bitumen

Using the data produced by Blaauw et al. [13] as baseline data, together with Eurobitume [4] estimates, typical indicator factors for PMB may be calculated. PMB is commonly used in South African pavement construction to provide effective solutions in certain situations. Various modifying agents are available, of which the most commonly used are homogenous Styrene-butadiene-styrene (SBS) modifiers [34] in pellet form. PMB is produced by mixing bitumen with the SBS modifier and pumping the mixture through a high shear mill to blend the SBS pellets. Estimates for the production of SBS are obtained directly from Boustead and Cooper [35]. To determine the impact of material transportation, values provided by Stipple [36] for fuel consumption and energy use are utilised. One truck size (14 ton) is considered for SBS transportation. It is assumed that the production of PMB occurs at the same refinery where bitumen is produced and that SBS polymer is transported 50 km from an external supplier to the refinery. Estimates for the energy use of PMB milling are provided by Eurobitume [4]. Using these data, typical indicator factors are calculated, shown in Table 8.

2.10. Cut back bitumen

Cut back bitumen is produced by adding controlled amounts of petroleum products, commonly Kerosene, to bitumen to reduce the viscosity of the product. This is done to allow for easier application of the bitumen at lower temperatures relative to conventional bitumen application. Cut back bitumen is often used as a prime coat on newly-constructed crushed stone or natural gravel base courses before construction of a surfacing layer; or as a tack coat in grit seals, sand seals, otta seals and single seals for lightly trafficked roads. In South Africa, three grades of (medium curing) cutback bitumen are available, namely [34]:

- MC10,
- MC30, and
- MC3000.

Kerosene is produced using the same distillation process required for the refinery of bitumen from crude oil. No quality data exists to the difference in energy use required for Kerosene production and this study assumes that Kerosene has the same indicator factors as bitumen for production. As such, the indicator factors for cut back bitumen are the same as paving-grade bitumen, summarised in Table 7.

2.11. Bitumen emulsion

Bitumen emulsions are a two-phase system consisting of water containing an emulsifier with a dispersion of bitumen droplets. Emulsification of bitumen is a process which aims to reduce the viscosity of a binder to resemble properties of fluid during handling and application. Emulsifiers generally consist of between 60% and 70% bitumen and 30% to 40% emulsified water by mass. Bitumen emulsions are commonly available in two classes [34]:

- Cationic, and
- Anionic.

The production of bitumen emulsion is assumed to occur within the refinery premises including the production of the emulsifier required. This study presents factors for a cationic (positively charged) emulsion. Most aggregates used in pavement construction in South Africa, such as granite and quartzite, are negatively charged acidic aggregates [34] and as such require a positively charged bitumen emulsion for compatibility purposes. Emulsions are stored at relatively low temperatures and require no additional external heating where the only emission from storage is assumed to be water [4]. The raw material composition by mass for typical cationic emulsified bitumen is paving-grade bitumen (65%), water (34%), hydrochloric acid (0.5%) and emulsifier (0.5%).

Hydrochloric acid is obtained when hydrogen chloride is mixed with water. Hydrogen chloride may be produced through the distillation of crude oil [37], among other means. This study assumes that all hydrogen chloride is produced by the refinery on-site and that the factors related to bitumen refinery reflect similar factors for hydrogen chloride, as shown in Table 7. The emulsifier and corresponding eco-profile used for this analysis is Redicote E-9 cationic emulsion. A distance of 50 km is assumed for the transportation of emulsion to the refinery. The indicator factors related to the production of the emulsion are obtained from Eurobitume [4] using typical net calorific values for energy conversion and

Table 8
Indicator factors to produce one-tonne Polymer Modified Bitumen in South Africa.

Indicator	Unit	3% SBS Bitumen[a]	4.5% SBS Bitumen[a]	6% SBS Bitumen[a]
Environmental Related Indicators				
Carbon Dioxide Emissions	kg CO_2e/t	601.17 (612.30)	790.81 (801.77)	980.46 (991.24)
Energy Use	MJ/t	3434.79 (3472.24)	4051.49 (4088.35)	4668.19 (4704.47)
Water Use	l/t	880.75 (887.61)	980.32 (987.07)	1079.88 (1086.53)
Emissions to Water	kg PAHs/t	2.53E−07 (2.53E−07)	2.49E−07 (2.49E−07)	2.45E−07 (2.45E−07)
Social Related Indicators				
Sulphur Dioxide Emissions	kg SO_2/t	4.37 (4.46)	5.99 (6.08)	7.6 (7.7)
Nitrogen Oxides Emissions	kg NOx/t	4.01 (4.05)	4.75 (4.80)	5.5 (5.55)
Particulate Matter Emissions	kg PM_{10}/t	0.16 (0.16)	0.22 (0.22)	0.29 (0.29)
Volatile Organic Compounds Emissions	kg VOC/t	0.66 (0.66)	0.65 (0.65)	0.64 (0.64)
DQI		75%		
DQI Reference		I, II, VIII, IX		

[a] Values in brackets represent inland scenario, with remaining values representing coastal scenario.

Table 9
Indicator factors to produce one-tonne bitumen emulsion in South Africa.

Indicator	Unit	Bitumen Emulsion[a]
Environmental Related Indicators		
Carbon Dioxide Emissions	kg CO_2e/t	1411.97 (1420.00)
Energy Use	MJ/t	5770.81 (5797.83)
Water Use	l/t	2551.36 (2556.30)
Emissions to Water	kg PAHs/t	2.05E−07 (2.05E−07)
Social Related Indicators		
Sulphur Dioxide Emissions	kg SO_2/t	11.44 (11.51)
Nitrogen Oxides Emissions	kg NOx/t	6.88 (6.91)
Particulate Matter Emissions	kg PM_{10}/t	0.43 (0.43)
Volatile Organic Compounds Emissions	kg VOC/t	0.48 (0.48)
DQI		82%
DQI Reference		I, IV

[a] Values in brackets represent inland scenario, with remaining values representing coastal scenario.

related emissions obtained from Eskom [20]. Further key steps required to produce bitumen emulsion are water heating and high shear milling of emulsions. This study assumes that water is heated from 10°C to 40°C and the energy required for this process is 125.57 MJ/t according to the specific heat capacity of water. The energy required to operate the high shear mill is the same as for PMB production. The indicator factors to produce bitumen emulsion are shown in Table 9. A notable observation made from Table 9 is that bitumen emulsion uses three times as much water as normal bitumen production.

2.12. *Aggregates*

The three categories of aggregates typically used in South African pavement construction are crushed stone, as well as construction sands and gravels (referred to collectively as natural aggregates in this study [38]. Crushed stone is defined as aggregates taken from hard rock, through methods such as blasting, and are then crushed to the desired size. Natural aggregates (sands and gravels) are commonly mined from alluvial deposits (i.e. pit run). A fourth uncommonly used category exists in which aggregates are manufactured to possess specific properties and characteristics, such as the combination of shale and clay to create light-weight aggregates. These types of aggregates are not considered in this study.

