LIFE CYCLE ASSESSMENT OF CONCRETE PAVEMENT USING RECYCLED AGGREGATE: ENDPOINT METHOD

JASON CHUA JUN CHENG

A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Honours) Civil Engineering

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

April 2021

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature : Jason

Name : JASON CHUA JUN CHENG

ID No. : 1604738

Date : 30 April 2021

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"Life-Cycle Assessment of Concrete Pavement Using Recycled Aggregate: Endpoint Method"** was prepared by **JASON CHUA JUN CHENG** has met the required standard for submission in partial fulfilment of the requirements for the award of Engineering (Honours) Civil Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature :

Supervisor : DR. ONG CHUAN FANG

Date : 08 May 2021

ACKNOWLEDGEMENT

First of all, I would like to express my great appreciation to Univerisity Tunku Abdul Rahman in giving me such an opportunity to conduct this project. This project allowed me to integrate the knowledge I had gained throughout my years at university, at the same time help me to develop a deeper understanding of the topic of the project.

The success and the outcome of this project required a lot of guidance and assistance from my supervisor, Dr. Ong Chuan Fang who advised me on the LCA and refined my research skills and outcomes. Dr. Ong also shared his experiences and gave comments on improving my project. Without his guidance, encouragement and support, I might not be able to complete this business plan within the time given.

I am grateful to all the parties who had contributed to the successful completion of this project. Last but not least, heartfelt thanks to my family and friends who had helped and given me encouragement in preparing and completing this project report.

Thank You.

ABSTRACT

The concrete pavement network plays an important role in the economy of the country by enabling the transport of people and goods, but it also leads to resource depletion and environmental impacts. In recent years, the demand for greener development and design in the market increases, and the construction industry starts to have more focus on this environmental trend. Thus, it is important to consider the Life Cycle Assessment to reduce environmental impacts for sustainable development. OpenLCA software is used to carry out a cradle-to-gate life cycle assessment by using Allocation at the Point of Substitution (APOS) approaches based on IMPACT 2002+ Endpoint method and ReCiPe Endpoint method. The pavements involved are conventional Portland cement concrete pavement and recycled aggregate Portland cement concrete pavement. This study focuses on the base course and subbase course of the pavement. The data for input and output of the material is taken from the Ecoinvent database. Due to the limitation of data, transportation distance was assumed based on the relevant study. There are four types of environmental impacts that have been analyzed including Ecosystem Quality, Resources, Human Health, and Climate Change. The comparison has been made between conventional pavement and recycled aggregate pavement where the results showed the uses of recycled aggregate in the pavement are able to reduce the environmental impacts. Despite both IMPACT 2002+ and ReCiPe Endpoint methods proved recycled aggregate pavement contributed a lesser impact, the results between the two life cycle assessment methods are incomparable due to huge differences in their weighting coefficients.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation
APOS	allocation at the point of substitution
ASTM	American Society for Testing and Materials
C&D	construction and demolition
CO_2	carbon dioxide
FHWA	Federal Highway Administration
GHG	greenhouse gas
ISO	International Organization for Standardization
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
MJ	Mega Joule
MPa	Mega Pascal
NA	natural aggregate
OPC	ordinary Portland cement
PCC	Portland cement concrete
RA	recycled aggregate
RA-PCC	recycled aggregate Portland cement concrete

CHAPTER 1

INTRODUCTION

1.1 General Introduction

In recent years, environmental aspects related to road construction are increasing. Concrete is the main construction material and most widely used in all types of civil engineering works. Normally, the aggregate used in concrete mixtures for the road pavement comprises approximately 80 to 85 % of the total mass of the concrete mixture (Chesner et al., 2002). The huge consumption of natural aggregate in the construction industry increases the global production of the natural aggregate to meet the demand which has increased the environmental concern.

With the increasing renewal of buildings across the world, the aggregate waste from building demolition as well as the quarry aggregate waste is continuing to grow. The global construction and demolition(C&D) waste reached 3.0 billion tons annually in 2012 (Akhtar and Sarmah, 2018). Besides, China generated 1130 million tons of C&D waste in 2014 and is ranked as the first C&D waste generator worldwide (Kabirifar et al., 2020). The extraction of natural aggregate is expensive and has a huge impact on the environment. For example, modern mining techniques required high water demands for extraction. At the same time, the generation of wastewater can pollute other water sources in the region surrounding the quarry. Also, most of the heavy mining machine is dependent on fossil fuels caused carbon dioxide emissions. Aggregate waste is an unavoidable product in quarry activities. The primary method to handle this waste is disposed of in landfills without being fully utilized (Mahayuddin et al., 2008). The aggregate waste disposal methods adopted by the industries cause severe problems, for example, disposed of wastes by the practice of landfilling created land pollution, water pollution, and consumes the landfill space. In order to minimize the environmental issues, the solution is to recycle the aggregate waste and utilize it in other industrial applications, for example, serve as a substitute for natural aggregate in the concrete pavement. Recycling of aggregate in the pavement is an environmentally sustainable choice that conserves aggregate and other resources, reduces emission of greenhouse gas (GHG), energy use, and consumption of landfill space.

At present, the increasing use of recycled coarse aggregate in the concrete pavements needs to be up-to-date studies on its environmental impacts. Life cycle assessment (LCA) is useful in analyzing a load of the process of the environment throughout their life cycle, from cradle-to-grave and the methodology is according to the ISO 14040 standard framework (Menoufi, 2011). The conventional pavement and recycled aggregate concrete pavement contribute to environmental impacts such as the release of the carbon dioxide during the production. To make a sustainable decision, it is crucial to study and compare the entire life cycle of each concrete pavement.

1.2 Background of the Study

The construction of roadway has been increasing from the beginning of the past century, especially in areas of high development country. In fact, it generated two important environmental issues such as increase the natural aggregate demand and aggregate waste. According to Freedonia Group (2019), the global demand for the aggregate in the construction fields is expected to increase by 2.3 % per year. At the same time, the pavement construction will have an impact on the environment due to the consumption of natural aggregate and its emission which pose a sustainability problem in the industry. Thus, recycling aggregate waste is an effective way of waste management to minimize environmental impacts. To achieve sustainable and long-term solutions, it is necessary to account for all environmental impacts as well as the economic cost over the lifetime of the project and need the right tools such as LCA approaches to do so.

To reduce the environmental issues, researchers had performed a study on the concrete mix with the recycled aggregate which has the potential use for Portland Cement Concrete(PCC) pavement. For example, the application of the recycled aggregate in the pavements is being considered for use in the O’Hare Modernization Project (Roesler et al., 2013). The laboratory testing was initiated and showed that the concrete made with recycled aggregate has a reduced density, compressive strength as well as an increased shrinkage (Malešev et al., 2014). However, the testing done with the two-stage mixing method shows that the bleeding and segregation is reduced by using recycled aggregate. On the other hand, a field test shows the mixture with recycled aggregate has similar workability as the natural aggregate concrete of the pavement (Federal Highway Administration, 2004). Another study by Roesler et al. (2013) shows there is no significant difference in the behavior between recycled aggregate pavement and conventional pavement.

Another research study related to the recycled aggregate in concrete base and subbase layer was done by Gnanendran and Woodburn (2003). The study shows that the unbound cementitious material in recycled concrete aggregate provides bonding of the base material which can improve structural strength in the base, resulting in improved load-carrying capacity. Compared to the natural aggregate, recycled aggregate provides a very good construction base as well as the subbase of the pavement. However, Gnanendran and Woodburn (2003) emphasize the recycled aggregate can possess a good compatibility characteristic only if the contaminants such as tile, brick, and wooden pieces meet the limitation requirements for acceptance as base and subbase materials for pavements. Moreover, the asphalt is allowed only a 3 % content due to the adhered mortar on the aggregate particles that tend to the lower compressive strength (Gnanendran and Woodburn, 2003). However, asphalt is a major component of the asphalt concrete pavement and therefore may be allowed in a higher percentage in case the mechanical characteristics of recycled aggregate are satisfied in the detailed laboratory testing (Gnanendran and Woodburn, 2003).

The inclusion of recycled aggregate in concrete pavement may impact several physical and mechanical properties. According to a previous study done by the Federal Highway Administration (2004), it was found that the recycled aggregate is always larger than the standards size of natural aggregate. Since the recycled fine aggregate may affect the performance of the pavement, thus appropriate production technology is required to reduce the negative effects to achieve an acceptable level (Malešev et al., 2014). The recycled aggregate in the pavement is irregular, mostly an angular shape with a rough and porous surface, therefore, the amount of water use to mix the concrete with recycled aggregate has a significantly higher than conventional pavement. The reason for that is the quantity of mortar attached to recycled aggregate increases the water absorption by up to 10 % (Malešev et al., 2014). Furthermore, the abrasion and crushing resistance of recycled aggregate pavement are lower due to the presence of mortar (Jindal et al., 2014). According to crushing tests conducted by Sagoe-Crentsil et al. (2001), the recycled aggregate in the pavement resulting in values of 23.1 %. On the other hand, the recycled aggregate may influence all physical properties especially the durability of the pavement without a well-established practice in concrete mix design (Vázquez, 2016). To conclude, the keys to successfully produce recycled aggregate for pavement is to understand the physical and mechanical properties of the aggregate and make any necessary engineering adjustments to ensure long-term performance of the pavement.

Nowadays, LCA plays an important role in quantifying these impacts to the eco-system. By input all the materials used and energy consumption in each stage of the process, the environmental impacts can be generated by using the LCA. Application of LCA gives a clear direction to the industry to reduce pollution during the life cycle of a product, preserve the natural resource which leads to environmental improvements and develops a more sustainable industry in near future. Within the steps of LCA, there are 2 approaches of characterization (midpoint approach and endpoint approach) that take place along the impact pathway in the LCA. The midpoint method is used to assess the impacts before the endpoint categories while the endpoint method focus on the environmental impact at the end of the chain (Menoufi, 2011). Normally, endpoint results would show a high impact on Ecosystem Quality and Human Health in the LCA (Brilhuis-Meijer, 2014). IMPACT 2002+ and ReCiPe are the two LCA methodologies that can be used to evaluate the environmental burdens of the concrete pavement at the endpoint level. One of the differences between these two methodologies is the number of impact categories. IMPACT 2002+ Endpoint method will evaluate the impacts in four endpoint damage categories (Climate Change, Ecosystem Quality, Human Health and Resources) while the ReCiPe Endpoint method evaluates the impacts in three endpoint damage categories (Ecosystem, Resources, and Human Health).

1.3 Problem Statement

Due to the infrastructure development, the rate of consumption of the aggregate and disposal had increased annually. According to the studies conducted by Danielsen and Kuznetsova (2015), the construction industry in the worldwide used up 22 billion tons of aggregate per year. A survey conducted by Shah et al. (2012) shows nearly 40 % of the solid wastes such as aggregate waste generated from the C&D wastes in developing countries of the Asian continent. Besides, the C&D wastes account for 75 % of the daily solid wastes of 10,000 tons daily in Dubai (Kartam et al., 2004). The low recycling percentage of aggregate waste in road construction projects contribute to increased environmental degradation as well as depletion of natural aggregate resources. Recycled coarse aggregate can use as the subbase material of the concrete pavement. However, the effect of recycled aggregate on water quality is the primary concern of most environmental agencies. To wash out the used aggregate from the concrete, a huge amount of water is required. According to the Sandrolini and Franzoni (2001), 200-400 kg of concrete required 1000 liters of water to remove the aggregate mechanically and reuse in the new mix for the pavement. This wastewater containing large amounts of solid particles and its extremely high pH may be discharged from the recycling plant where contribute to the negative effects on water quality in the surrounding environment. Additionally, recycled aggregate has a higher water consumption compared to the natural aggregate. Concrete pavement made using recycled coarse aggregate needs approximately 5 % more water than the conventional pavement to attain optimum in the production (Federal Highway Administration, 2004).

According to Ivel et al. (2019), there is no measurement of the recycled aggregate in the asphalt and concrete pavement. In addition, the LCA of the concrete pavements using IMPACT 2002+ Endpoint method and ReCiPe Endpoint method analysis is a topic not covered in the previous study. The system boundary in the study is limited to the raw material production until disposal stage, Ecoinvent database is applied. Other than that, most of the LCA in a single study is only includes one kind of pavement, for example, LCA study on conventional pavement shows there is lack of comparison of the environmental impact between concrete pavement with and without the recycled aggregate (Stripple, 2001). The large amount of data required in the

LCA study on the pavement and it is resource consuming. According to Huang (2007), the assumption such as transportation distance of material and energy input has been made in the LCA study of recycled aggregate pavement. Since the output of LCA is strongly dependent on its input, if data collection is poor, or if the wrong assumption is made, the study will not lead to solid conclusions. Consequently, the application of LCA is not fully adapted to the sector of the road industry in past, at the same time, relevant practice in concrete pavements, particularly when recycled coarse aggregate is involved, is limited. Thus, it is necessary to promote and to encourage the road industry to shift toward maximizing the application of recycled aggregate in the concrete pavement to maintain the security and preserve the environment.

1.4 Aim and Objectives

Life Cycle Assessment (LCA) is a useful technique to assess the potential environmental impacts of a product over its entire life cycle. This study aims to evaluate the environmental impacts regarding the use of recycled aggregate in the concrete pavement to develop more sustainable solutions. To achieve the aim of the study, the objectives are listed as follows:

(i) To identify the life cycle inventory of conventional Portland Cement Concrete(PCC) pavement and recycled aggregate Portland Cement Concrete(RA-PCC) pavement (base course and subbase course).

(ii) To determine the environmental impacts in the life cycle of conventional PCC pavement and RA-PCC pavement based on IMPACT 2002+ Endpoint method and ReCiPe Endpoint method.

(iii) To compare the environmental impacts of conventional PCC pavement and RA-PCC pavement based on IMPACT 2002+ Endpoint method and ReCiPe Endpoint method.

1.5 Scope of the Study

Life Cycle Analysis has been commonly adopted to assess the environmental impacts of the road industry. LCA can assess the impacts resulting from all inputs (raw materials, electricity, and water consumption) and outputs (waste, pollutants, and emissions) of each life cycle phase. Since there is a wide range of production conditions and various types of materials processing in the manufacturing of the pavements, this is important to limit the scope of the work and to focus the efforts. Therefore, the life cycle stage, impact category, and environmental category have been limited in this study scope of work. The system boundary of the LCA is focusing on cradle-to-gate analysis by using APOS approaches. Ecoinvent 3.5 database is used as the LCA database for the analysis. Data will be taken from the previous study while it is not available in the database. To make this study feasible, it is necessary to make some assumptions. For example, the environmental burden from the transportation of waste inside the recycling plant is not considered in this study. Other than that, the base layer of Portland cement concrete pavement using recycled aggregate is assumed to be compacted properly until the thickness and strength similar to the conventional pavement (Snyder, 2018).

The concrete used in this pavement analysis is Portland cement concrete (PCC) which the reference of the mix design proportion for the base and subbase are obtained from the study done by Jain et al. (2012) and Prasittisopin et al. (2017). This study will focus on the application of the recycled coarse aggregate as a substitution of natural aggregate for the base and subbase of the concrete pavement where the recycled aggregate is taken from the C&D wastes from old buildings (Rosado et al., 2017). Furthermore. This study is focusing on IMPACT 2002+ Endpoint method and ReCiPe Endpoint method to perform a detailed environmental assessment on the conventional PCC pavement and RA-PCC pavement. IMPACT 2002+ Endpoint method and ReCiPe Endpoint method are selected due to their high similarity in their impact category. The economic and social impacts of those pavements are not included in this pavement life cycle assessment.