To obtain the various indicator factors for aggregate production in South Africa, an average energy requirement from various international sources was used [36,39-47]. These data are assumed to represent similar processes and environments relevant to South Africa. A split of 1:1.25 is used for the energy differences between diesel and electricity, respectively [36], with calorific values and electricity generation factors obtained following the steps of previous analyses. The stages of production considered for crushed stone are material extraction, transport and three stages of crushing. The stages of production considered for natural aggregates are material extraction and transportation. Average indicator factors to produce one-tonne of crushed stone and natural aggregate are shown in Table 10.

When considering recycled demolition aggregates typically obtained from existing unbound granular layers, energy-, emission- and water-savings are realised through the reduced need to excavate and transport the material to the site. To calculate these savings, a construction scenario has been utilised where the savings are calculated including only a 5 km site transport distance. The density of loose demolition aggregate is taken as 1750 kg/m^3. The resulting savings are calculated as 15%, with a 5% material spoil by volume included in the calculations. It is assumed that the recycled demolition aggregates won from the existing pavement structure generally conform to the natural aggregate material requirements of COTO [27]. Use of demolition aggregates for crushed stone layers is not advisable [27]. Table 11 shows the indicator factors for typical demolition aggregates in South Africa.

2.13. *Cement and lime*

Cement and lime are typically used in South African pavement construction to stabilise granular pavement layers. Stabilisation may be required for a variety of reasons, including to modify the properties of poor-quality (marginal) or deleterious material and to increase the bearing strength of compacted layers. The production of cement and lime is generally localised to Gauteng, with scattered plants in Durban, Kimberley, Port Elizabeth and Cape Town [48]. Energy requirements to produce cement and lime have been obtained from various international sources [36,39-42]. These data are assumed to represent similar processes and environments relevant to South Africa. Following the steps previously described, indicator factors are calculated for typical cement and lime production in South Africa, shown in Table 12. The water used during the extraction and transportation of raw material to the processing plant to produce cement has not been investigated in detail and typical water usage values provided refer to the water used in electricity generation alone and may be an underestimate.

2.14. *Hot-, warm- and cold-mix asphalt*

Hot-, warm-, and cold-mix asphalt (HMA, WMA and CMA) are designed pre-mixes of graded aggregates and bituminous-based binders, applied on road pavements to provide a smooth and safe riding surface and protect the underlying layers [49]. Indicator factors are provided for all three of these asphalt types in this study.

To produce HMA, hot bitumen is mixed with heated aggregate, where the aggregate is typically heated using an oil burner. This study assumes the use of a medium-heavy oil [21,50] for the heating process

Table 10
Indicator factors to produce one-tonne aggregate in South Africa.

Indicator	Unit	Crushed Stone	Natural Aggregate
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/t	14.38	6.35
Energy Use	MJ/t	72.99	32.22
Water Use	l/t	16.46	7.27
Emissions to Water	kg PAHs/t	6.11E−08	2.70E−08
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/t	0.10	0.05
Nitrogen Oxides Emissions	kg NOx/t	0.07	0.03
Particulate Matter Emissions	kg PM_{10}/t	4.01E−03	1.77E−03
Volatile Organic Compounds Emissions	kg VOC/t	0.00	0.00
DQI		73%	71%
DQI Reference		IX - XVIII	IX - XIII

Table 11
Indicator factors to produce one-tonne recycled demolition aggregate in South Africa.

Indicator	Unit	Recycled Demolition Aggregates
Environmental Related Indicators		
Carbon Dioxide Emissions	kg CO_2e/t	4.4
Energy Use	MJ/t	22.33
Water Use	l/t	5.04
Emissions to Water	kg PAHs/t	1.87E−08
Social Related Indicators		
Sulphur Dioxide Emissions	kg SO_2/t	0.03
Nitrogen Oxides Emissions	kg NOx/t	0.02
Particulate Matter Emissions	kg PM_{10}/t	0.00
Volatile Organic Compounds Emissions	kg VOC/t	0.00
DQI		71%
DQI Reference		IX-XIII

Table 12
Indicator factors to produce one-tonne cement/lime in South Africa.

Indicator	Unit	Cement	Lime
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/t	927.54	47.88
Energy Use	MJ/t	4707.00	243.00
Water Use	l/t	1061.43	54.80
Emissions to Water	kg PAHs/t	3.94E−06	2.03E−07
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/t	6.60	0.34
Nitrogen Oxides Emissions	kg NOx/t	4.57	0.24
Particulate Matter Emissions	kg PM_{10}/t	0.26	0.01
Volatile Organic Compounds Emissions	kg VOC/t	0.00	0.00
DQI		76%	79%
DQI Reference		III – V, IX-XII, XVIII	III-V, X

with a mix design of 6% bitumen content. The energy requirements are predominantly met by medium-heavy heating oil (90%) and electricity (10%). A total of 480 MJ is assumed to be required for the HMA production process, including heating, mixing and other peripheral activities [36,51,52]. Calorific values [21] and relevant factors [50] are obtained following the steps previously described. Table 13 provides the indicator factors to produce one-tonne HMA both inclusive and exclusive of bitumen and aggregate indicator factors. A transport distance of 50 km is assumed for both bitumen and aggregate.

To produce WMA, the energy requirement was simply reduced by 30% compared to HMA [53]. Table 14 provides the indicator factors to produce one-tonne WMA both inclusive and exclusive of bitumen and aggregate indicator factors. A transport distance of 50 km is assumed for both bitumen and aggregate.

To produce CMA, an energy requirement was obtained from Lundberg et al. [51]. The remaining data were obtained following the steps previously described. Table 15 provides the indicator factors to produce one-tonne CMA both inclusive and exclusive of bitumen and aggregate indicator factors. A transport distance of 50 km is assumed for both bitumen and aggregate.

2.15. *Construction and demolition operations*

The energy usage and related emissions for general construction and demolition operations are considered in this LCI. The LCI accounts for most of the typical activities required to construct and demolish a road. The typical activities include loading, excavating, dumping, compacting, paving and general activities such as applying tack coat, spraying water and sweeping. Typical energy requirements were obtained from Stripple [36] and Wang et al. [54]. Typical emission values were obtained from EEA [19] and UN – ESY [21] following the steps previously described. Average indicator factors for these construction activities in South Africa are shown in Table 16 and Table 17. Various assumptions are incorporated into these estimates to reflect the most experienced construction conditions. These assumptions are shown in the supplementary information. The estimates were obtained from various sources and do not necessarily represent the view or findings of the respective companies referenced. Further research is required to provide a broader range of activities accounting for a wider range of plant machinery. For transportation of one kilometre, fuel consumption requirements for a general 14-ton short distance hauler and a 32-ton long-distance

Table 13
Indicator factors to produce one-tonne HMA in South Africa.

Indicator	Unit	HMA Production Process	HMA[a]
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/t	39.34	69.36 (70.06)
Energy Use	MJ/t	480	723.20 (725.51)
Water Use	l/t	19.68	76.05 (76.47)
Emissions to Water	kg PAHs/t	8.04E−07	9.56E−07 (9.56E−07)
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/t	0.27	0.43 (0.44)
Nitrogen Oxides Emissions	kg NOx/t	0.28	0.50 (0.50)
Particulate Matter Emissions	kg PM_{10}/t	5.14E−03	0.01 (0.01)
Volatile Organic Compounds Emissions	kg VOC/t	3.16E−04	0.04 (0.04)
DQI		79%	79%
DQI Reference		IV, V, IX, XIX, XX, XXI	II, IV, V, IX, XIX, XX, XXI

[a] Values in brackets represent inland scenario, with remaining values representing coastal scenario.

Table 14
Indicator factors to produce one-tonne WMA in South Africa.

Indicator	Unit	WMA Production Process	WMA[a]
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/t	27.54	48.55 (49.04)
Energy Use	MJ/t	336	506.24 (507.86)
Water Use	l/t	13.78	53.23 (53.53)
Emissions to Water	kg PAHs/t	5.62E−07	6.69E−07 (6.69E−07)
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/t	0.19	0.30 (0.31)
Nitrogen Oxides Emissions	kg NOx/t	0.2	0.35 (0.35)
Particulate Matter Emissions	kg PM_{10}/t	3.60E-03	0.01 (0.01)
Volatile Organic Compounds Emissions	kg VOC/t	2.53E-04	0.03 (0.03)
DQI		79%	79%
DQI Reference		IV, V, IX, XIX, XX, XXI	II, IV, V, IX, XIX, XX, XXI

[a] Values in brackets represent inland scenario, with remaining values representing coastal scenario.

Table 15
Indicator factors to produce one-tonne cold mixed asphalt in South Africa.

Indicator	Unit	CMA Production Process	CMA[a]
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/t	11.06	41.79 (41.84)
Energy Use	MJ/t	135	335.7 (338.01)
Water Use	l/t	5.54	61.9 (62.33)
Emissions to Water	kg PAHs/t	2.26E−07	2.99E−07 (2.99E−07)
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/t	0.076	0.24 (0.25)
Nitrogen Oxides Emissions	kg NOx/t	0.079	0.30 (0.30)
Particulate Matter Emissions	kg PM_{10}/t	0.001	0.01 (0.01)
Volatile Organic Compounds Emissions	kg VOC/t	1.00E-04	0.04 (0.04)
DQI		79%	79%
DQI Reference		IV, V, IX, XIX, XX, XXI	II, IV, V, IX, XIX, XX, XXI

[a] Values in brackets represent inland scenario, with remaining values representing coastal scenario.

Table 16
Indicator factors for construction and demolition activities per loose cubic meter in South Africa.

Indicator	Unit	Wheel loader	Excavator	Dumper	Milling - asphalt
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/loose m^3	0.18	0.24	0.52	0.2
Energy Use	MJ/loose m^3	2.43	3.22	6.9	2.69
Water Use	l/loose m^3	0.00	0.00	0.00	0.00
Emissions to Water	kg PAHs/loose m^3	4.52E−09	5.99E−09	1.28E−08	5.00E−09
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/loose m^3	8.74E−05	1.16E−04	2.48E−04	9.66E−05
Nitrogen Oxides Emissions	kg NOx/loose m^3	1.65E−03	2.18E−03	4.68E−03	1.82E−03
Particulate Matter Emissions	kg PM_{10}/loose m^3	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/loose m^3	0.00	0.00	0.00	0.00
DQI		82%			
DQI Reference		III, V, IX, XXI			

Table 17
Indicator factors for construction and demolition activities per square meter in South Africa.

Indicator	Unit	Compactor - soil	Compactor - asphalt	Compactor – asphalt (pneumatic)	Paver
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/m^2	0.04	0.06	0.04	0.05
Energy Use	MJ/m^2	0.6	0.79	0.48	0.66
Water Use	l/m^2	0.00	0.00	0.00	0.00
Emissions to Water	kg $PAHs/m^2$	1.11E−09	1.46E−09	8.84E−10	1.23E−09
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/m^2	2.14E−05	2.82E−05	1.71E−05	2.37E−05
Nitrogen Oxides Emissions	kg NOx/m^2	4.04E−04	5.33E−04	3.22E−04	4.47E−04
Particulate Matter Emissions	kg PM_{10}/m^2	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/m^2	0.00	0.00	0.00	0.00
DQI		82%			
DQI Reference		III, V, IX, XXI			
Indicator	Unit	Grader	Concrete sawing and sealing	Concrete milling	General activity
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/m^2	0.01	0.04	5.52	0
Energy Use	MJ/m^2	0.12	0.5044	73.7	7.54E−03
Water Use	l/m^2	0.00	0.00	0.00	0.00
Emissions to Water	kg $PAHs/m^2$	2.23E−10	9.38E−10	1.37E−07	1.40E−11
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/m^2	4.31E−06	1.81E−05	2.65E−03	2.71E−07
Nitrogen Oxides Emissions	kg NOx/m^2	8.13E−05	3.42E−04	5.00E−02	5.11E−06
Particulate Matter Emissions	kg PM_{10}/m^2	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/m^2	0.00	0.00	0.00	0.00
DQI		82%			
DQI Reference		III, V, IX, XXI			

Table 18
Indicator factors for transportation of one-tonne-kilometre in South Africa.

Indicator	Unit	14-ton short distance	32-ton long distance
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/tonne-km	0.064	0.031
Energy Use	MJ/tonne-km	0.850	0.416
Water Use	l/tonne-km	0.00E+00	0.00E+00
Emissions to Water	kg PAHs/tonne-km	1.58E−09	7.73E−10
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/tonne-km	3.05E−05	1.49E−05
Nitrogen Oxides Emissions	kg NOx/tonne-km	5.76E−04	2.82E−04
Particulate Matter Emissions	kg PM_{10}/tonne-km	6.74E−04	3.30E−04
Volatile Organic Compounds Emissions	kg VOC/tonne-km	3.88E−05	1.90E−05
DQI		82%	
DQI Reference		III, V, IX, XXI	

hauler [36] were used. Factors were obtained following the steps previously described and are shown in Table 18.

2.16. Asphalt with reclaimed asphalt pavement

Reclaimed asphalt pavement (RAP) is most often produced by milling an existing asphalt pavement and screening the material for use in a new asphalt mix or use as aggregate base. Asphalt recycling in South Africa is done by four methods: cold in-place recycling, cold in-plant recycling, hot in-place recycling, and hot in-plant recycling [55].