1.6 Contribution of Study

In this generation, sustainability is a great concern in road infrastructure construction and management. According to Harvey et al. (2014), the application of LCA can help to define pavement systems to support decision making regarding changes to the practices to minimize the impacts of pavements on the environment, human health, as well as the costing. Nowadays, the LCA of pavement becomes a very significant study because it can generate a sustainable solution for future development in the road industry. This study allows the concrete mix suppliers to evaluate any change of impacts in constructing the pavement with consideration of recycled aggregate in the timeline, therefore they can enhance their production line to produce a more environmentally friendly pavement.

LCA has major roles in integrated waste management and pollution studies, encourages the development of sustainable pavement construction which promotes the efficient use of recycled material and the reduction of aggregate waste. The LCA study improves the eco-profile of technologies for the road pavements which taking into account eco-design strategies, sustainability development, and technological feasibility (Praticò et al., 2020). A survey found that LCA was used for supporting R&D to improve process design (Jacquemin et al., 2012).

Undergo Life cycle assessment of the RA-PCC pavement, the overall impacts on the environment can be determined and it provides the investor with environmental information, which is something that can improve their trust in the investment of RA-PCC pavement. Uses of recycled aggregate in pavement construction is possible to reduce operating costs and preserve the natural resources for future use. Hopefully, this study can be used to promote sustainable development in the future.

1.7 Outline of the Report

This report consists of 5 chapters in total. Chapter 1 provides a brief introduction and research background of this project study. Besides, the problem statement, aims and objectives, scope and limitation of the study, contribution of study, and the outline of the report are included in this chapter as well. A literature review is done in Chapter 2 on the life cycle assessment on the conventional PCC pavement and RA-PCC pavement. The framework of the life cycle assessment and the method used in the assessment are discussed in this chapter. Chapter 3 discuss the methodology of the project study, the goal and scope are defined with the input data used in the analysis. The life cycle impact assessment and interpretation are highlighted in Chapter 3. In Chapter 4, results and discussions are shown in tables and graphs and are analysed accordingly. Comparison between 2 LCIA methods used in this study are conducted. Conclusions has been made in Chapter 5 with recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the aspects of conventional pavement and recycled aggregate concrete pavement would be further discussed. The environmental impacts that resulted from the concrete pavements were being discussed as well as their life cycle assessment. Other than that, different methodologies adopted in the LCA will be mentioned in this chapter.

2.2 Portland Cement Concrete(PCC) Pavement

The PCC pavements are usually made from Portland cement, aggregate, sand, and water. In recent years, the concrete pavement utilized for different pavement applications such as highways, and parking lots because of its low maintenance advantages (Darabadi et al., 2018). Normally, a concrete pavement structure consists of the surface course, base layer, and subbase layer. In some cases, the subbase layer will be constructed to provide for structural strength. The top structural layer of the surface course is directly in contact with traffic loads and it provides most of the strength. It protects the base layer from wheel abrasion, at the same time waterproof the entire pavement structure. The underlying base and subbase layers are orders of magnitude less stiff, lower-quality materials are allowed in these layers (Rodriguez, 2019). However, the layers still make important contributions to pavement strength as well as drainage improvement. The subbase layer consists of crushed aggregate, it disperses the load from the base course before transmitting to the subgrade. The base layer consists of crushed aggregate and cementing material such as Portland cement and lime fly ash, which support and disperse the traffic loads (Phummiphan et al., 2018). Figure 2.1 shows the basic structure of Portland cement concrete(PCC) pavement.

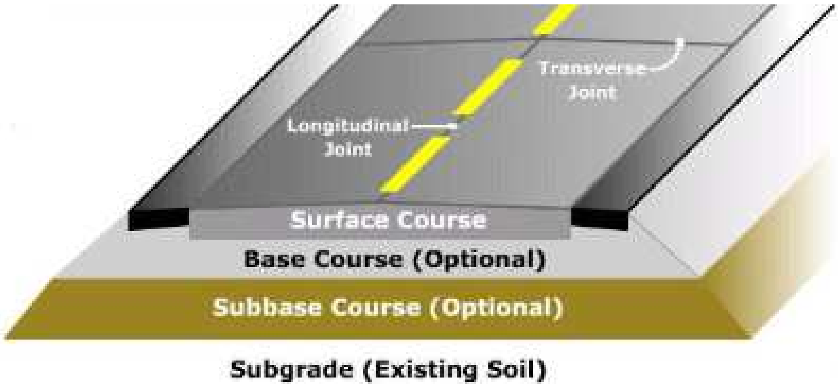


Figure 2.1: Portland cement concrete(PCC) pavement (Mishra, 2019)

The thickness of the subbase and base are usually governed by the depth of frost penetration, subgrade type, and availability of water near the subgrade. According to Nwanosike et al. (2015), the thickness of the base and subbase layer commonly ranges from a minimum of 100 mm to a maximum of 300 mm. Table 2.1 shows the standard thickness of the pavement layers. The base and subbase not only include primary aggregate, most of the time, the waste and by-product such as recycled aggregate will also be used in the pavement. However, the materials should meet the requirements of AASHTO. For example, the percentages of contaminants stick on the recycled aggregate should be limited to 3-4 % to maintain its quality (Nwanosike et al., 2015). The study conducted by Snyder (2018) showed the thickness of concrete pavement using recycled coarse aggregate can be similar to the conventional pavement in case there is compacted properly following the AASHTO guideline.

Table 2.1 : Standard thickness of pavement layer (Adams et al., 2014)

Type of Layer	**Standard Thickness**
Surface Course	150-300 mm
Base	100-300 mm
Subbase	100-300 mm

2.3 Environmental Impacts of Concrete Pavement

Portland cement is one of the main ingredients for the concrete pavement which acts as a binding agent when in contact with water and binds the aggregate as it hardens. The production of cement involved the process of mining, burning, grinding, etc. There are not only involved consumption of large quantities of raw materials and energy but also release a significant amount of solid waste and gaseous to the atmosphere. This is including large volumes of CO_2 emitted to the atmosphere. According to Stajanča and Eštoková (2012), this industrial sector will bring about 6 % of the total CO_2 in the atmosphere.

Environmental impacts of using natural coarse aggregate in the pavement have two aspects. One is the emission of CO_2 and other harmful substances to the environment during quarrying and processing of aggregate in the plant. Another one is the energy consumption in the transportation of aggregate. Evaluation of these impacts in energy use and CO_2 emissions are studied more than other impacts, global warming which leads to climate change is now the most concern.

In 2008, the UK construction aggregate sector produced about 207 million tons of natural aggregate and responsible for 0.46 % of the total carbon emissions (Meininger and Stokowski, 2011). A study conducted by the Department for Energy and Climate Change in 2010 showed the official estimate of total CO_2 emission is 2.45 million tons per 532.8 million tons of aggregate produced (Meininger and Stokowski, 2011). With this amount of CO_2 emission released to the atmosphere is sufficient to possess a considerable impact on the environment.

The machine used for mining aggregate and transportation of aggregate from pit to manufacture plant consumes the fuel oil and release CO_2, which indirectly damages the environment. Therefore, the use of energy in production and their by-product are one of the sources of environmental impacts. As the energy input increase, the amount of harmful by-product release to the environment increased (Mitchell, 2012).

On the other hand, the generation of a large quantity of aggregate waste creating a shortage of land for infrastructure development, for example, disposal of aggregate waste at the landfill sites in India. The study showed aggregate waste expected to reach million tons in 2047 and this waste would be about 170 km^2 comparison with 20 km^2 in 1997(Jindal et al., 2014). Depletion of landfill not only cause land shortage problem, but the issues will also be further aggravated, causing other economic environmental, social, and rise.

2.4 Aggregate Demand

Aggregate plays an important role in the construction industry. Aggregate typically accounts for 70 to 80 % by volume for concrete mixes (Martinez-Arguelles et al., 2019). In recent years, the construction industry grows dramatically and increases the consumption of the aggregate as raw materials in the concrete. The global demand for natural aggregate in the manufacturing of concrete is growing by 7.7 % per year and is expected to reach 66.2 billion metric tons in 2022. An aggregate demand analysis provided by MPA (2017) showed the aggregate demand will be peaking at 220 million tons per year in 2023. Overall, this means the construction industry will face a cumulative aggregate demand of around 3.5 billion tons over the next 15 years. On the other hand, a huge amount of aggregate is required for the construction of the pavement. As reported in the FHWA study estimates the U.S road industry will spend about 700 million tons of aggregate for the pavement (Meininger and Stokowski, 2011). The continuous exploitation of aggregate for development use has a major impact on the environment such as CO_2 emission and depletion of natural resources. The aggregate demand for different industry application shown in Table 2.2.

Table 2.2: Great Britain: Demand of primary aggregates by major end-use (MPA, 2017)

Principal uses	**Thousand tons**			
	Sand& gravel	**Crushed rock**	**Total**	**%**
Concrete aggregates	35 381	14 279	49 660	32.1
Other screened, graded aggregates and surface dressings	6 555	19 572	26 127	16.9
Roadstone, coated	181	17 597	17 778	11.5
Roadstone, uncoated	-	22 179	22 179	14.4

Building/asphalting sand	6 960	-	6 960	4.5
Railway ballast	-	2 990	2 990	1.9
Armourstone/gabion	-	976	976	0.6
Constructional fill	7 052	20 831	27 883	18.0
Total sales	56 129	98 423	154 552	100

Source: Annual Minerals Raised Inquiry, Office for National Statistics (ONS)

2.5 Aggregate Waste

Nowadays, the disposal of Construction & Demolition(C&D) waste has become a major concern, especially in developing countries. The construction industry generates about 35 % of industrial waste in the world (Fadiya et al., 2014). Another study conducted by Jindal et al. (2014) showed that around 40 % of this C&D waste is concrete waste. Disposal of this used concrete increases the aggregate waste which may lead to an environmental impact. According to Sharkawi et al. (2016), Egypt is one of the main countries which has generated a huge amount of C&D waste harmfully affecting the environment. Normally, the aggregate waste is generated in the construction, renovation, or demolition of buildings and infrastructure. About 4.0 million tons of waste aggregate is generated per year in Egypt, however, the aggregate recycling is unexercised and the current method of managing such waste is through disposal in landfills (Sharkawi et al., 2016). Even though some of the researchers are studying the feasibility of recycling C&D waste, however, there are no such local integrated results are available for application, therefore causing large deposits of C&D (Sharkawi et al., 2016).

In 2005, UK had generated a total of 89.6 million tons of C&D waste, which 28 million tons were sent to landfills (Fadiya et al., 2014). Million tons of the aggregates were disposal while the aggregate demand is increasing in the world. Australia is facing a similar problem as UK, about 7 million tons of C&D waste was disposed of in landfills from 2006 to 2007 (Fadiya et al., 2014). Today, the world is generating about 1.3 billion tons of solid waste every year and is expected to reach 2.2 billion tons in 2025 (Taffese, 2018). This may due to inefficient waste management practices in the construction site. Moreover, construction possesses a significant environmental impact through the quarry activities. Aggregate wastes may be generated from the quarrying activities such as washing and cutting of crushed rocks during the production stages (Adajar, 2017). Table 2.3 shows the environmental impact of the aggregates.

Table 2.3: Environmental Impact of Aggregates (The Concrete Society, 2019)

Stage in aggregate processing	**Major environmental impacts**
Quarrying and processing raw material	Scarring of landscape
	Dust and noise
	Some sources are in areas of outstanding natural beauty
	Proximity to major centers of population
	Loss of agricultural land (or removal from use for many years)
	Energy consumption; carbon dioxide emissions etc.
Delivery of aggregate to concrete production plant	Fuel, noise and traffic

Source: Concrete and the Environment, published in CONCRETE in September 2001

2.6 Recycled Aggregate Production

Recycled coarse aggregate as the alternative materials for the replacement of primary aggregate in the concrete pavement is discussed in this study. Recycled aggregate is usually produced from the C&D wastes, this waste will be collected from site and transport to the recycling plant. The aggregate recycling system is shown in Figure 2.2. The system consists of 4 main phases which are waste collection, reduction of size, separation of impurities, and screening (Klee, 2004). The production of recycled aggregate is shown in Figure 2.2.

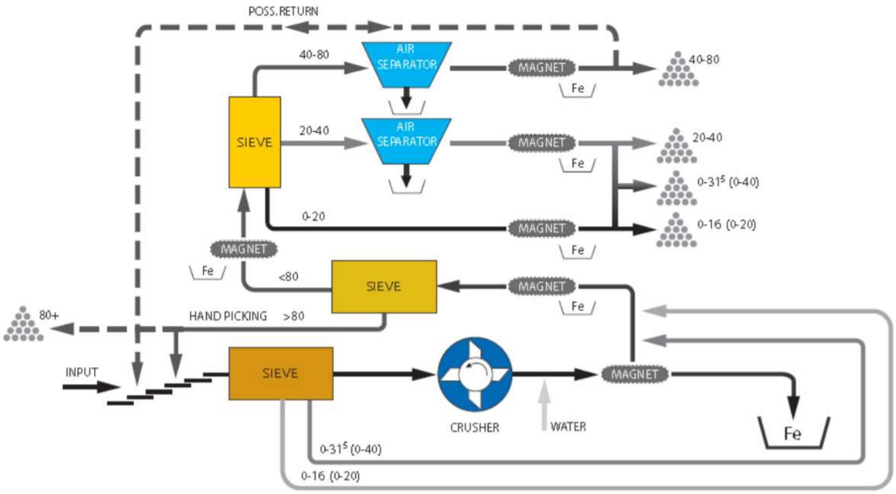


Figure 2.2: Production of recycled aggregate (Klee, 2004)

The production of recycled aggregate involves crushing the concrete material to a gradation comparable to the roadway base aggregate. Fresh recycled aggregate may contain an amount of debris and reinforcing steel, and the aggregate must be processed to remove this debris. Sometimes air separators may use to remove lighter materials such as wood and plastics (Klee, 2004). The magnetic separator in the next phase will separate out the impurities including the iron scrap. The removed iron scrap will be extracted and kept for recycling use for other manufacturing processes and generation of power in the factory. In the next stage, the aggregate is passing over the sieve decks to screen out the deleterious particles and lower quality material from the system (Klee, 2004).

In addition, the mortar on the surface of aggregate will be removed by beneficiation methods. Thermal beneficiation generating thermal stress on the aggregate at about 500 °C which through thermal expansion to remove the adhered mortar (Jindal et al., 2014). In mechanical beneficiation, the aggregate is allowed to pass between two cylinders that rotate at high speed to remove the adhered mortar from the aggregate. Chemical treatment such as exposure of the aggregate particles to sodium sulfate solution to separate mortar from the aggregate through the freeze-and-thaw action (Jindal et al., 2014). After removed adhered mortar, the coarse aggregate and fine aggregate will be separated by a vibrating screen and the recycled aggregate is ready to use.

2.6.1 Use of Recycled Aggregate in Pavement

A direct engineering solution to reduce the use of natural aggregate is to adopt the recycled coarse aggregate as the alternative materials in the construction industry. Aggregate other than natural aggregate is called recycled aggregate. This aggregate can be obtained from the recycling of C&D waste. The used aggregate will be processed into appropriate size and reuse in different industrial applications. One of the examples is reused in the pavement base and subbase. Even though the recycled aggregate is lower in quality, but it is suitable to use for the base and subbase of the pavement (Meininger and Stokowski, 2011). There is also some guideline prepared in ASTM D18.14 Subcommittee, stated the standard guide for recycled aggregate as a substitute material in the concrete pavement (Edil, 2011). Table 2.4 shows the uses of the aggregate and relative level of quality needed for different industry applications.