This study considers two scenarios: cold- and hot-in plant recycling, corresponding to conservative scenarios, to calculate the energy requirements and associated indicator factors to produce one-tonne of asphalt with RAP. Warm in-plant recycling is not covered by Manual 36/TRH21 [55] and as such not considered in this study. The mixture contains 22% RAP by weight for a mix design of 6% bitumen content, representing a common mix design implemented in South Africa [55]. This mix design aims to act as a benchmark scenario, but designers may design their own mixtures and calculate corresponding indicator factors using the inventory provided in this study.

Indicator factors to produce one-tonne of asphalt with RAP in South Africa are shown in Table 19 for an average for both inland and coastal scenarios, as the difference between scenarios is minute. These indicator factors include consideration of asphalt milling and crushing operations.

A notable observation from Table 19 is that the energy use and associated indicator factors for asphalt with RAP are between roughly 27–46% lower than their conventional asphalt counterparts.

2.17. Concrete and steel

Concrete pavements have long been used in South Africa, especially on high trafficked truck arterials linking South Africa's economic zone (Gauteng) to its harbours (Durban, Port Elizabeth and Cape Town). Using a typical energy requirement of 65.4 MJ for the mixing process of concrete and an energy split of diesel (75%) and electricity (25%), the indicator factors for pavement concrete were calculated. The mixture constituents are shown in Table 20 with indicator factors shown in Table 21. For pavement steel, indicator factors are obtained directly from the World Steel Association [56], also shown in Table 21.

3. Data validation

To validate results, a comparison may be made between the carbon equivalent emissions (used as key output variable for this analysis) of similar notable life cycle inventories for common pavement materials and construction processes. The carbon equivalent emissions indicator is selected as key output variable as most LCIs consistently report on it and it is used by most countries as a default to quantify environmental sustainability. This comparison is shown in Table 22.

Table 19
Indicator factors to produce one-tonne asphalt with RAP in South Africa.

Indicator	Unit	HMA+RAP	CMA+RAP
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/t	50.82	22.55
Energy Use	MJ/t	620.15	275.15
Water Use	l/t	25.43	11.28
Emissions to Water	kg PAHs/t	1.04E−06	4.61E−07
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/t	0.35	0.16
Nitrogen Oxides Emissions	kg NOx/t	0.36	0.16
Particulate Matter Emissions	kg PM_{10}/t	0.01	2.94E−03
Volatile Organic Compounds Emissions	kg VOC/t	4.67E−04	2.07E−04
DQI		79%	
DQI Reference		IV, V, IX, XIX, XX, XXI	

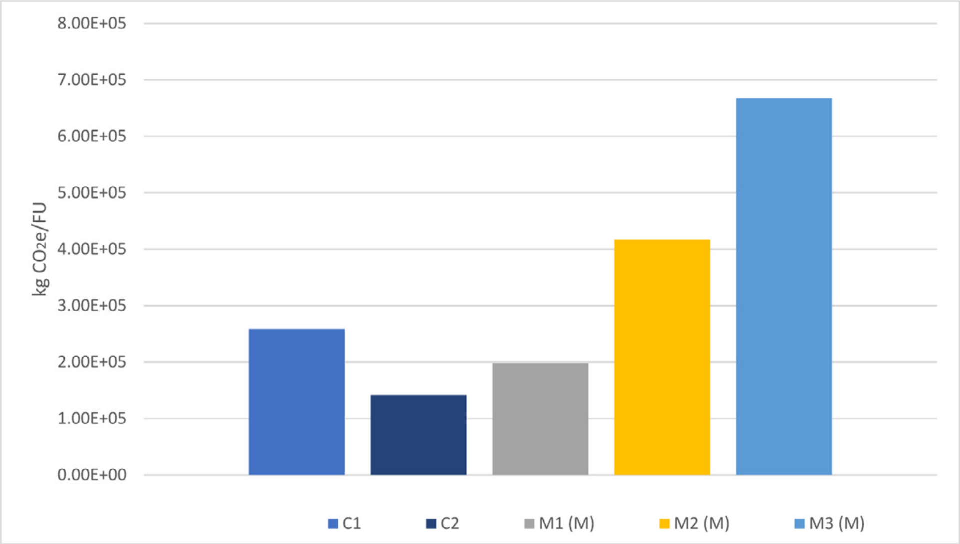

Fig. 3. Comparison of pavement option Carbon equivalent emissions.

Table 20
Basic material to produce pavement concrete.

Mixture	Weight per m^3 produced concrete (kg)
Cement	400
Crushed aggregate	1200
Put run natural aggregate	700
Water	170

What is demonstrated from these comparisons is that there is good correlation between other inventories and the results presented in this study. What is not shown in Table 22, is the general lack of consideration by many inventories to include other key indicators such as water use and the various social emissions. The inventories used for comparison each incorporate various specific assumptions, such as using energy requirements as a key input variable and utilising location specific electricity generation and fuel consumption factors used by Stripple [36]. A similar methodology has been applied to develop the inventory presented in this paper.

As previously discussed, viewing certain inventories as 'golden black boxes' often results in the use of poor-quality data, gaps in research being filled by default data and a general lack of consideration for location-specific evaluations. An additional flaw present in LCI models is the inconsistency in selecting indicator categories; where energy and carbon

Table 21
Indicator factors to produce one-tonne pavement concrete and steel in South Africa.

Indicator	Unit	Pavement concrete	Pavement steel
Environmental Related Indicators			
Carbon Dioxide Emissions	kg CO_2e/t	159	1263.6
Energy Use	MJ/t	806.89	2.00E+04
Water Use	l/t	319.61	527.9
Emissions to Water	kg PAHs/t	6.75E−07	0.00
Social Related Indicators			
Sulphur Dioxide Emissions	kg SO_2/t	1.13	2.584
Nitrogen Oxides Emissions	kg NOx/t	0.78	2.162
Particulate Matter Emissions	kg PM_{10}/t	0.04	0.8107
Volatile Organic Compounds Emissions	kg VOC/t	0.00	0.08402
DQI		76%	87%
		III – VI, IX-XII, XVIII	III-V, XXI

Table 22
Comparison of carbon equivalent emissions for common pavement materials.

LCI	Unit	Bitumen	Asphalt	Aggregate	Concrete	Steel
Eurobitume [4]	kg CO_2e/t	174.25	-	-	-	-
Eurobitume [5]	kg CO_2e/t	136.80	-	-	-	-
Stripple [36]	kg CO_2e/t	173.00	34.4	1.42	328.00	2220.00
Hammond and Jones [57]	kg CO_2e/t	191.00	53.60	17.00	152.33	1270.00
South Africa	kg CO_2e/t	**233.36**[a]	**70.06**[a]	**36.53**	**159.00**	**1263.60**

[a] Inland bitumen factors used for comparison

Table 23
Pavement design options [31].