Table 2.4: Uses of Aggregate and Relative Level of Quality Needed (Meininger and Stokowski, 2011)

Lower Quality	Backfill and Bedding
	Subbase, Select Material, and Subgrade Improvement
↓	Base Course (Unbound and Stabilized) • Stabilized (Asphalt, Cement, and Lime-Fly Ash) • Dense Graded
	Aggregate Surfaced Roads (Gravel Roads)
	Chip Seal, Cover Material
	Portland Cement Concrete • Lean Concrete Base (Dense or Open Graded) • Structural Concrete • Concrete Pavement
	Hot-Mix Asphalt and Warm-Mix Asphalt • Dense Graded • Open Graded
Higher Quality	Drainage and Riprap
	Filter Aggregates

In the past, the recycled aggregate is an uncommon material use in the construction industry. However, it becomes more dominant when the worlds move toward sustainable development. The study on the environmental impact of the pavement is increasing over the years. The utilization of recycled coarse aggregate in road construction can minimize the demand for natural resources and waste disposal, at the same time give both economic and environmental benefits (Klee, 2004). Thus, some countries had started to implement aggregate recycling technology in the pavement industry to gain these advantages. The countries involved in aggregate recovery projects are shown in Table 2.5.

Table 2.5: Aggregate recovery in different countries (Klee, 2004)

Country	**Aggregate Recovery**
US	• 38 states use recycled concrete aggregate for road subbase.
Brazil	• Sao Paulo and Belo Horizonte have aggregate recycling facilities which recycled aggregate is used mainly for road subbase. • Legislation exists promoting C&D waste management.
Netherlands	• All concrete is recycled except for some residual process waste. • Landfill of concrete waste is banned.

The study also showed recycled aggregate is better used for road base and subbase course applications compared to the primary aggregate. The reason is that recycled coarse aggregate always has better compaction properties, less cement is required for and cheaper materials (Klee, 2004). The use of recycled materials for pavement is a sustainable move in the road industry. However, different pavement applications have their design standard, specification and quality to be followed in order to utilize the aggregate and offer a long lifetime of pavement. The standards, specifications, and quality controls for the use of aggregates are shown in Table 2.6.

Table 2.6: Standards, specifications and quality controls for the use of aggregates (WRAP, 2013)

Product and Use	**Standard**	**Specification**	**Quality Controls**
Unbound recycled aggregate: pavement	BS EN 13242: Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction	Highways Agency Specification for Highway Works: Series 800 HAUC: Specification for the reinstatement of openings in highways BS EN 13285: Unbound mixtures: Specifications	BS EN 13242: Level 4 Attestation Evaluation of Conformity to BS EN 16236* SHW: Quality Control procedures in accordance with the Quality Protocol to produce aggregates from inert waste SROH: Compliance with SHW
Recycled aggregate for asphalt	BS EN 13043: Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas	Highways Agency Specification for Highway Works: Series 900 HAUC: Specification for the reinstatement of openings in highways	Highways Agency Specification for Highway Works: Series 900 HAUC: Specification for the reinstatement of openings in highways
Recycled aggregate for hydraulically bound mixtures	BS EN 13242: Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction	Highways Agency Specification for Highway Works: Series 800 HAUC: Specification for the reinstatement of openings in highways BS EN 14227-1 to 5 Hydraulically Bound Mixtures: Specifications	BS EN 13242: Level 4 Attestation Evaluation of Conformity to BS EN 16236* SHW: Quality Control procedures in accordance with the Quality Protocol for the production of aggregates from inert waste SROH: Compliance with SHW

The Centre for Pavement and Transportation Technology (CPATT) has successfully carried out the concrete test containing recycled aggregate (Jindal et al., 2014). The results for compressive and flexural strength showed the recycled aggregate is negatively affecting the strength. Another study was conducted by FHWA's Turner-Fairbank Highway Research Center (TFHRC) to review properties of concrete manufactured with recycled concrete aggregate for the concrete pavement (Jindal et al., 2014). The result also showed concrete pavement with recycled aggregate has a lower compressive strength, however, the compressive strength is found to be above the required level. Moreover, the study shows the recycled aggregate has higher water absorption and lower specific gravity compared to primary aggregate.

2.7 A Life Cycle Approach to Sustainable Construction

Construction activities are major contributors to the environmental degradation issue especially climate change. Nowadays, more and more construction industries are moving towards sustainable development, the companies are aiming for environmental labeling to help them improve the environmental sustainability and consumption patterns in their project. Green construction practices such as using the green building materials in the new project can help the company to earn a tax break (Jones, 2018). It creates alternative solutions that allow the decision-maker to select a longer-term with consideration of all environmental issues. The technique such as LCA developed to analyze environmental impacts in the construction, use, and waste disposal from the worksite.

2.8 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a comparative tool to quantify the total environmental impacts of the product across its lifetime. A cradle-to-grave analysis is adopted to evaluate the life cycle of a product from raw material, through production, use, and final disposal by assessing the input and output of the production process. The analysis can significantly reduce the complexity of an LCA by creating a clearer and faster internal analysis processes. Others, LCA is important in the product chain which increasingly uses as a strategy of business development. Application of LCA in civil engineering acts as a technique for assessing solid waste management. For instance, the increasing use of recycled aggregate in PCC pavement should have further study on its environmental impacts (Martinez-Arguelles et al., 2019). Already accredited by some of the industries, LCA is being accepted and practiced in the pavement industry to evaluate and compare the environmental impacts throughout the pavement life.

Regarding International Standards 14040 (ISO, 2006), the methodological framework for LCA consists of four key phases: goal and scope definition phase, inventory analysis, impact assessment, interpretation. Figure 2.3 shows the methodological framework for LCA. The individual phases of an LCA will use the results of the other phases and iterative approach between each phase contributes to the consistency of the analysis result.

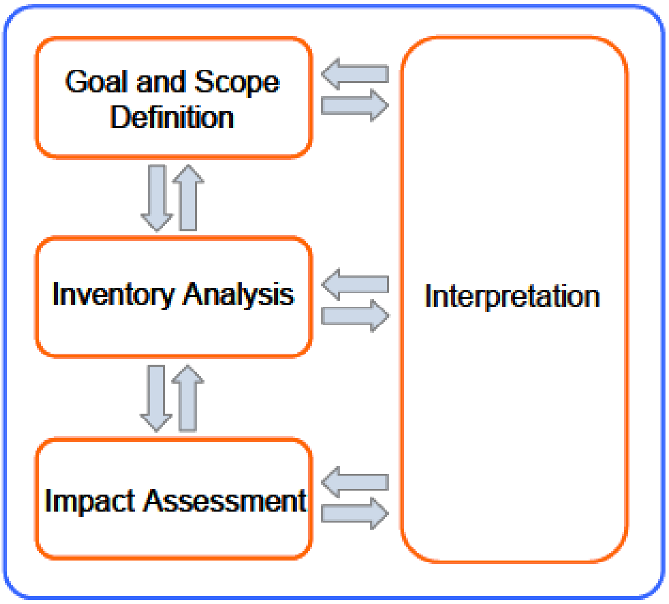


Figure 2.3: The methodological framework for LCA (Lehtinen et al., 2011)

2.8.1 Goal & Scope Definition

The first step of LCA is the definition of the goal and scope. It is a very important phase of LCA methodology because this is determining the exact approach to be followed in the process. However, the goal and scope can be modified during data collection (Curran, 2017). Defining the goal includes application, audience, and how the investigation is to be carried out. In the scope of LCA, the system boundary, functional unit, functions of the product system, allocation procedures, impact categories, methodology of impact assessment, assumptions, limitations, data requirement as well as the type and format of the report required for the study will be stated (Mälkki, 2011). A functional unit is considered as a reference point to allow reasonable assumptions to be made and set a limitation for the assessment. A rise in the amount of the functional unit will naturally increase the linked inputs, outputs, and impacts (Crawford, 2011a). For the system boundary, it usually begins with the extraction of natural resources, continues with transportation, manufacturing, use and operation, and disposal at the end of its useful life.

2.8.2 Life Cycle Inventory (LCI)

The next step is the life cycle inventory which includes data collection and calculation procedures. The input and output data are collected before proceeding to the life cycle assessment. Collecting the data is the most time consuming, thus Ecoinvent database will use to reduce the complexity in data collection (De Haes and Van Rooijen, 2005). All the significant environmental impacts will be quantified in the development of an inventory. It consists of raw resources, energy, water, and emissions throughout different stages of the life cycle of a product. The LCI analysis result is strongly dependent on the input types and quantities, transportation methods as well as disposal of the product.

2.8.3 Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment is the step in evaluating the potential environmental impact based on the inventory analysis result. The environmental impact of a product`s inventory is examined in LCIA. This process interprets the inventory data and transforms into impact indicators with certain environmental impact categories (Mälkki, 2011). Midpoint and Endpoint indicators are two approaches of characterization that can take place along the impact pathway in the life cycle of a product. In addition, LCIA also provides information for the life cycle interpretation phase.

2.8.4 Life Cycle Interpretation

The final phase of the LCA is life cycle interpretation which the results from LCIA and LCI phase is examined and assessed. In other word, a comparison of data collected from inventory analysis and impact assessment stages will use to make decisions and conclusions. The product with lesser impact on the environment is selected (Crawford, 2011b).

2.8.5 System Boundaries

System boundaries in LCA must be specified to assess a product life cycle become easier. System boundaries limit all the processes throughout the products life cycle that are included in the LCA study. Figure 2.4 shows the system boundary of a product. There are three main options to define which processes lie within the system boundaries:

a) Cradle-to-Grave

Cradle-to-grave is a full LCA where the product life cycle from the manufacture phase to the disposal phase. This model will consider the impacts from extraction of raw materials, transportation, manufacturing, and ends when the materials are returned to the earth.

b) Cradle-to-Gate

Cradle-to-gate only focuses on the impacts of a product life cycle from the manufacture phase to the factory gate. The impact generated after transport to the consumer will not be considered in this model. Thus, it can significantly reduce the complexity of the assessment when the use and disposal phase of the product is excluded (Ali et al., 2014).

c) Cradle-to-Cradle

Cradle-to-cradle is the assessment where the disposal waste at the end of the life cycle replaced with the recycling process for the manufacturing use of another product. Cradle-to-cradle is also known as a closed-loop recycling, the impact from the use of the primary product is minimized (Ali et al., 2014).

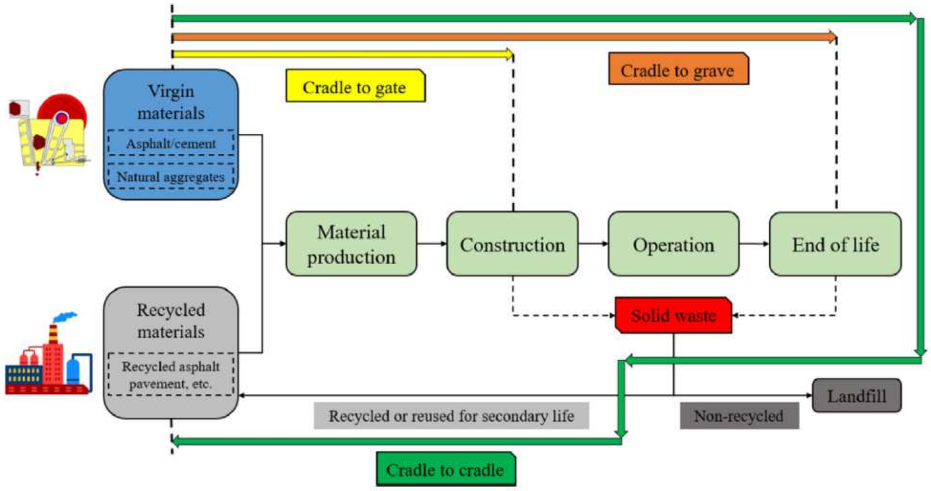


Figure 2.4: System Boundaries of Pavement LCA (Li et al., 2019)

2.8.6 System Model

A system model is a collection of modeling choices made for the database. According to the ISO standard for LCA, there is no fixed solution to the impact allocation problems (ISO, 2006). A large degree of freedom is given, and it allows a different way of the data interpretation. The modeling is based on the same data of real-world processes. Ecoinvent database is available in three system models: Cut-Off System Model, Consequential System Model, and APOS System Model (Wernet et al., 2016). Different modeling choices will bring to different studies benefit. One of the system models will be chosen to conduct LCA and it is depending on the data availability as well as the goal and scope of the study.

The Cut-Off method is commonly used to allocate inputs and outputs for the LCA of a product. According to this method, the cut-off point allocated at the end of the activity producing the recyclable materials, and the materials are removed burden-free from the recycling processes (Ponsioen, 2019). The environmental impact of the by-product is excluded from the product system. For APOS system model, the allocation of recycled materials required further treatment at the end of the product system, and therefore the environmental impacts of by-products are included in modeling. The difference between these two methods is the allocation of recycling and waste treatment products. Thus, APOS method required the datasets for by-products of waste treatments. Moreover, a consequential system model is a substitution-based approach, substitution is used to resolve multi-functionality in datasets instead of allocation (Wernet et al., 2016). The co-production in the life cycle of a product takes into account in the modeling. The co-product as a substitute which means the impacts of other sources are avoided. A lot of assumptions such as product quality will be made in this method (Ponsioen, 2019).

2.8.7 Midpoint Method and Endpoint Method

It is challenging in transforming of the raw data into useful information in LCA. Thus, it is important to select a method that can presents the results with the right level of detail before the data interpretation (Brilhuis-Meijer, 2014). Midpoint method and Endpoint method in LCIA are used to calculate and visualize LCA data to present an understandable data for different audiences. The differences between these two methods are shown in Table 2.7. Table 2.8 and Table 2.9 show the Midpoint and Endpoint oriented LCIA methodologies respectively.

Table 2.7: Differences between Midpoint method and Endpoint method (Brilhuis-Meijer, 2014, Menoufi, 2011)

Midpoint Method	Endpoint Method
Focuses on the impact earlier along the impact chain, and before the endpoint is reached	Focuses on environmental impact at the end of this cause-effect chain
Large number of midpoint indicators	Less number of endpoint indicators
Difficult to interpret the data due to large number of impacts	Easier to interpret the data and more understandable
Show the result in more detailed way	Show the result without indicating the source
Midpoint results have lower statistical uncertainty	Endpoint results have higher statistical uncertainty
Problem oriented	Damage oriented

Table 2.8: Midpoint oriented LCIA methodologies studied (Menoufi, 2011)

Methodology	**Impact categories (Midpoint categories)**	**Areas of protection**
RECIPE	Ozone depletion, mineral resource depletion, fossil fuel depletion, water depletion, oxidant formation, photochemical, climate change, freshwater eutrophication, marine ecotoxicity, urban land occupation, acidification, marine eutrophication, agricultural land occupation, particulate matter formation, natural land transformation, and terrestrial ecotoxicity	Eco system, resources, and human health
IMPACT 2002+	Global warming, ozone depletion, non-renewable energy, human toxicity, aquatic ecotoxicity, respiratory effects, aquatic eutrophication, land occupation, ionizing radiation, photochemical oxidant formation, terrestrial eutrophication and acidification terrestrial ecotoxicity, and mineral extraction	Eco system, resources, climate change, quality, human health,
EDIP 2003	Ozone depletion, global warming, human toxicity, acidification, aquatic eutrophication, terrestrial eutrophication, photochemical ozone formation, noise, and ecotoxicity\	Ecosystem, resources, and human health
TRACI	Ozone depletion, fossil fuel depletion, global warming, eco-toxicity, acidification, eutrophication, human health criteria pollutants, human health cancer, human health non-cancer, and smog formation	Ecosystem, resources, and human health

Table 2.9: Endpoint oriented LCIA methodologies studied (Menoufi, 2011)

Methodology	**Damage categories (Endpoint categories)**	**Areas of protection**
RECIPE	Damage to Eco system diversity Damage to resources availability Damage to human health	Eco system, resources, and human health
IMPACT 2002+	Damage to human health Damage to resources availability Damage to climate change Damage to Eco system diversity	Eco system, resources, quality, climate change, and human health
JEPIX	Photochemical oxidant formation, air emissions, ozone depletion, respiratory effects, primary energy resources, water consumption, surface water emissions, radioactive emissions, emissions to groundwater and soil, endocrine disruptors, cancer caused by radio nuclides emitted to the sea, gravel consumption, land filled municipal (reactive) wastes, hazardous wastes (stored underground), biodiversity losses, and radioactive wastes	Eco system, resources, and human health

2.8.8 OpenLCA Software

OpenLCA is an open-source, user-friendly, and free software for life cycle assessment (Noi et al., 2017). It can perform a fast, transparent, and reliable calculations on the LCA of a product and present the LCA result in a detailed way (GreenDeLTa, 2020).

In the past few years, openLCA created a website, called openLCA Nexus. It provides free databases for use in openLCA modelling. Ecoinvent 3.5 database is used to conduct this study. The database can be directly imported into openLCA. Ecoinvent is the world’s largest transparent life cycle inventory database consists of 10,000 over datasets that cover different industrial sectors such as transport, agriculture, energy supply, and waste treatment (GreenDeLTa, 2020). The Ecoinvent database provides access to unit processes as well as to cradle-to-gate inventory. Table 2.10 shows several LCA studies conducted by some researchers on the concrete pavement and Table 2.11 shows different applications of recycled aggregate in geotechnical and road pavement.

Table 2.10: Previous LCA Study on the Concrete Pavement (Li et al., 2019)

References	RA Types	Application	Functional unit	System boundary	Impact category
Marinkovi_c et al. (2013)	RCP	Substitute for unbound aggregates in base layer	1 kg of aggregate Materials	Materials production	Energy use, AP, GWP, EP, FSETP, and TETP
Vidal et al. (2013)	RAP	15 % substitution for virgin materials in HMA and WMA	1 km of pavement	The entire life cycle	GWP, fossil depletion and CED
Aurangzeb et al. (2014)	RAP	30, 40, 50 % substitution for virgin materials in HMA	1 km of pavement	The entire life cycle except for use and EOL phase	Energy use and GWP
Anthonissen and Braet (2014)	RAP	Hot in-plant recycling (50 % RAP)	1 ton of asphalt mixture	Materials production	Ecosystem, human health, and resources
Yang and Ozerauthor (2015)	RAS and RAP	Substitute for raw materials in HMA	1.6 km of asphalt overlay	Materials production and use phase of asphalt overlay	Energy use and GWP

Table 2.10: (Continued)

Farina et al. (2016)	CR and RAP	Rubberized asphalt mixture through wet or dry process	1 lane-km of milling	Materials production and construction	Ecological, resource consumption, and Human health
Rosado et al. (2017)	C&D waste	Substitute for unbound aggregates in base and subbase layers	1 ton of aggregate	Materials production	Energy use, land use, and respiratory inorganics

Table 2.11: Applications of recycled aggregates in geotechnical and road pavement (Dhir et al., 2019)

References	Country	RA Types	Applications
MTO (2013)	Ontario	RCA, MRA	Base, subbase, subgrade, and backfill material
VicRoads (2013)	Victoria	RCA, MRA	Subbase and light-duty base
Caltrans (2015)	California	RCA	Base and subbase
DelDOT (2016)	Delaware	RCA	Base, patch materials
CDOT (2017)	Colorado	RCA	Base, embankment
DPTI (2018)	South Australia	RCA	Pavement materials
RMS (2018)	New South Wales	RCA	Bound and unbound base and subbase
TMR (2018)	Queensland	RCA, MRA	Subbase

2.9 Applications of LCA on Pavement

Expanding and maintaining the pavement network is a resource-consuming process. According to Santero (2010), there are about 350 million tons of raw materials that are invested in the pavement construction industries annually, which covers over 8 million lane-miles of the public road. However, this does not include the pavement for industrial facilities, parking lots, and so on. The requirements on the pavement will continue to grow as there is a growing demand for the infrastructures. Thus, it creates a challenge to meet this demand using sustainable and environmentally-friendly engineering practices.

The life cycle of pavement includes the production of raw materials, construction, maintenance, use, and end-of-life poses a significant impact on the environment. In the last decade, pavements have been evaluated using the LCA to quantify the environmental impact from its cradle-to-grave life cycle.

Häkkinen and Mäkelä (1996) conducted an LCA study on the asphalt pavement with virgin materials and recycled materials for concrete pavement. The functional unit studied is 1 km of pavement. Fuel consumption and its burden during the construction phase are excluded from the study. As a process LCA, the pavements are evaluated by some important criteria such as energy consumption, CO_2 emission, land pollution, etc. The environmental evaluation includes each phase of the life cycle except the end of life phase. WisDOT specifications do not limit the replacement of primary aggregate with recycled pavement materials in the base layer, as long as the recycled concrete aggregate meets the strength and gradation parameters for both base or subbase, as much material can be used as available (Bloom et al., 2016).

Mroueh et al. (2000) conducted LCA to compare the environmental impacts of conventional pavement with the pavement using industrial by-products such as crushed concrete waste and fly ash to substitutes for virgin materials. The result shows that utilized recycled or waste materials were more environmentally friendly than the control case which used only virgin materials. Another LCA study conducted by Mroueh et al. (2000) estimated that the use of slag to replace natural aggregate decreased the environmental burdens of the pavement. In 2008, Chiu et al. conducted an LCA study and showed the concrete pavement using recycled asphalt has benefits to the environment (Farina et al., 2017). The study conducted by Uhlmeyer and Russell (2018) shows the concrete pavements built with recycled aggregate have equivalent performance to pavements made with conventional aggregate. The environmental impacts are quantified using Eco-indicator 99 approach. The study also shows the glassphalt in the pavement has a higher impact compared to the traditional concrete pavement.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter provides a comprehensive methodology of case studies on the use of recycled aggregate in PCC pavement. The recycled coarse aggregate will be used as a substitute material for natural coarse aggregate in base and subbase of the pavement. In the life cycle assessment framework, there are four main stages to perform LCA which are the definition of the goal and scope, life cycle inventory, life cycle impact assessment, and life cycle interpretation. A numerous assumption has been made in this study due to the limitation of data in different stages of the pavement's life cycle.

3.2 Goal and Scope definition

The study presents a comparative analysis of the environmental between the conventional PCC pavement and PCC pavement using recycled coarse aggregate derived from an LCA framework using the cradle-to-gate approach. The system boundary only considers the processes from extraction of materials until the construction stage. According to Marinković et al. (2013), the energy consumption in the manufacturing of the concrete pavement might different by different manufacturers, therefore, it is necessary to make some assumptions. For example, energy consumption to produce concrete pavement by different manufacturers are the same.

In this study, the intended respondents is the road industry which aims to help them to understand the environmental impacts associated with each alternative material such as natural aggregate and recycled aggregate in the pavement, where to provide a solution to optimize processes to reduce these impacts. With respect to the manufacturing of conventional pavement, the following processes were considered: extraction, transportation of raw material to the plant, and crushing, sieving, and so on. For the concrete pavement using recycled aggregate, activities such as extraction and transportation of raw material, transportation of aggregate waste from demolished structures to the recycling process plant were included.

The methodologies selected for life cycle impact assessment is IMPACT 2002+ Endpoint method and ReCiPe Endpoint method considering a functional unit of 1 km long of pavement, similar functional unit is adopted in LCA conducted by Bloom et al. (2016). According to Shi et al. (2019), most of the RA-PCC pavements were constructed using the same pavement structure parameter such as the same thickness as the control pavement. In this study, both PCC pavement and RA-PCC pavement are assumed to have a 7 m width, where the thickness of base and subbase is 0.345 m and 0.200 m respectively (Treloar et al., 1999, Treloar et al., 2004). The dimensions of subbase and base and their materials used are summarized in Table 3.1. Four categories of damage: Human Health, Ecosystem Quality, Climate Change, And Resources will be analyse through this study. All inputs and outputs are related to the functional unit and resulting in different levels of environmental impact (Crawford, 2011a).

Table 3.1: Dimensions and materials used in subbase and base layer (Treloar et al., 1999, Treloar et al., 2004)

Pavement Layers	**Dimensions**			**Materials**
	Length (m)	**Width (m)**	**Depth (m)**	
Base Course	1000	7.0	0.345	- Portland Cement - Recycled Coarse Aggregate - Sand - Fly ash
Subbase Course	1000	7.0	0.200	- Recycled Coarse Aggregate

The system models adopted in this study is APOS model. All the environmental impacts from the by-product during the life cycle of the concrete pavement will be included. However, the landfill of aggregate waste and the transportation of aggregate waste from collectors to landfill sites were excluded from the system. The system boundary of the conventional PCC pavement and RA-PCC pavement is shown in Figure 3.1, where processes from the extraction of raw materials until the construction stage were included. The use phase, and demolition phase have been omitted in this study as the focus is based on the cradle-to-gate assessment.

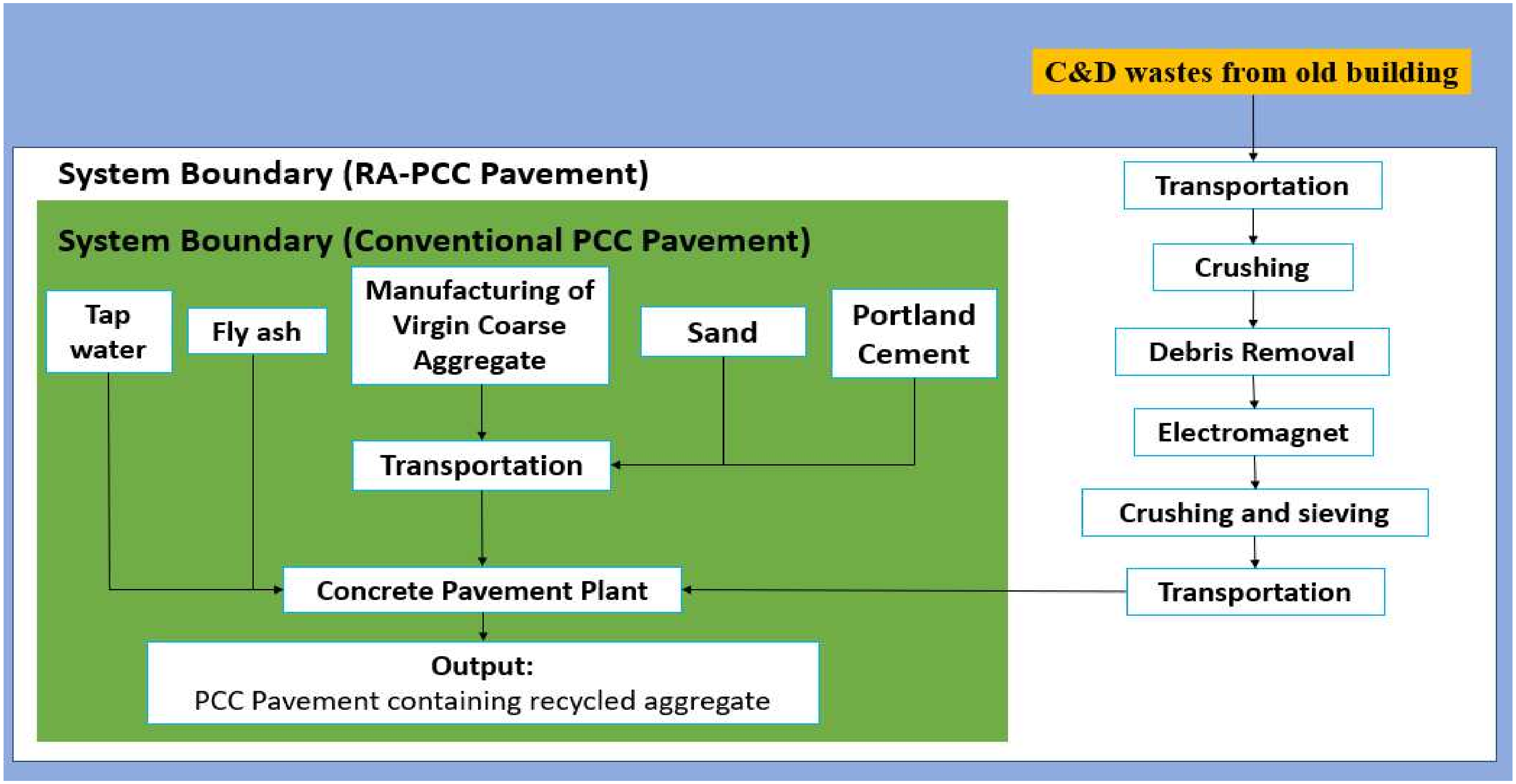


Figure 3.1: System Boundary of RA-PCC Pavement

3.3 Life Cycle Inventory

This step involved the collection of input and output data for the pavement construction process. The data sources for this LCA study are taken from the Ecoinvent 3.5 database with the APOS modelling system. The input data consisted of the consumption of raw materials, energy, water, and transportation. The output included damage to Human Health, Ecosystem Quality, Climate Change, and Resources.

The mix design for the pavements is referring to the study conducted by Jain et al. (2012) and Prasittisopin et al. (2017). The replacement of natural aggregate by the recycled aggregate is 100 % in the study. The mixed design ratio for both pavements used in this study is shown in Table 3.2 and Table 3.3. In this study, the design service life of this conventional pavement was found to be 32 years and 27 years for RA-PCC pavement (Shi et al., 2019). The energy consumption in producing the subbase is 783806 kWh while 3932500 kWh for the base of both conventional concrete PCC pavement and RA-PCC pavement (Marinković et al., 2013, Treloar et al., 2004). Since the recycled aggregate is not available in the Ecoinvent database, the input for the manufacturing of 1-ton aggregate will be taken from the study by Rosado et al. (2017) and shown in Table 3.4.

Aggregate transportation is another significant difference that must be considered during the life cycle assessment of concrete pavement. The aggregate transportation differences between natural aggregate and recycled aggregate are the transport distance. Generally, the natural aggregate can be directly transported from quarry to concrete pavement plant. Unlike the delivery way of natural aggregate, transportation of recycled aggregate usually contains transportation of concrete waste from demolished buildings to recycling process plant and delivering RCA to concrete pavement factory. It is assumed of 100 km for natural aggregate and 25 km for recycled aggregate in this study referring to Ding et al. (2016). Besides, the transportation of cement, sand and fly ash to the plant is assumed to be 100 km (Nisbet and Van Geem, 1997). The size of lorry used is16-32 metric tons which is referring to the previous study conducted by Giani et al. (2015).

The compressive strength of the conventional PCC pavement and RA-PCC pavement at 14 days, 28 days, and 56 days are summarized in Table 3.5.

The compressive strength for the RA-PCC pavement at 56 days is 38.8 MPa, which is lesser than the conventional PCC pavement with 40.3 MPa. However, compressive strength for RA-PCC is still higher than 21 MPa, which is the minimum requirement of compressive strength for PCC pavement according to AASHTO guidelines (Crovetti, 2005). For PCC pavement with the replacement of natural aggregate by recycled aggregate shows a great potential to be used in road construction but RA replacement less than 50 % is recommended to be used in the road construction purposes (Jain et al., 2012). Table 3.6 shows the origin of each dataset involved in this pavement LCA study. The input for raw material production shown in Table 3.7. Besides, Figure 3.2, Figure 3.3, Figure 3.4 show the input data for conventional PCC pavement, RA-PCC pavement, and production of recycled aggregate respectively.