Datum Design – C1		
Pavement Layer	**Thickness (mm)**	**Description**
Surface Course	40	Continuous graded (medium) asphalt
Tack-coat	-	Tack-coat of 30% stable-grade emulsion
Primer	-	MC 30 cut-back bitumen
Base	150	G1 crushed stone
Upper Sub-base	150	C4 Layer
Lower Sub-base	150	C4 Layer
Total Thickness	490	-
Alternative Design – C2		
Pavement Layer	**Thickness (mm)**	**Description**
Surface Course	30	A-E2 SBS modified asphalt (3%)
Tack-coat	-	Tack-coat of 30% stable-grade emulsion
Primer	-	MC 30 cut-back bitumen
Base	150	G5 + 1.2% Organosilane
Upper Sub-base	150	G5 + 0.7% Organosilane
Lower Sub-base	-	-
Total Thickness	330	-

Table 24
Pavement maintenance options over 40-year analysis period.

Maintenance Options	Year 10	Year 20	Year 30	Year 40
M1 – Proactive maintenance approach	Resurfacing	Resurfacing and replace part of the base (partial reconstruction)	Resurfacing and periodic maintenance	Resurfacing and replace part of the base (partial reconstruction)
M2 - Partial proactive/reactive maintenance approach	Resurfacing	Periodic maintenance (5% patch/year)	Full depth reconstruction	Periodic maintenance (5% patch/year)
M3 - Reactive maintenance approach	Periodic maintenance	Full depth reconstruction	Periodic maintenance	Full depth reconstruction

emissions are typically focused on with other important indicators omitted. Focus on a holistic inventory which incorporates both environmental and social indicators are important to report on and this approach has been followed during this study.

4. Life cycle inventory – worked example

To demonstrate the use of the LCI developed in this study, a worked example is provided for two pavement build-ups previously compared [31] from a cost perspective. The FU used for this analysis is a 7.2 m wide, 1 km long pavement structure. The pavement build-ups used for comparison are shown in Table 23. A maintenance regime is also proposed for evaluation and shown in Table 24 for a proactive-, partial proactive/reactive-, and reactive-maintenance approaches. The alternative design has been shown by Jordaan et al. [31] to provide an expected 30–40% cost saving. This analysis aims to not only demonstrate environmental and social benefit but also how the alternative design can assist in mitigating identified climate change risks for the region, such as an increased intensity in heat stress and drought [58].

For the analysis, it is assumed that crushed stone is obtained from a commercial source 50 km away from the project location, with bitumen-based products obtained from the Natref refinery in Sasolburg (100 km away). For the C4 and G5 layers, locally available materials are utilised with organosilane and cementitious products sourced from 50 km away. Typical construction processes and activities (e.g. material extraction, production, transport and construction) are considered for both pavement options. Compaction densities are obtained from COTO [27]. The results of the analysis are summarised in Table 25.

The results from Table 25 show that the alternative design saves between 25% and 56% on emissions, 56% on energy use and 58% on water use. The majority of the energy used and emissions generated were concentrated in the material extraction and production phases and are in line with the findings of Giunta et al. (2020); whereas the majority of the water used was in the construction phase. The water savings equate to 338,560 litres of water per pavement kilometre. Using the South African Free Basic Water Policy [59] minimum daily water requirement recommendation of 25 litres per capita per day for drinking, basic- and food-hygiene, the water savings realized from the alternative

Table 25
Life cycle analysis results for pavement construction options.

Indicator	Unit	Datum Design – C1	Alternative Design – C2	Saving for C2
Environmental Related Indicators				
Carbon Dioxide Emissions	kg CO$_2$e/FU	258,785	141,922	116,863 (55%)
Energy Use	MJ/FU	1,570,050	877,824	692,225 (56%)
Water Use	l/FU	798,717	460,157	338,560 (58%)
Emissions to Water	kg PAHs/FU	1.54E-03	8.55E-04	6.85E-04 (56%)
Social Related Indicators				
Sulphur Dioxide Emissions	kg SO$_2$/FU	1,795	1,002	793 (56%)
Nitrogen Oxides Emissions	kg NOx/FU	1,410	780	629 (55%)
Particulate Matter Emissions	kg PM$_{10}$/FU	493	123	370 (25%)
Volatile Organic Compounds Emissions	kg VOC/FU	55	26	29 (47%)

Table 26
Life cycle analysis results for pavement maintenance options over a 40-year period.

Indicator	Unit	M1	M2	M3
Environmental Related Indicators				
Carbon Dioxide Emissions	kg CO$_2$e/FU	198,070.24	417,142.42	667,497.78
Energy Use	MJ/FU	1,883,321.98	2,881,817.36	4,406,468.60
Water Use	l/FU	613,011.37	1,364,057.41	2,144,381.44
Emissions to Water	kgPAHs/FU	2.43E−03	3.16E−03	4.70E−03
Social Related Indicators				
Sulphur Dioxide Emissions	kg SO$_2$/FU	1,250.33	2,822.09	4,544.28
Nitrogen Oxides Emissions	kg NOx/FU	1,411.50	2,434.30	3,791.16
Particulate Matter Emissions	kg PM$_{10}$/FU	278.24	768.04	1,258.98
Volatile Organic Compounds Emissions	kg VOC/FU	100.60	112.75	162.08

design are equivalent to the water needs of a typical local settlement of 2,000 people for one week per kilometre pavement built.

The results from Table 26 show similar savings when the reactive maintenance approach is compared to the partial and reactive maintenance approaches. Fig. 3 summarises the results for the various construction and maintenance options presented in this worked example for a 40-year analysis period. It is noted that pavements are typically constructed with a 20-year design period in South Africa, which may be extended through a thorough proactive maintenance regime [60]. From Fig. 3 it is observed that the maintenance regimes have higher emission values compared to the initial construction, attributed to the reduced design life for pavements in South Africa. It is further seen that proactive maintenance approaches may significantly benefit the environmental sustainability of a pavement with accompanied economic and social benefit.

5. Conclusions

- The study provides an LCI for most materials, processes, and construction activities required for pavement construction and maintenance in South Africa. The inventory is summarised in Table 27 and Table 28.
- The LCI provided in this study is based on reasonable quality data and provides rational estimates for environmental and social impacts of pavement development in South Africa.
- There is a drive within South African roads authorities to promote sustainable technologies and practices. However, targeted efforts are required from roads authorities to focus on the supply chain of pavement materials, which account for most of the environmental and social impacts of pavement development. It is recommended that authorities promote the participation of industry in furthering the development of the inventory proposed in this study.
- Certain social indicators are not yet well understood. Further research is required to develop valid quantification and impact models.
- A worked example is provided to demonstrate the implementation of the inventory developed in this study.
- Research is required to quantify the impacts of the road user related emissions in South Africa.
- Holistic sustainability can only be achieved if all three tenets of sustainability (i.e. economic, environmental, social) are confidently evaluated. Further research is required to develop a model that can quantify holistic sustainability.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.treng.2021.100049.