Table 3.2: Mix Design of Conventional PCC Pavement (Jain et al., 2012, Prasittisopin et al., 2017)

Conventional PCC Pavement			
Input data	**Amount (tons)**		**Total (tons)**
	Base	Subbase	
Portland Cement (tons)	628.26		628.26
Fly ash (tons)	143.60		143.60
Natural aggregate (tons)	2455.61	3447.77	5903.38
Sand (tons)	2125.32		2125.32
Water (tons)	306.88		306.88
Recycled coarse aggregate (tons)	0	0	0.00

Table 3.3: Mix Design of RA-PCC Pavement (Jain et al., 2012, Prasittisopin et al., 2017)

RA-PCC Pavement			
Input data	**Amount (tons)**		**Total (tons)**
	Base	Subbase	
Portland Cement (tons)	639.03		639.03
Fly ash (tons)	143.60		143.60
Natural aggregate (tons)	0	0	0.00
Sand (tons)	2039.16		2039.16
Water (tons)	315.35		315.35
Recycled coarse aggregate (tons)	2268.92	3447.77	5716.69

Table 3.4: Input for Manufacturing of 1ton Aggregate (Rosado et al., 2017)

Consumption	NA Production	RA Production
Natural Aggregate (t)	1.05	-
C&D Waste (t)	-	1.25
Electricity (kWh)	3.72	2.22
Diesel (MJ)	8.28	19.55
Lubricating Oil (kg)	0.006	0.008
Water (L)	8.07	0.80

NA: Natural aggregate; RA: Recycled aggregate

Table 3.5: Compressive Strength of Concrete Pavement (Jain et al., 2012)

Percentage of Recycled Aggregate	Compressive Strength (MPa)		
	14days	28days	56days
0 %	32.04	37.2	40.3
100 %	32.04	37.9	38.8

Table 3.6: Origin of dataset

Dataset	Origin
Portland Cement	Switzerland
Coarse Aggregate	Switzerland
Tap water	Switzerland
Fly ash	Switzerland
Sand	Switzerland
Energy Usage	Switzerland
Lubricating oil	Rest of World
Transportation	Rest of World
Diesel	Global

Table 3.7: Input for Raw Material Production (Ecoinvent, 2020)

Material	LCI Data Source	Data Quality Assessment
Cement, Portland	cement production, Portland | cement, Portland | APOS, U	• The dataset describes the production of cement (CEM I) in Switzerland and covers the representative production mix of CEM I 42.5 und CEM I 52.5 R as defined in EN 197-1. • The activity starts with the clinker in the silo to be used for cement production and with the additional ingredients of the cement at the gate of the cement plant. • The activity includes also the electricity used for the grinding of the clinker, grinding aids, heat for the drying of additions etc. and ends with the cement produced in the cement mill. The dataset does not include packaging and administration.
Energy usage at concrete mixing plant	unreinforced concrete production, with cement CEM II/A | concrete, normal | APOS, U	• This dataset contains the production of unreinforced concrete with cement without contain any reinforcement steel or other metals. It can be used in all exposition classes, except for applications with exposure to frost with or without de-icing agents, to abrasion or to chemicals; for concrete with reinforcement, the application shall be very dry, e.g. in buildings with very low humidity.

Table 3.7 (Continued)

Fly ash	Ecoinvent process: treatment of fly ash and scrubber sludge, hazardous waste incineration | fly ash and scrubber sludge | APOS, U	• Inventoried waste contains 100 % separator sludge; waste composition (wet, in ppm): upper heating value 0.9 MJ/kg • waste-specific air and water emissions from incineration, auxiliary material consumption for flue gas cleaning.
Gravel, crushed	gravel production, crushed | gravel, crushed | APOS, U	• This dataset represents the production of 1 kg of crushed gravel. From the total amount (100 %) of mined gravel round, crushed and sand, about 15 % is crushed gravel. From gravel at ground, unexcavated. • This activity ends with the crushed gravel produced and the recultivation process done. This dataset includes the whole manufacturing process, internal processes (transport, etc.) and infrastructure.

Table 3.7 (Continued)

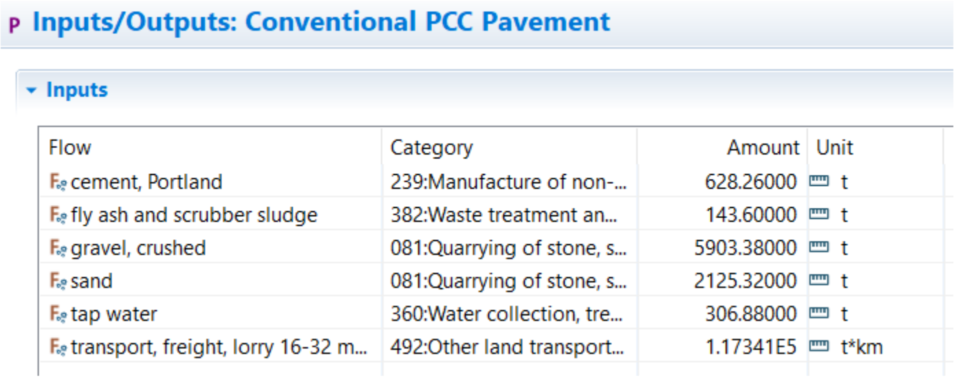
Sand	gravel and sand quarry operation | gravel, round | APOS, U	• This dataset corresponds to the production of 1 kg of sand (35 %) and gravel (65 %). From the total sectoral production volume (100 %) of mined gravel round, crushed and sand, about 85 % is gravel round and sand This activity ends with the gravel and sand dogged and the recultivation process done.
Tap water	tap water production, conventional treatment | tap water | APOS, U	• This dataset represents production of 1 kg of tap water under pressure at facility gate, ready for distribution in network. It represents average operation of conventional treatment for production tap water. Conventional treatment includes coagulation and decantation, filtration and disinfection. Other treatment such as oxidation (ultraviolet radiation, ozone) and other adjustment (pH, alkalinity, etc.) can be present in some plant.

Table 3.7 (Continued)

Transportation	transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | APOS, U	• This dataset represents the service of 1tkm freight transport in a lorry of the size class 16-32 metric tons gross vehicle weight (GVW) and Euro III emissions class. The transport datasets refer to the entire transport life cycle i.e. to the construction, operation, maintenance and end of life of vehicle and road infrastructures. • From combustion of fuel in the engine. The dataset takes as input the infrastructure of the lorry and road network, the materials and efforts needed for maintenance of these and the fuel consumed in the vehicle for the journey.
Diesel	diesel, burned in diesel-electric generating set, 10 MW | diesel, burned in diesel-electric generating set, 10 MW | APOS, U	• Generic module to estimate emissions due to the use of diesel during crude oil exploration. From cradle, i.e. including all upstream activities. Diesel consumption, emissions and infrastructure for the use of diesel in electric generating sets. Transport to site not included.

Table 3.7 (Continued)

Lubricating oil	lubricating oil production | lubricating oil | APOS, U	• This dataset represents the production of 1 kg of liquid lubricating oil, including additives. • The most important function of lubricants is the reduction of friction and wear. Apart from important applications in internal combustion engines, vehicle and industrial gearboxes, compressors, turbines, or hydraulic systems, there are a vast number of other applications which mostly require specifically tailored lubricants. • This dataset is based on literature and industrial data. The additives included in the lubricating oil are based on Raimondi et al. (2012). The energy consumption is approximated based on data from a large chemical factory (Gendorf, 2016).

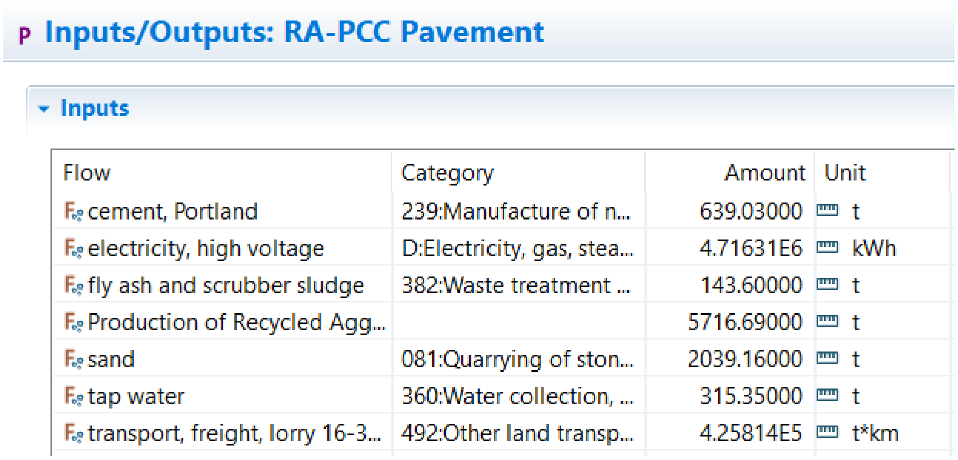


Inputs/Outputs: Conventional PCC Pavement

Inputs

Flow	Category	Amount	Unit
cement, Portland	239:Manufacture of non-...	628.26000	t
fly ash and scrubber sludge	382:Waste treatment an...	143.60000	t
gravel, crushed	081:Quarrying of stone, s...	5903.38000	t
sand	081:Quarrying of stone, s...	2125.32000	t
tap water	360:Water collection, tre...	306.88000	t
transport, freight, lorry 16-32 m...	492:Other land transport...	1.17341E5	t*km

Figure 3.2: Input Data of Conventional PCC Pavement

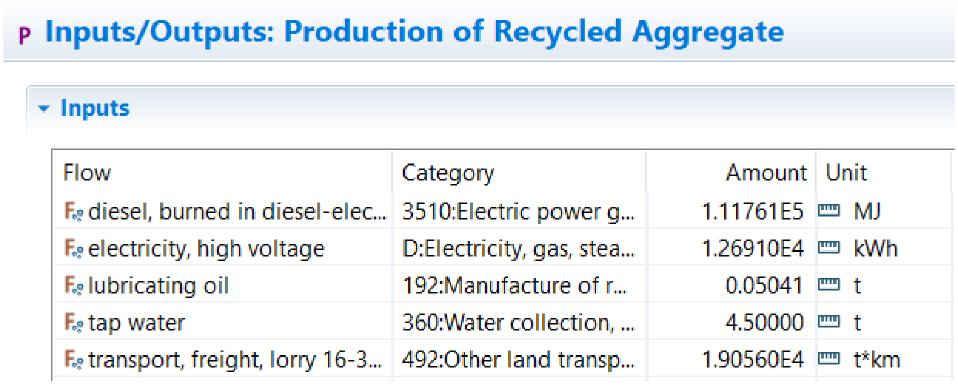


Inputs/Outputs: RA-PCC Pavement

Inputs

Flow	Category	Amount	Unit
cement, Portland	239:Manufacture of n...	639.03000	t
electricity, high voltage	D:Electricity, gas, stea...	4.71631E6	kWh
fly ash and scrubber sludge	382:Waste treatment ...	143.60000	t
Production of Recycled Agg...		5716.69000	t
sand	081:Quarrying of ston...	2039.16000	t
tap water	360:Water collection, ...	315.35000	t
transport, freight, lorry 16-3...	492:Other land transp...	4.25814E5	t*km

Figure 3.3: Input Data of RA-PCC Pavement



Inputs/Outputs: Production of Recycled Aggregate

Inputs

Flow	Category	Amount	Unit
diesel, burned in diesel-elec...	3510:Electric power g...	1.11761E5	MJ
electricity, high voltage	D:Electricity, gas, stea...	1.26910E4	kWh
lubricating oil	192:Manufacture of r...	0.05041	t
tap water	360:Water collection, ...	4.50000	t
transport, freight, lorry 16-3...	492:Other land transp...	1.90560E4	t*km

Figure 3.4: Input of Recycled Aggregate Production in openLCA

3.4 Life Cycle Impact Assessment

In the life cycle impact assessment (LCIA), the inventory is analyzed for environmental impacts. A comprehensive evaluation will be created where the input data is translated into the environmental impacts. LCIA evaluates the product life cycle based on the functional unit. The important steps involved in the LCIA are the selection of impact categories, classifying, characterizing, normalizing, grouping, and environmental impact integration (Tojo and Hirasawa, 2014). In this study, the environmental impacts of the pavements are evaluated using IMPACT 2002+ Endpoint method and ReCiPe Endpoint method. Both methodologies will assess the impacts based on their damage categories.

Firstly, impact categories are selected to determines which technique will be used to evaluate the environmental impacts such as global warming, resource consumption, ozone layer depletion, and so on. The impact assessment method used in this study was Endpoint method. In Endpoint method, four damage categories are commonly used to evaluate the environmental impacts: Human Health, Climate Change, Ecosystem Quality, and Resources. The next step is to classify the impacts, where the inventory data is sorted into their related impact categories and results in several substances being grouped into one impact category (Tojo and Hirasawa, 2014). For example, the cement and aggregate are grouped into resource consumption. Characterizing impacts involves assessing the environmental impacts of damage categories. The characterization factors that have been created for each environmental problem in the impact category are designated (Huijbregts et al., 2017). Next, it is necessary to normalize the assessment results obtained by characterizing each impact category in order to make relative comparisons (Tojo and Hirasawa, 2014). The impacts resulting from different categories will be grouped according to certain fixed conditions and continue with the integration of the environmental impacts. The total environmental impact is obtained by quantifying the impact of these categories. The procedure for conducting the life cycle impact assessment is summarised in Figure 3.5.

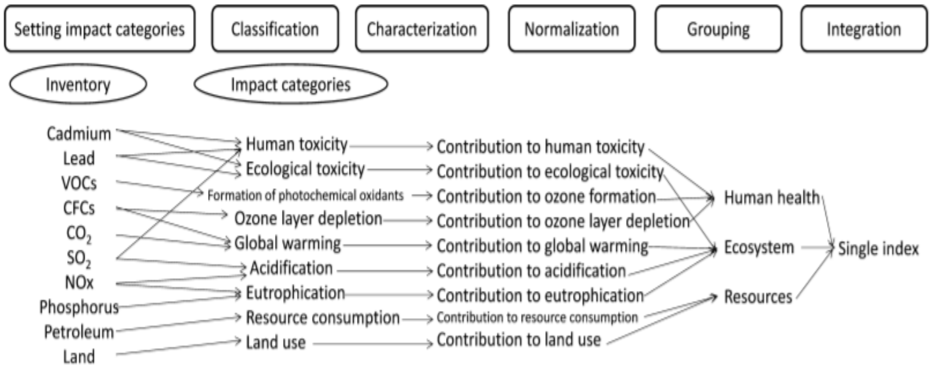


Figure 3.5: Procedure for conducting life cycle impact assessment (Tojo and Hirasawa, 2014)

3.5 Life Cycle Interpretation

The environmental impacts of the conventional PCC pavement and RA-PCC pavement were compared according to their damage categories. IMPACT 2002+ Endpoint method will evaluate the impacts in four endpoint damage categories (Ecosystem Quality, Climate Change, Resources, and Human Health) while the ReCiPe Endpoint method evaluates the impacts in three endpoint damage categories (Ecosystem Quality, Resource, and Human Health).