Table 27
Inventory for pavement materials in South Africa.

Indicator	Unit	Treated water	Bitumen[a]	3% SBS PMB	4.5% SBS PMB	6% SBS PMB	Bitumen emulsion[a]
Environmental Related Indicators							
Carbon Dioxide Emissions	kg CO_2e/t	0.12	221.89 (233.36)	601.17 (612.30)	790.81 (801.77)	980.46 (991.24)	1411.97 (1420.00)
Energy Use	MJ/t	0.4	2201.40 (2240.00)	3434.79 (3472.24)	4051.49 (4088.35)	4668.19 (4704.47)	5770.81 (5797.83)
Water Use	l/t	1000.16	681.61 (688.68)	880.75 (887.61)	980.32 (987.07)	1079.88 (1086.53)	2551.36 (2556.30)
Emissions to Water	kg PAHs/t	0.00	2.61E–07 (2.61E–07)	2.53E–07 (2.53E–07)	2.49E–07 (2.49E–07)	2.45E–07 (2.45E–07)	2.05E–07 (2.05E–07)
Social Related Indicators							
Sulphur Dioxide Emissions	kg SO_2/t	1.01E-03	1.13 (1.23)	4.37 (4.46)	5.99 (6.08)	7.60 (7.70)	11.44 (11.51)
Nitrogen Oxides Emissions	kg NOx/t	4.84E-04	2.51 (2.56)	4.01 (4.05)	4.75 (4.80)	5.50 (5.55)	6.88 (6.91)
Particulate Matter Emissions	kg PM_{10}/t	4.00E-05	0.03 (003)	0.16 (0.16)	0.22 (0.22)	0.29 (0.29)	0.43 (0.43)
Volatile Organic Compounds Emissions	kg VOC/t	0.00	0.68 (0.68)	0.66 (0.66)	0.65 (0.65)	0.64 (0.64)	0.48 (0.48)
Indicator	**Unit**	**HMA**[a]	**WMA**[a]	**CMA**[a]	**HMA + RAP**	**CMA + RAP**	
Environmental Related Indicators							
Carbon Dioxide Emissions	kg CO2e/t	69.36 (70.06)	48.55 (49.04)	41.79 (41.84)	50.82	22.55	
Energy Use	MJ/t	723.20 (725.51)	506.24 (507.86)	335.70 (338.01)	620.15	275.15	
Water Use	l/t	76.05 (76.47)	53.23 (53.53)	61.90 (62.33)	25.43	11.28	
Emissions to Water	kg PAHs/t	9.56E-07 (9.56E–07)	6.69E–07 (6.69E–07)	2.99E–07 (2.99E–07)	1.04E–06	4.61E–07	
Social Related Indicators							
Sulphur Dioxide Emissions	kg SO2/t	0.43 (0.44)	0.30 (0.31)	0.24 (0.25)	0.35	0.16	
Nitrogen Oxides Emissions	kg NOx/t	0.50 (0.50)	0.35 (0.35)	0.30 (0.30)	0.36	0.16	
Particulate Matter Emissions	kg PM10/t	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01	2.94E–03	
Volatile Organic Compounds Emissions	kg VOC/t	0.04 (0.04)	0.03 (0.03)	0.04 (0.04)	4.67E–04	2.07E–04	
Indicator	**Unit**	**Organosilane**	**Crushed stone**	**Natural aggregate**	**Recycled aggregate**	**Cement**	**Lime**
Environmental Related Indicators							
Carbon Dioxide Emissions	kg CO_2e/t	1260.82	14.38	6.35	4.4	927.54	47.88
Energy Use	MJ/t	6,398.34	72.99	32.22	22.33	4707	243
Water Use	l/t	1442.83	16.46	7.27	5.04	1061.43	54.8
Emissions to Water	kg PAHs/t	5,36E–06	6.11E–08	2.70E–08	1.87E–08	3.94E–06	2.03E–07
Social Related Indicators							
Sulphur Dioxide Emissions	kg SO_2/t	8.97	0.1	0.05	0.03	6.6	0.34
Nitrogen Oxides Emissions	kg NOx/t	6.21	0.07	0.03	0.02	4.57	0.24
Particulate Matter Emissions	kg PM10/t	0.35	4.01E-03	1.77E-03	0	0.26	0.01
Volatile Organic Compounds Emissions	kg VOC/t	0	0	0	0	0	0
Indicator	**Unit**	**Pavement concrete**	**Pavement steel**				
Environmental Related Indicators							
Carbon Dioxide Emissions	kg CO_2e/t	159	1,367.23				
Energy Use	MJ/t	806.89	2.00E+04				
Water Use	l/t	250.78	7480.7				
Emissions to Water	kg PAHs/t	6.75E-07	0.00				
Social Related Indicators							
Sulphur Dioxide Emissions	kg SO_2/t	1.13	4.01				
Nitrogen Oxides Emissions	kg NOx/t	0.78	1.72				
Particulate Matter Emissions	kg PM10/t	0.04	4.17E-03				
Volatile Organic Compounds Emissions	kg VOC/t	0	0.62				

[a] Values in brackets represent inland scenario, with remaining values representing coastal scenario.

Table 28
Inventory for pavement construction activities in South Africa.

Indicator	Unit	Wheel loader	Excavator	Dumper	Milling - asphalt
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/loose m^3	0.18	0.24	0.52	0.2
Energy Use	MJ/loose m^3	2.43	3.22	6.9	2.69
Water Use	l/loose m^3	0.00	0.00	0.00	0.00
Emissions to Water	kg PAHs/loose m^3	4.52E−09	5.99E−09	1.28E−08	5.00E−09
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/loose m^3	8.74E−05	1.16E−04	2.48E−04	9.66E−05
Nitrogen Oxides Emissions	kg NOx/loose m^3	1.65E−03	2.18E−03	4.68E−03	1.82E−03
Particulate Matter Emissions	kg PM_{10}/loose m^3	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/loose m^3	0.00	0.00	0.00	0.00
Indicator	Unit	Compactor - soil	Compactor - asphalt	Compactor – asphalt (pneumatic)	Paver
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/m^2	0.04	0.06	0.04	0.05
Energy Use	MJ/m^2	0.6	0.79	0.48	0.66
Water Use	l/m^2	0.00	0.00	0.00	0.00
Emissions to Water	kg PAHs/m^2	1.11E−09	1.46E−09	8.84E−10	1.23E−09
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/m^2	2.14E−05	2.82E−05	1.71E−05	2.37E−05
Nitrogen Oxides Emissions	kg NOx/m^2	4.04E−04	5.33E−04	3.22E−04	4.47E−04
Particulate Matter Emissions	kg PM_{10}/m^2	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/m^2	0.00	0.00	0.00	0.00
Indicator	Unit	Grader	Concrete sawing and sealing	Concrete milling	General activity
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/m^2	0.01	0.04	5.52	0.00
Energy Use	MJ/m^2	0.12	0.5044	73.7	7.54E−03
Water Use	l/m^2	0.00	0.00	0.00	0.00
Emissions to Water	kg PAHs/m^2	2.23E−10	9.38E−10	1.37E−07	1.40E−11
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/m^2	4.31E−06	1.81E−05	2.65E−03	2.71E−07
Nitrogen Oxides Emissions	kg NOx/m^2	8.13E−05	3.42E−04	5.00E−02	5.11E−06
Particulate Matter Emissions	kg PM_{10}/m^2	0.00	0.00	0.00	0.00
Volatile Organic Compounds Emissions	kg VOC/m^2	0.00	0.00	0.00	0.00
Indicator	Unit	14-ton short distance	32-ton long distance		
Environmental Related Indicators					
Carbon Dioxide Emissions	kg CO_2e/tonne-km	0.064	0.031		
Energy Use	MJ/tonne-km	0.85	0.416		
Water Use	l/tonne-km	0.00	0.00		
Emissions to Water	kg PAHs/tonne-km	1.58E−09	7.73E−10		
Social Related Indicators					
Sulphur Dioxide Emissions	kg SO_2/tonne-km	3.05E-05	1.49E-05		
Nitrogen Oxides Emissions	kg NOx/tonne-km	5.76E-04	2.82E-04		
Particulate Matter Emissions	kg PM_{10}/tonne-km	6.74E-04	3.30E-04		
Volatile Organic Compounds Emissions	kg VOC/tonne-km	3.88E-05	1.90E-05		

References

[1] FHWALife Cycle Assessment of Pavements, Tech Brief, Federal Highway Administration, Washington, D.C., USA, 2014 FHWA-HIF-15-001.

[2] N. Santero, E. Masanat, A. Horvath, Life cycle assessment of pavements. Part I: critical review, Res., Conserv. Recycl. 55 (9–10) (2011) 801–809.

[3] J. Harvey, A. Saboori, M. Dauvergne, W.JvdM. Steyn, A. Jullien, H. Li, Comparison of new pavement construction GHG and energy impacts in different regions, Papers from the International Symposium on Pavement Life Cycle Assessment, University of California, 2014 ISBN 978-0-692-29357-7.

[4] EurobitumeThe Eurobitume Life-Cycle Inventory for bitumen, Version 2, European Bitumen Association, Brussels, Belgium, 2012.

[5] EurobitmeThe Eurobitume Life-Cycle Inventory for bitumen, Version 3.1, European Bitumen Association, Brussels, Belgium, 2020.

[6] T.M. Gulotta, M. Mistretta, F.G. Practicò, A life cycle scenario analysis of different pavement technologies for urban roads, Sci. Total Environ. 673 (2019) 585–593 Issue 18.

[7] S. Bressi, G. D'Angelo, J. Santos, M. Giunta, Environmental performance analysis of bitumen stabilized ballast for railway track-bed using life cycle assessment, Constr. Build. Mater. 188 (2018) 1050–1064.

[8] M. Giunta, M. Mistretta, F.G. Practicò, M.T. Gulotta, Environmental sustainability and energy assessment of bituminous pavements made with unconventional materials, in: Proceedings of the 5th International Symposium on Asphalt Pavements and Environment (APA), 2020, pp. 123–132, doi:10.1007/978-3-030-29779-4_12.

[9] U. Berardi, Clarifying the new interpretations of the concept of sustainable building, Sustain. Cities Soc. 8 (2013) 72–78.

[10] ISOInternational Organisation for Standardisation. ISO 14040, Environmental Management – Life Cycle Assessment – Principles and framework, ISO, Geneva, Switzerland, 2006.

[11] CERCentre for Environmental Rights. The Myth of 'Clean Coal' – Why Coal can only ever be Dirty, CER, Cape Town, South Africa, 2019 Available at cer.org.za.

[12] WHOWorld Health Organisation. Air Quality Guidelines Global update: Particulate Matter, Ozone, Nitrogen Dioxide and Sulphur Dioxide, WHO, Copenhagen, Denmark, 2005 EUR/05/5046029.

[13] S.A. Blaauw, J.W. Maina, L.J. Grobler, Life cycle inventory for bitumen in South Africa, Transp. Eng. J. 2 (2020), doi:10.1016/j.treng.2020.100019.

[14] IPCCSummary for Policymakers. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, England, 2007.

[15] M. Brander, Greenhouse Gases, CO2, CO2e, and Carbon: What do all these Terms Mean?, Ecometrica, Edinburgh, Scotland, 2012 Available at Ecometrica.com.

[16] UNUnited Nations. 2019 Global Status Report for Buildings and Construction. Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector. UN Environment Programme, Global Alliance for Buildings and Construction, International Energy Agency, 2019 Available at wedocs.unep.org.

[17] M. Khan, F. Nasir, F. Mohammad, Eutrophication of Lakes in A. A. Challenges and Solutions; Volume II of Eutrophication: Causes, Consequences and Control, Springer Science + Business Media Dordrecht, 2014 ISBN 978-94-007-7814-6, doi:10.1007/978-94-007-7814-6_1.

[18] AQANational Environmental Management: Air Quality Act. Act No. 39, Department of Environmental Affairs, Pretoria, South Africa, 2004.

[19] EEAEuropean Environment Agency. Air Pollutant Emission Inventory Guidebook. Technical Guidance to Prepare National Emission Inventories, EEA, Luxembourg, Luxembourg, 2019 ISSN 1977-8449.

[20] EskomEnvironmental Implications of Using or Saving Electricity, Eskom Holdings, Sandton, South Africa, 2014 Available at Integratedreport.eskom.co.za.

[21] UN – ESYUnited Nations- Energy Statistics Yearbook, Statistic Division, UN. Brussels, Belgium, 2017.

[22] W.J. Steyn, P. Paige-Green, Evaluation of issues around road materials for sustainable transport, in: Proceedings of the 28th South African Transportation Conference, Pretoria, South Africa, 2009 ISBN Number: 978-1-920017-39-2.

[23] COLTO, Commission of Land Transport OfficialsStandard Specifications for Road and Bridge Works, COLTO, Pretoria, South Africa, 1988.

[24] SABITASouth African Bitumen Association: Design and use of asphalt in road pavements, SABITA, Cape Town, South Africa, 2018 SABITA Manual 35/TRH8.

[25] Blue DropBlue Drop Report, Department of Water and Sanitation, Pretoria, South Africa, 2017 Available at dwa.gov.za.

[26] P. Verlicchi, V. Grillini, Surface water and groundwater quality in South Africa and Mozambique – Analysis of the most critical pollutants for drinking purposes and challenges in water treatment selection, Water 12 (305) (2020), doi:10.3390/w12010305.