Life cycle assessments commonly assess damage to human health using the concept of disability-adjusted life years (DALYs) which is dominated by respiratory effects caused by inorganic substances emitted into the air (Humbert et al., 2005). In ReCiPe Endpoint method, the “human health” damage category is the sum of the midpoint categories of human toxicity, ozone layer depletion, ionizing radiation photochemical, ozone form, particular form, and climate change. For IMPACTS 2002+ Endpoint method, the damage from the pavements to the “human health” is quantified by the sum of the impacts from human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, and photochemical oxidation (Menoufi, 2011). Ecosystems are heterogeneous and very complex to monitor. One approach to describing ecosystem quality is in terms of energy, matter, and information flows (Laurin and Dhaliwal, 2017). Ecosystem quality in LCA was expressed as the potentially disappeared fraction of species (PDF) integrated over area and time. The respective damage unit is PDF×m^2×yr for both IMPACTS 2002+ Endpoint method and ReCiPe Endpoint method. In other words, the amount of damage to the ecosystems is quantified based on the fraction of species that disappeared on 1 m^2 of the earth's surface during one year (Laurin and Dhaliwal, 2017).

The resource depletion and rising of the material demand may increase the market prices, which could also negatively affect the ability to maintain and expand the man-made environment (Goedkoop et al., 2009). In ReCiPe Endpoint method, the increased cost is used to weight the damage to the Resources. In IMPACTS 2002+ Endpoint method, MJ ("Mega Joules") is used to measures the amount of energy required to extract the resource. In addition, the damage category "Climate change" is the same category as the midpoint category "global warming" where the impact is expressed in "kg CO_2-eq" (Humbert et al., 2005). The influence of the LCIA method on the ranking of the pavement options was investigated for each impact category within each methodology. The total impact score was calculated by total up the scores of the indicators of each category. The concrete pavement with lesser emission or to say the lesser environmental impact was recommended.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the results of life cycle impact assessment of 1 km of conventional concrete pavement with the RA-PCC pavement using IMPACT 2002+ and ReCiPe Endpoint methods. The impact categories investigated including Ecosystem Quality, Human Health, Climate Change, and Resources. The impact score is calculated by total up the value of the indicators of each category and showed in the bar chart. The greater score values indicated the pavements generated higher impacts to the environment compared to lower values. Besides, the difference between conventional pavement and RA-PCC pavement and the comparison of the impact results by using IMPACT 2002+ and ReCiPe Endpoint methods were discussed in this chapter as well.

4.2 LCIA using IMPACT 2002+ Endpoint Method

The impact assessment results for the conventional pavement and RA-PCC pavement by IMPACT 2002+ Endpoint method were presented and compared in the bar charts of Figure 4.1. The positive value in the bar chart indicates that the net effect is damage on the environment, while the negative value indicates that the credits are larger than the burdens and give a positive impact to the environment by avoiding certain emissions to the environment. The overall performance of RA-PCC pavement appears better, as it has remarkable environmental benefits in the damage categories of Ecosystem Quality and Resources. For the Ecosystem Quality and Resources categories, both pavements showed negative values, the higher negative values by the RA-PCC pavement indicated it contributes greater positive impacts compared to the conventional pavement.

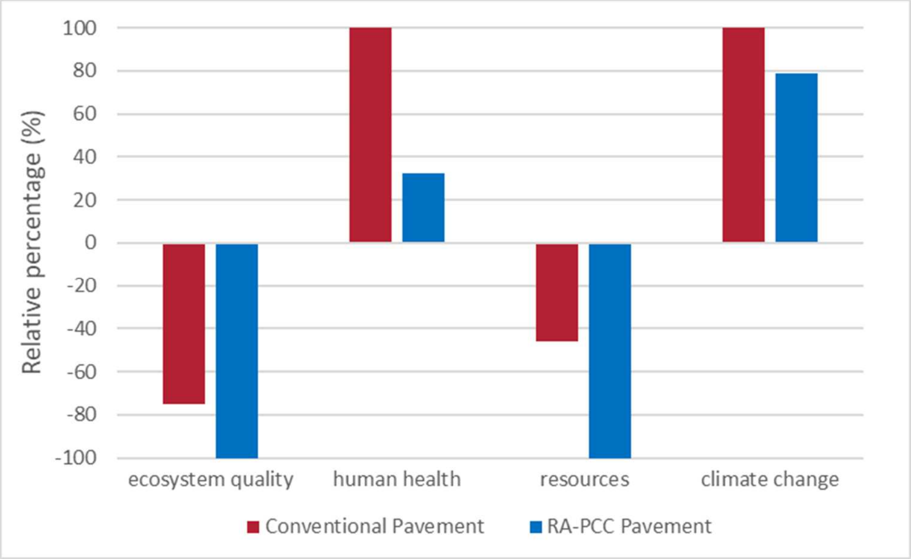


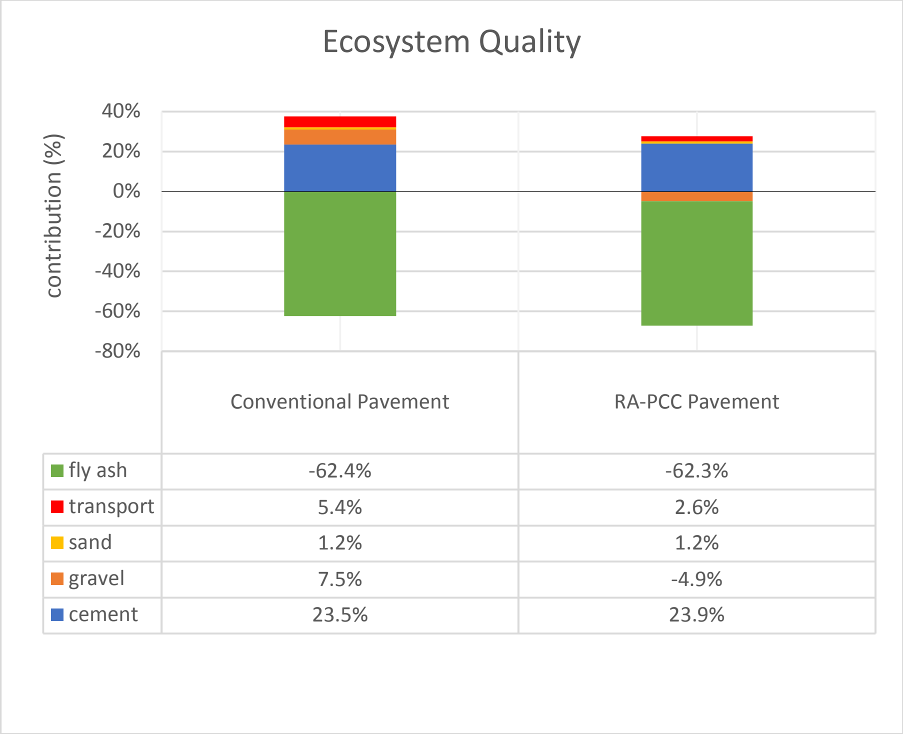
Figure 4.1: Relative Results for the Selected Impact Assessment Categories by IMPACT 2002+ Endpoint Method

Figure 4.2, Figure 4.3, Figure 4.4, and Figure 4.5 showed the contribution of 1 km of conventional pavement and RA-PCC pavement for the impact category of Ecosystem Quality, Human Health, Resources, and Climate Change by IMPACT 2002+ Endpoint method. Fly ash is the highest contributor of positive impact in all categories except Climate Change category. This is due to the use of fly ash in the pavements can create a credit to the environment by avoiding the impacts from the disposal of the fly ash at the landfill. In Climate Change category, cement production generated a large amount of CO_2 which contributes more than 50 % of the total impact. The negative impact from the natural aggregate is about 5.5 %, while the positive impact from recycled aggregate is about 4.4 % in the Climate Change category. Both pavements have the almost equal contribution of the environmental impacts from the production of sand and tap water. The impact from the tap water was less than 0.1 % which was ignored in this study.

Besides, the contribution of the transportation of the RA-PCC pavement was lower compared to the conventional pavement in all the categories. These have resulted from the differences in the transportation distance of the aggregate used. The natural aggregates are obtained from the rural area which is located far from the factory, while the recycled aggregate factory is located closer to the pavement factory, and therefore the impacts generated from the combustion of the fossil fuel in the transportation for the RA-PCC pavement is always lower when compared to the conventional pavement.

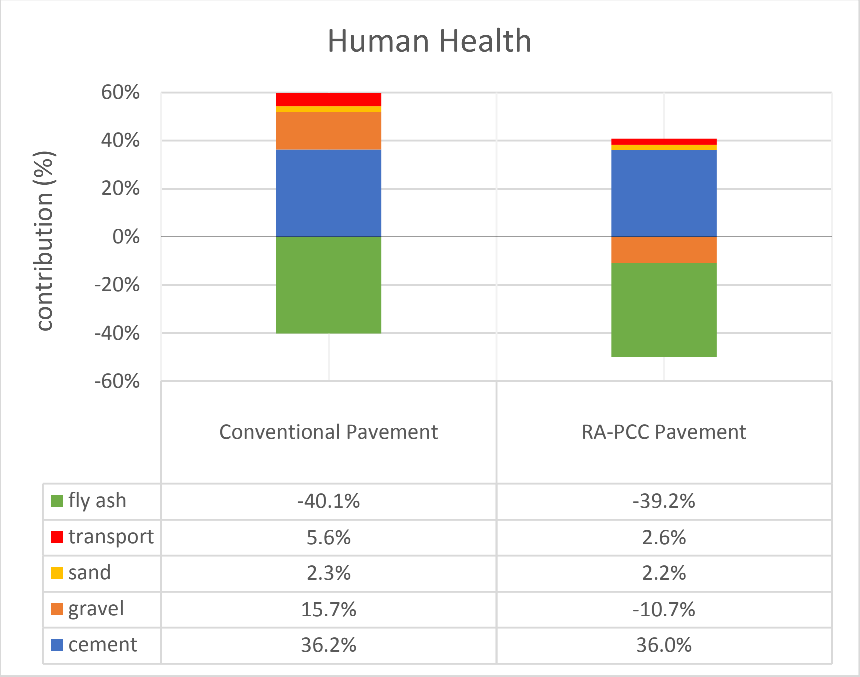
With the replacement of the natural aggregate by the recycled aggregate in the pavement, most of the impacts from the aggregate production were avoided. This can be clearly observed from the results of Ecosystem Quality category; the natural aggregate contributes about 7.5 % of the impacts while the recycled aggregate contributes -4.9 % of the impacts. In addition, significant environmental benefits were obtained from the avoided landfilling of aggregate wastes and the recycling of the aggregate which reduced the need for mining and production of natural aggregate. Also, the low energy consumption and CO_2 emission in the production of recycled aggregate generated a positive impact of -4.39 MJ in the Resources category.

For the Human Health, the result also showed a negative value that builds up -10.7 % of emissions to produce recycled aggregate. The consumption during the aggregate recycling process contributed to the additional environmental impacts. Under APOS method, the negative impacts were offset by the avoided impact from the natural aggregate production (Ponsioen, 2019). When summed up the scores, the impacts from the concrete pavement with recycled aggregate as replacement is lower than the conventional pavement in all the categories discussed under IMPACT 2002+ Endpoint method. Table 4.1 and Table 4.2 showed the contribution of individual processes in the manufacturing of the conventional pavement and RA-PCC pavement respectively.



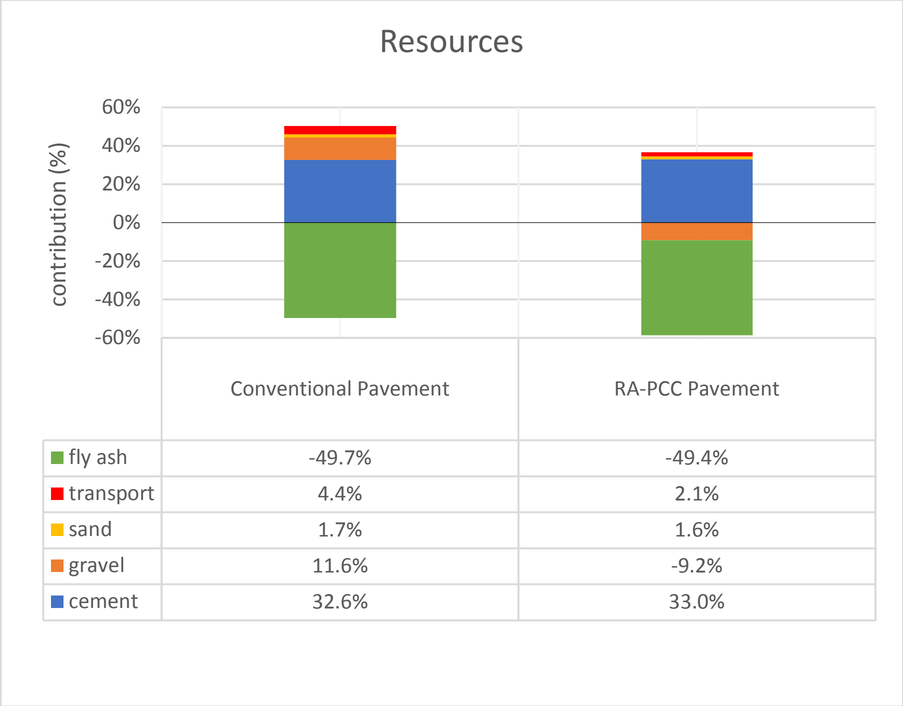
	Conventional Pavement	RA-PCC Pavement
🟩 fly ash	-62.4%	-62.3%
🟥 transport	5.4%	2.6%
🟨 sand	1.2%	1.2%
🟧 gravel	7.5%	-4.9%
🟦 cement	23.5%	23.9%

Figure 4.2: Ecosystem Quality Impact as Measured by IMPACT 2002+ Endpoint Method



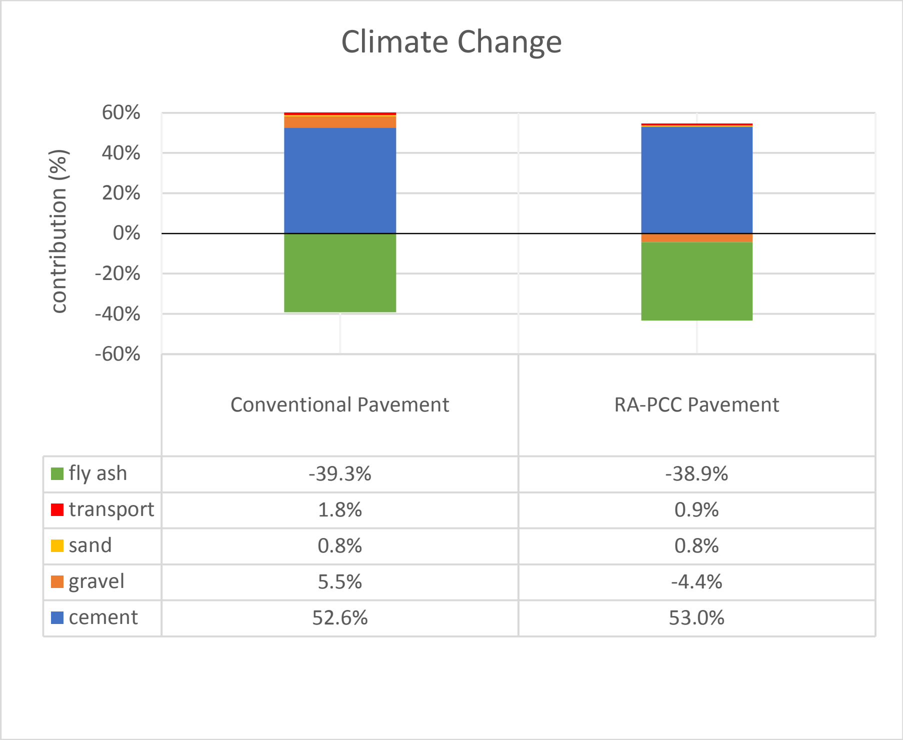
	Conventional Pavement	RA-PCC Pavement
🟩 fly ash	-40.1%	-39.2%
🟥 transport	5.6%	2.6%
🟨 sand	2.3%	2.2%
🟧 gravel	15.7%	-10.7%
🟦 cement	36.2%	36.0%