[27] COTOCommission of Transport Officials. Draft Standard Specifications for Road and Bridge Works, COTO, Pretoria, South Africa, 2020.

[28] J.M. Huizenga, M. Silberbauer, R. Dennis, I. Dennis, An inorganic water chemistry dataset (1972-2011) of rivers, dams and lakes in South Africa, Water SA 39 (2) (2013) 335–340.

[29] C.D. Swartz, M. van der Merwe, S.D. Freese, Energy Efficiency in the South African Water Industry: A Compendium of Best Practices and Case Studies, Water Research Commission, Pretoria, South Africa, 2013 Report No. TT 565/13.

[30] CSIR-CRRICentral Road Research Institute. Laboratory evaluation of Zycosoil (nano technology based) for subbase soils, aggregates (weak and riverbed) and sand, CSIR-CRRI, New Delhi, India, 2010.

[31] G.J. Jordaan, A. Kilian, N. Muthivelli, D. Dlamini, Practical application of nano-technology in roads in southern Africa, 8th Africa Transport Technology Transfer Conference, 2017.

[32] M.M. Kidgell, W.J.vdM. Steyn, G. Jordaan, Effect of nano-modified emulsions (NME) (nano-salines) stabilisers on the properties of dolomite, South African Transportation Conference, 2019.

[33] SE, 2019. Silicones Europe. Silicon-chemistry carbon balance. An assessment of greenhouse gas emissions and reductions. Available at https://www.silicones.eu/wp-content/uploads/2019/05/SIL_exec-summary_en.pdf.

[34] SABITASouth African Bitumen Association. A Guide to the Selection of Bituminous Binders for Road Construction – Manual 30, SABITA, Cape Town, South Africa, 2011.

[35] I. Boustead, D.L. Cooper, Eco-Profile of SBS, International Institute of Synthetic Rubber Producers, Houston, Texas, 1998.

[36] H. Stripple, Life Cycle Assessment of Road – a Pilot Study for Inventory Analysis, Swedish Environmental Research Institute, Stockholm, Sweden, 2001 Issue 1210, pp. 96p + a p.

[37] B. Wu, X. Li, Y. Li, J. Zhu, J. Wang, Hydrolysis reaction tendency of low-boiling organic chlorides to generate hydrogen chloride in crude oil distillation, Energy Fuels 30 (2) (2016) 1524–1530, doi:10.1021/acs.energyfuels.5b02926.

[38] H.H. Weinert, The Natural Road Construction Materials of Southern Africa, National Book Printers, Cape Town, South Africa, 1980.

[39] T. Häkkinen, K. Mäkelä, Environmental Adaption of Concrete: Environmental Impact of Concrete and Asphalt Pavements, Technical Research Centre of Finland, Espoo, Finland, 1996.

[40] AthenaAthena Institute. A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential, Athena Institute, Pennsylvania, USA, 2006.

[41] EcoInventLife Cycle Inventory Database, Swiss Centre for Life Cycle Inventories, Dubendorf, Switzerland, 2011.

[42] UK PC EPDUnited Kingdom Average Portland Cement Environmental Product Declaration, Mineral Products Association (UK), 2014 EPD-MPA-20140025-CAG1-EN.

[43] US LCIU.S. Life Cycle Inventory Database, National Renewable Energy Laboratory, 2012 http://www.nrel.gov/lci/.

[44] EPD Franzefoss, Franzefoss Pukk AS, Environmental Product Declaration. Crushed Stone Construction Aggregate Products, The Norwegian EPD Foundation, 2018 NEPD-1537-527-EN.

[45] Torr Quarry EPDEnvironmental Product Declaration – Limestone Aggregate, Aggregate Industries UK Limited, 2018 BREG-EN-EPD-No. 000199.

[46] Glensanda Quarry EPDEnvironmental Product Declaration – Granite Aggregate, Aggregate Industries UK Limited, 2018 BREG-EN-EPD-No. 000205.

[47] Bardon Hill Quarry EPDEnvironmental Product Declaration – Granite Aggregate, Aggregate Industries UK Limited, 2018 BREG-EN-EPD-No. 000206.

[48] GCRThe Global Cement Report, The Global Cement Report$^{\text{TM}}$, Surrey, UK, 2019.

[49] S.A. Blaauw, J.W. Maina, E. Horak, Towards a mix design model for the prediction of permeability of hot-mix asphalt, Constr. Build. Mater. 221 (2019) 637–642.

[50] NAEINational Atmospheric Emissions Inventory. Online Emissions Inventory for Fuel Oil, NAEI, 2018 Available at naei.beis.gov.uk.

[51] R. Lundberg, T. Jacobson, P. Redelius, J.A. Östlund, Production and durability of cold mix asphalt, 6th Eurasphalt and Eurobitume Congress, 2016, doi:10.14311/EE.2016.074.

[52] TRLTransport Research Laboratory. Use of Lower Temperature Asphalt in Pavement Construction, Demonstration site construction, in service performance and specification, Berkshire, UK, 2014 Report PPR742. TRL.

[53] M. Zaumanis, J. Jansen, V. Haritonovs, J. Smirnovs, Development of calculation tool for assessing the energy demand of warm mix asphalt, Transp. Res. Arena – Europe. Proc. – Soc. Behav. Sci. 48 (2012) 163–172.

[54] T. Wang, I.S. Lee, J. Harvey, A. Kendall, A.B. Lee, C. Kim, UCPRC Life Cycle Assessment Methodology and Initial Case Studies for Energy Consumption and GHG Emissions for Pavement Preservation Treatments with Different Rolling Resistance, California Department of Transportation, Sacramento, California, USA, 2012 UCPRC-RR-2012-02.

[55] SABITA, Technical recommendations for highways 21Use of Reclaimed Asphalt in the Production of Asphalt, SABITA, Cape Town, South Africa, 2017.

[56] World Steel AssociationLCI Data for Steel Products – Engineering Steel, World Steel Association, Brussels, Belgium, 2019 Available at worldsteel.org.

[57] Hammond, G.P., Jones, C.I., 2019. Embodied energy and carbon – The ICE database. Available at http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.

[58] F. Engelbrecht, A. Le Roux, K. Arnold, J. Malherbe, Green Book. Detailed Projections of Future Climate Change over South Africa, CSIR, Pretoria, 2019 Available at: csir.co.za.

[59] FBWP, Free Basic Water PolicyFree Basic Water – Implementation Strategy 2007: Consolidating and Maintaining. Department of Water Affairs and Forestry – Directorate: Policy and Strategy, Department of Water Affairs and Forestry, Pretoria, South Africa, 2007 Available at gov.za.

[60] Kannemeyer, L., 2016. South African road network condition needs and funding. SANRAL. Pretoria, South Africa. Available at sarf.org.za/wp-content/uploads/2016/08/Louw-Kannemeyer.pdf.