Figure 4.3: Human Health Impact as Measured by IMPACT 2002+ Endpoint Method



	Conventional Pavement	RA-PCC Pavement
🟩 fly ash	-49.7%	-49.4%
🟥 transport	4.4%	2.1%
🟨 sand	1.7%	1.6%
🟧 gravel	11.6%	-9.2%
🟦 cement	32.6%	33.0%

Figure 4.4: Resources Impact as Measured by IMPACT 2002+ Endpoint Method



	Conventional Pavement	RA-PCC Pavement
🟩 fly ash	-39.3%	-38.9%
🟥 transport	1.8%	0.9%
🟨 sand	0.8%	0.8%
🟧 gravel	5.5%	-4.4%
🟦 cement	52.6%	53.0%

Figure 4.5: Climate Change Impact as Measured by IMPACT 2002+ Endpoint Method

Table 4.1: Contribution of Individual Processes in Manufacturing of Conventional Pavement by IMPACT 2002+ Endpoint Method

Process	**Impact Categories**			
	Ecosystem Quality (PDF×m^2×yr)	**Human Health (DALYs)**	**Resources (MJ)**	**Climate Change (kg CO$_2$-eq)**
Fly ash	-11.59	-39.63	-23.7	-42.02
Transport	1.01	5.54	2.1	1.93
Sand	0.23	2.29	0.74	0.87
Gravel	1.39	15.53	3.14	5.88
Cement	4.37	35.80	15.4	56.32

Table 4.2: Contribution of Individual Processes in Manufacturing of RA-PCC Pavement by IMPACT 2002+ Endpoint Method

Process	**Impact Categories**			
	Ecosystem Quality (PDF×m^2×yr)	**Human Health (DALYs)**	**Resources (MJ)**	**Climate Change (kg CO$_2$-eq)**
Fly ash	-11.59	-39.63	-23.7	-42.02
Transport	0.49	2.67	1.01	0.93
Sand	0.22	2.20	0.75	0.83
Gravel	-0.90	-10.88	-1.11	-4.78
Cement	4.44	36.41	15.7	57.29

4.3 LCIA using ReCiPe Endpoint Method

The impacts results generated by the ReCiPe Endpoint method were presented and compared in the bar charts of Figure 4.6. To allow comparison across the pavements in the contribution patterns, the impact scores were converted into common metrics for each impact category. The maximum result was set to 100 % and the results of the other variants are displayed in relation to this result. The results comparing both types of pavements showed that RA-PCC pavement has lower impact values compared to the conventional pavement in all categories. In the Human Health and Resources categories, RA-PCC pavement resulted in a negative score, meaning that any environmental burdens have been avoided, in contrast to the conventional pavement that resulted in a positive value. In this study, the environmental impacts are strongly related to the types of aggregate used in the pavement.

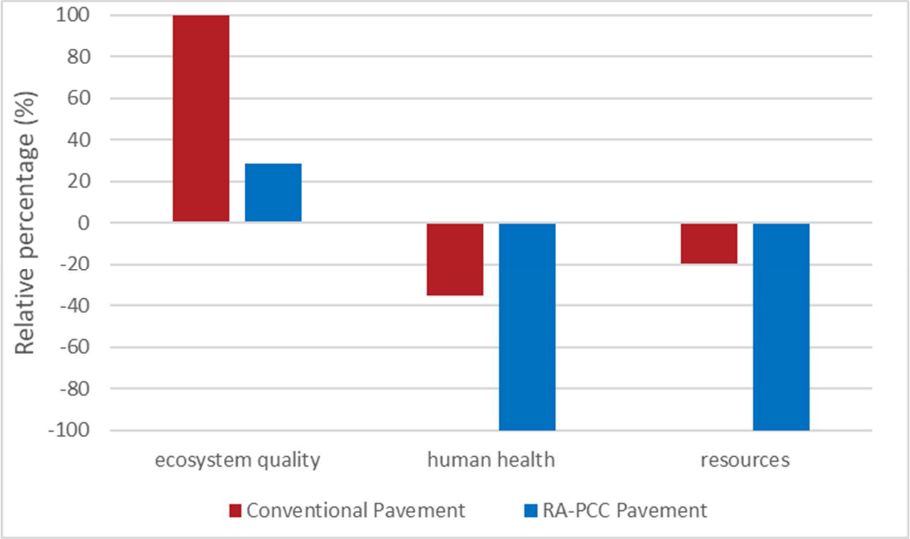


Figure 4.6: Relative Results for the Selected Impact Assessment Categories by ReCiPe Endpoint Method

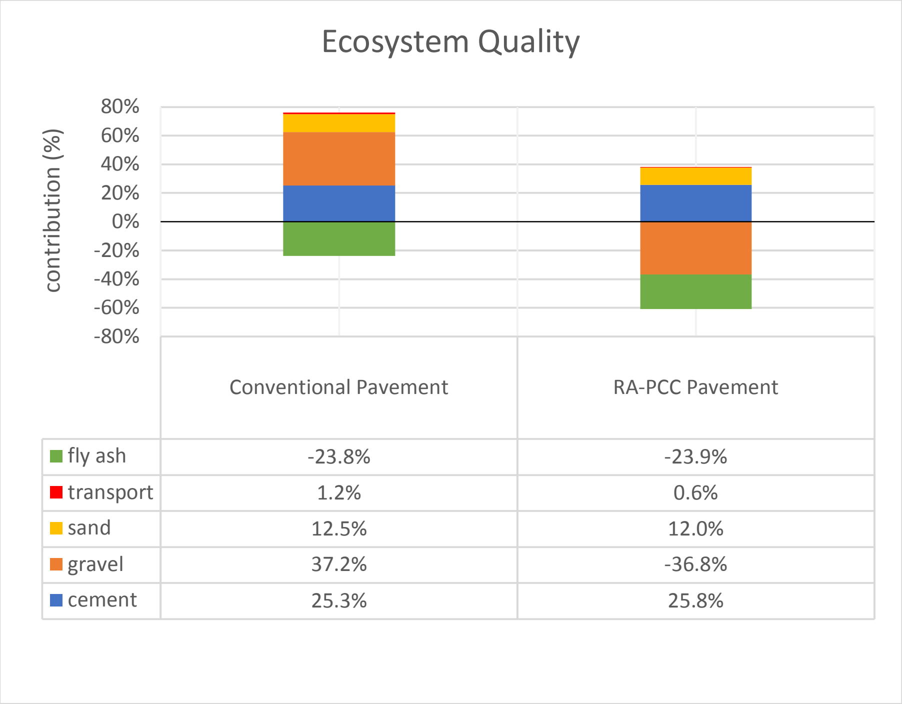
Figure 4.7, Figure 4.8, Figure 4.9, and Figure 4.10 showed the contribution of 1 km conventional pavement and RA-PCC pavement for impact category of Ecosystem Quality, Human Health, and Resources. Under ReCiPe Endpoint method, a major percentage of recycled aggregate in the RA-PCC pavement reflected an improvement of all the parameters analyzed in each category. The results showed fly ash is the main credit for both pavements in Human Health and Resources categories. This is related to the avoided landfill and transportation that has a significant amount of emissions avoided during the process.

In Ecosystem Quality category, the main contributor is the aggregate which occupied 37.2 % of total impacts. With the use of recycled aggregate in the pavement, the negative impacts generated from natural aggregate production were avoided, at the same time aggregate recycling and reuse in the RA-PCC pavement reflected a positive impact of -26555.35 PDF×m^2×yr. Despite there is more cement required in the manufacturing of RA-PCC pavement, however, the negative impacts from the cement were enough to balance out by the credits from the recycled aggregate.

Moving from the use of natural aggregate to recycled aggregate in the pavement, there was a reduction of the total score of about 65 % in the Human Health category, which can permit to reduce the total score of about 19.3 %. The production of recycled aggregate contributed additional impacts of 1199.5 DALYs in the Human Health category. The main contributor of this additional environmental impact in aggregate recycling is the high consumption of the diesel involved. The consumption of diesel contributed 623.2 DAYLs which were allocated for the crushing, debris removal, and sieving during the recycling process. However, the RA-PCC showed -9077.26 DAYLs after considering the avoided impacts from the natural aggregate production and benefits to the environment.

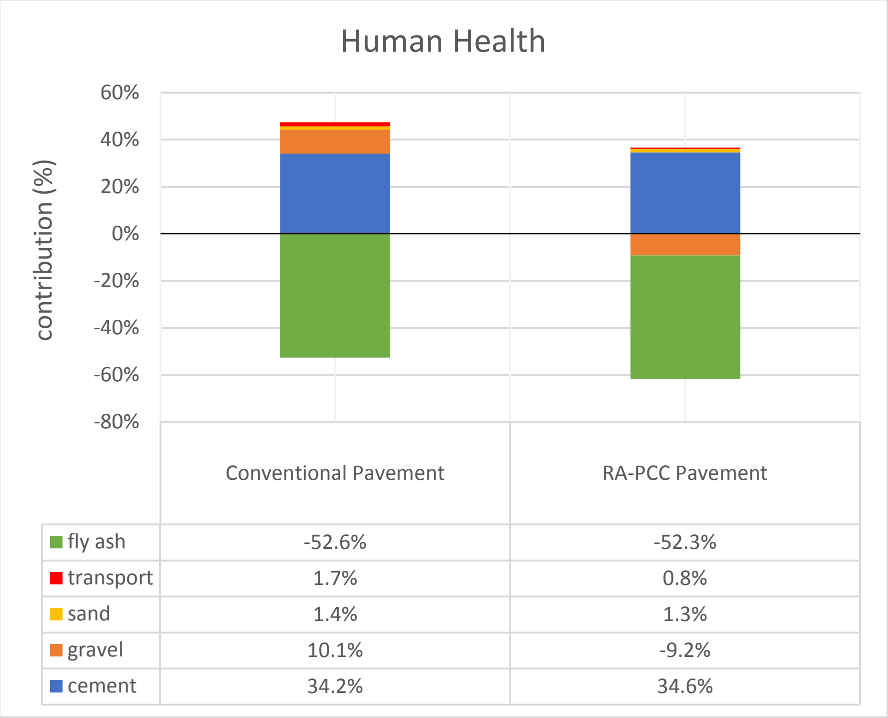
The positive impacts in the Resources are mainly due to the recycling of the aggregate, while the avoided impacts are related to the use of fly ash in the pavement. On the other hand, replacing the natural aggregate in concrete pavement allowed reduction of impacts in the Resources category, not only avoided 11.4 % impacts from natural aggregate, but also contributed 9.1 % of the positive impacts under APOS method. This was due to the recycling process requires fewer steps than the natural aggregate production which was avoided the environmental burdens. The increased cost reduced from -$545.17 to -$ 5177.35 when switching to the RA-PCC pavement.

Table 4.3 and Table 4.4 showed the contribution of individual processes in the manufacturing of the conventional pavement and RA-PCC pavement, using ReCiPe Endpoint method. The negative values of the gravel production in the RA-PCC pavement reflected the positive impacts by the recycled aggregate as the replacement for the natural aggregate in the pavement.



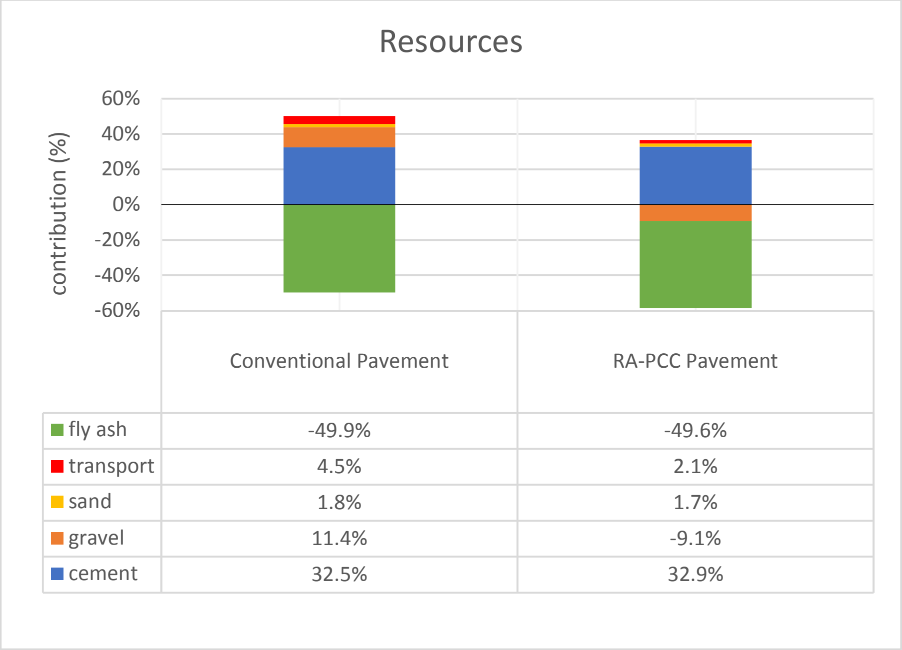
	Conventional Pavement	RA-PCC Pavement
🟩 fly ash	-23.8%	-23.9%
🟥 transport	1.2%	0.6%
🟨 sand	12.5%	12.0%
🟧 gravel	37.2%	-36.8%
🟦 cement	25.3%	25.8%

Figure 4.7: Ecosystem Quality Impact as Measured by ReCiPe Endpoint Method



	Conventional Pavement	RA-PCC Pavement
🟩 fly ash	-52.6%	-52.3%
🟥 transport	1.7%	0.8%
🟨 sand	1.4%	1.3%
🟧 gravel	10.1%	-9.2%
🟦 cement	34.2%	34.6%

Figure 4.8: Human Health Impact as Measured by ReCiPe Endpoint Method



	Conventional Pavement	RA-PCC Pavement
🟩 fly ash	-49.9%	-49.6%
🟥 transport	4.5%	2.1%
🟨 sand	1.8%	1.7%
🟧 gravel	11.4%	-9.1%
🟦 cement	32.5%	32.9%

Figure 4.9: Resources Impact as Measured by ReCiPe Endpoint Method

Table 4.3: Contribution of Individual Processes in Manufacturing of Conventional Pavement by ReCiPe Endpoint Method

Process	**Impact Categories**		
	Ecosystem Quality ($PDF \times m^2 \times yr$)	**Human Health (DAYLs)**	**Resources ($)**
Fly ash	-17205.80	-52093.10	-10927.20
Transport	862.19	1672.79	926.14
Sand	9050.92	1363.21	362.71
Gravel	26889.00	10039.10	2368.04
Cement	18272.20	33884.80	6725.14

Table 4.4: Contribution of Individual Processes in Manufacturing of RA-PCC Pavement by ReCiPe Endpoint Method

Process	**Impact Categories**		
	Ecosystem Quality ($PDF \times m^2 \times yr$)	**Human Health (DAYLs)**	**Resources ($)**
Fly ash	-17205.80	-52093.10	-10927.20
Transport	416.48	808.03	447.37
Sand	8683.99	1307.95	348.00
Gravel	-26555.35	-9077.26	-1885.95
Cement	18585.50	34465.70	6840.43

4.4 Comparison of Conventional Concrete Pavement with RA-PCC Pavement

From the LCIA results, the overall performance of the RA-PCC pavement is more environmentally friendly compared to conventional pavement. The environmental impacts caused by the pavements are mainly subjected to the amount of cement, aggregate, and fly ash, as well as the water, electricity, and transportation that contributed to an insignificant impact. However, the aggregate is the main contributor to the differences of the impact score in most of the damage category and this is due to huge amount of the natural aggregate has been replaced in the RA-PCC pavement. Furthermore, the use of natural aggregate in concrete pavement contributes a lot of negative impacts such as high CO_2 emissions, high energy consumption, as well as accelerate the depletion of natural resources. In fact, natural aggregate production in the conventional pavement is the process that caused a major impact on the environment.

The utilization of aggregate waste would minimize the natural aggregate used in pavement construction leading to conservation. According to the research done by Purdue University (2011), recycled aggregate can reduce the construction cost of the pavement by as much as 20 %. Despite the RA-PCC pavement would reduce the construction cost, a conventional concrete pavement is still more widely used and adopted generally in the pavement industry. This is because of the low distribution of facilities to recycle the aggregate and a significant hauling distance is possible. According to Verian et al. (2013), there are only 20 of the 92 counties in Indiana have a facility that accepts C&D wastes and reuses for base and subbase of pavement. Therefore, the pavement industries should improve their facilities and technologies to increase the application of recycled aggregate in the concrete pavement, which is a sustainable solution and benefits to the environment.

The RA-PCC pavement has a lesser environmental impact, but it has affected the performance of the pavement. The abrasion resistance of RA-PCC pavement is 7.4 % lower than conventional pavement due to the residual mortar on the surface of recycled aggregate (Jindal et al., 2014). Moreover, the mortar also increased the water absorption of the recycled aggregate which make the water consumption of RA-PCC pavement higher than conventional pavement by 4.22 %. Both pavements have almost equal compressive strength, which is between 40.3 MPa and 38.3 MPa. In terms of design service life, the conventional pavement was designed to be 32 years and 27 years for RA-PCC pavement. Additionally, maintenances of RA-PCC pavement is more frequent than conventional pavement due to the lower durability of RA-PCC pavement (Shi et al., 2019). Thus, a higher maintenances cost of the RA-PCC pavement is needed for long-term performance of the pavement.

4.5 LCA Methods Comparison

In this study, IMPACT 2002+ and Recipe Endpoint methods have been chosen because they are able to calculate and compare the impact scores of Human Health, Ecosystem Quality, and Resources categories. The measurement units of both methods allow a direct comparison in the Ecosystem Quality and Human Health categories. In Human Health category, IMPACT 2002+ gives a negative impact but ReCiPe gives a positive impact for both pavements. This is because weighting coefficient of the fly ash evaluated by ReCiPe is higher as compared to IMPACT 2002+, the high positive impacts generated by ReCiPe and made the overall performance of the pavements benefit to the environment. For Ecosystem Quality, ReCiPe gives a higher impact to the environment due to the high weighting coefficient of the sand. The negative impacts of sand generated by ReCiPe is higher compared to IMPACT 2002+ and increased its environmental impacts. Furthermore, IMPACT 2002+ and ReCiPe have almost similar distribution pattern to the Resources category.

As far as the comparison of LCA methods were concerned, the comparison between the values of the indicators of IMPACT 2002+ and ReCiPe Endpoint methods should be avoided in this study. This is because the impact score by ReCiPe is much higher than IMPACT 2002+ and might affect the accuracy of the LCIA results of the pavements. Normally, a product will be evaluated and considered as the most harmful one, regardless of the method adopted. However, it is possible for a different product to be considered as the most harmful by different methods. This can be explained by the different weighting coefficients for each impact score by different LCA methods (Stavropoulos et al., 2016). Therefore, it is recommended to use more different assessment methods to increase the consistency and accuracy of the result.

4.6 Sustainability and Sustainable Development

The recycled aggregate used in the concrete pavement reduced the environmental impacts without affecting overall performance of the pavement. The compressive strength of RA-PCC pavement only reduced by 5 % as compared to the conventional pavement (Jain et al., 2012). Besides, the RA-PCC consumed a lower amount of raw materials which can decelerated the depletion of the natural resource. The RA-PCC pavement can also reduce amount of C&D wastes which is able to turn these wastes into construction material for the pavement, at the same time, the landfilling of these wastes was avoided. Lesser emission and natural resources consumption in the RA-PCC pavement is a sustainable solution in the pavement industries. Furthermore, the RA-PCC pavement can save up to 20 % of the construction cost compared to the conventional pavement (Purdue University, 2011). However, frequent maintenance of the surface of RA-PCC pavement may have required to ensure long-term performance of the pavement. The excavation may be also needed to add the base and subbase material to ensure the bearing capacity of the pavement within the limit range (Pourkhorshidi et al., 2020). The maintenance cost of RA-PCC pavement is higher, but it is still more economic due to low initial cost. In addition, the service life of conventional pavement and RA-PCC pavement are comparable. Thus, it is encouraged to use recycled aggregate in the concrete pavement.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This study evaluated the environmental impact of Portland cement concrete pavement containing recycled aggregate as the replacement material for the natural aggregate in the base and subbase under APOS method. The objectives of this study had been fulfilled which are identifying life cycle inventory of the pavements, determining and compare the environmental impacts from the manufacturing of conventional PCC pavement and RA-PCC pavement based on IMPACT 2002+ Endpoint method and ReCiPe Endpoint method.

The damage categories which has been analysed Included Human Health Climate Change, Ecosystem Quality and Resources. The results from both IMPACT 2002+ and ReCiPe Endpoint methods showed that the manufacturing of the conventional PCC pavement contributes a higher impact to the environment as compared to the RA-PCC pavement in all damage categories. The results were also tabulated in graphs which indicate the relative impact contribution of every material to the respective categories. It is noticed that the use of recycled aggregate in the pavement had significantly reduced the overall environmental impact of the pavement. This is due to the avoided impacts created the credits to the environment through the reduction of carbon emission during the natural aggregate production and other pollutants that were found in the transportation of the aggregate wastes and landfilling.

A large impact value was resulted by ReCiPe Endpoint method, while the result by IMPACT 2002+ Endpoint method showed a small impact value. The impact scores between both LCA methods have a huge difference due to the different weighting factors of each method, therefore a direct comparison of the results should be avoided in this study. However, in order to make the results of both LCA methods to be comparable, the weighting factors can be calculated for pairs of the methods (Stavropoulos et al., 2016).

Through this study, recycled aggregate was seen to be the potential material to substitute the natural aggregate in concrete pavement. The advantages to use the recycled aggregate include providing solution to the waste disposal problems of C&D wastes, reducing the consumption of natural resources, a more environmentally friendly way in the pavement industry to ensure the supply of construction minerals in future development. The construction cost of RA-PCC pavement saved up to 20 % compared to conventional pavement (Purdue University, 2011). Even though there is a 5 % of reduction in compressive strength and additional maintenance cost of the RA-PCC pavement, the low initial cost and its excellent performance has made it an economic production (Jain et al., 2012).

The RA-PCC pavement reduces the environmental impacts from mining and quarrying, turns the impacts into benefits of the economy, which the quality and performance of the pavement is keeping at an acceptable level, However, the application of recycled aggregate in the pavement is not a simple task because of the several factors that become barriers, which limit the change in the common practice of the industry. Thus, all parties involved in the pavement industry, including government should take-action such as providing funds, developing appropriate specifications, and encourage the use of recycled aggregate in pavement industry.

5.2 Limitation of Study

In this study, the life cycle assessment was limited to cradle-to-gate analysis, where processes from the extraction of raw materials until the construction stage of the pavement were included, while the use phase, and demolition phase have been excluded. There are only two impact assessment methods used and it is unable to obtain the accurate results. Besides, the system expansion was not included in defining the system boundary. Furthermore, the transportation distance is assumed according to the previous research which is 100 km for cement, sand, fly ash, and natural aggregate while 25 km for the recycled aggregate. It may be different from the actual transportation distance and lead to different emissions and fuel consumption. Due to the lack of local input and environmental information needed for the life cycle assessment, most of the environmental impact analyses were done based on the sources from Switzerland.

5.3 Recommendations

Based on the limitation of the study discussed, there are some recommendations that can be done for future research:

(i) The production of recycled aggregate from C&D wastes should be added to the database to improve the consistency of the analysis.

(ii) More data collection should be carried out in local manufacturing of concrete pavement as the existing data source of the pavement industry in Malaysia is insufficient.

(iii) The transportation detail is an important factor in this study. Hence, the study should be targeted at the specific road and at specific destinations.

(iv) Each factory has different consumption in manufacturing of the concrete pavement. Thus, data and information on the consumption of electricity and other energy should be collected from the targeted factory.

(v) System expansion should be included to increase the accuracy of the result.

(vi) Expansion of study can be done for cradle-to-cradle which includes a closed-loop recycling of the material.

(vii) More impact assessment methods can be adopted to make comparisons and enhance the accuracy of the analysis.

REFERENCES

Adajar, M. A., 2017. Utilization of Aggregate Quarry Waste in Construction Industry. *International Journal of GEOMATE*.

Adams, C. A., Amofa, N. Y. & Boahen, R., 2014. Effect of Geogrid Reinforced Subgrade on Layer Thickness Design of Low Volume Bituminous Sealed Road Pavements. *IRJES,* 3**,** 59-67.

Akhtar, A. & Sarmah, A. K., 2018. Construction and demolition waste generation and properties of recycled aggregate concrete: a global perspective. *Journal of Cleaner Production,* 186**,** 262-281.

Ali, A., Negm, A. M. & Bady, M., 2014 Estimating carbon emissions from industrial process by using life cycle assessment tool. IAC 2014: International Conference on Industry Academia Collaboration, Cairo, Egypt, 2014.

Bloom, E. F., Horstmeier, G. J., Ahlman, A. P., Edil, T. B. & Whited, G., 2016. Assessing the Life Cycle benefits of Recycled material in road construction. *Geo-Chicago 2016.*

Brilhuis-Meijer, E., 2014. Consider your audience when doing impact assessment. *Amersfoort, The Netherlands: Pré Consultants*.

Chesner, W. H., Collins, R. J., MacKay, M. H. & Emery, J., 2002. User guidelines for waste and by-product materials in pavement construction. Recycled Materials Resource Center.

Crawford, R., 2011a. *Life Cycle Assessment in the Built Environment*.

Crawford, R. H., 2011b. *Life Cycle Assessment in The Built Environment,* London and New York, Spon Press.

Crovetti, J. A., 2005. *Early opening of Portland Cement Concrete (PCC) pavements to traffic,* Wisconsin Highway Research Program.

Curran, M. A., 2017. Overview of goal and scope definition in life cycle assessment. *Goal and Scope Definition in Life Cycle Assessment.* Springer.

Danielsen, S. & Kuznetsova, E., 2015. Environmental impact and sustainability in aggregate production and use. *Engineering Geology for Society and Territory-Volume 5.* Springer.

Darabadi, B. K., Khiavi, A. K., Ouria, A. & Rasouli, R., 2018. Evaluation of the compactness of subbase and base geomaterials by using stiffness. *Sādhanā,* 43**,** 195.

De Haes, H. U. & Van Rooijen, M., 2005. Life Cycle Approaches–The road from analysis to practice. *UNEP/SETAC Life Cycle Initiative*.

Dhir, R. K., de Brito, J., Silva, R. V. & Lye, C. Q., 2019. 13 - Environmental Impact, Case Studies and Standards and Specifications. *In:* Dhir, R. K., de Brito, J., Silva, R. V. & Lye, C. Q. (eds.) *Sustainable Construction Materials.* Woodhead Publishing.

Ding, T., Xiao, J. & Tam, V. W., 2016. A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. *Waste management,* 56**,** 367-375.

Ecoinvent, 2020. Ecoinvent Database Search. Available at: https://v35.ecoquery.ecoinvent.org/Search/Index

Edil, T. B., 2011. Specifications and recommendations for recycled materials used as unbound base course.

Fadiya, O. O., Georgakis, P. & Chinyio, E., 2014. Quantitative Analysis of the Sources of Construction Waste. *Journal of Construction Engineering,* 2014**,** 651060.

Farina, A., Zanetti, M. C., Santagata, E. & Blengini, G. A., 2017. Life cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubber and reclaimed asphalt pavement. *Resources, Conservation and Recycling,* 117**,** 204-212.

Federal Highway Administration, 2004. *Transportation Applications of Recycled Concrete Aggregate: FHWA State of the Practice National Review*, Federal Highway Administration.

Freedonia Group, 2019. Global Construction Aggregates - Demand and Sales Forecasts, Market Share, Market Size, Market Leaders

Giani, M. I., Dotelli, G., Brandini, N. & Zampori, L., 2015. Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling. *Resources, Conservation and Recycling,* 104**,** 224-238.

Gnanendran, C. & Woodburn, L., 2003. Recycled Aggregate for Pavement Construction and the Influence of Stabilisation. *Publication of: ARRB Transport Research, Limited.*

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. & Van Zelm, R., 2009. ReCiPe 2008. *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level,* 1**,** 1-126.

GreenDeLTa, 2020. openLCA – the Life Cycle and Sustainability Modeling Suite. Available at: http://www.openlca.org/openlca/

Häkkinen and Mäkelä, 1996. Häkkinen, T. and Mäkelä, K., Environmental Impact of Concrete and Asphalt Pavements, in Environmental adaption of concrete. Technical Research Center of Finland. Research Notes 1752. 1996.

Harvey, J., Meijer, J. & Kendall, A., 2014. Life Cycle Assessment of Pavements:[Techbrief]. United States. Federal Highway Administration.

Huang, Y., 2007. *Life cycle assessment of use of recycled materials in asphalt pavements.* Newcastle University.

Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A. & van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment,* 22**,** 138-147.

Humbert, S., Margni, M. & Jolliet, O., 2005. IMPACT 2002+: user guide. *Draft for version,* 2.

ISO, 2006. International Standard ISO 14040. Switzerland: ISO copyright office. Available at: https://www.iso.org/standard/38498.html

Ivel, J., Watson, R., Abbassi, B. & Abu-Hamatteh, Z. S., 2019. Life cycle analysis of concrete and asphalt used in road pavements. *Environmental Engineering Research,* 25**,** 52-61.

Jacquemin, L., Pontalier, P.-Y. & Sablayrolles, C., 2012. Life cycle assessment (LCA) applied to the process industry: a review. *The International Journal of Life Cycle Assessment,* 17**,** 1028-1041.

Jain, J., Verian, K. P., Olek, J. & Whiting, N., 2012. Durability of pavement concretes made with recycled concrete aggregates. *Transportation research record,* 2290**,** 44-51.

Jindal, A., R.N, G. D. & Kumar, P., 2014. Recycled Concrete Aggregates for Rigid Pavements: A Review.

Jones, K., 2018. The Path to Green & Sustainable Construction. Available at: https://www.constructconnect.com/blog/path-green-sustainable-construction

Kabirifar, K., Mojtahedi, M., Wang, C. & Tam, V. W., 2020. Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. *Journal of Cleaner Production***,** 121265.

Kartam, N., Al-Mutairi, N., Al-Ghusain, I. & Al-Humoud, J., 2004. Environmental management of construction and demolition waste in Kuwait. *Waste management,* 24**,** 1049-1059.

Klee, H. Briefing: The Cement Sustainability Initiative. Proceedings of the Institution of Civil Engineers-Engineering Sustainability, 2004. Thomas Telford Ltd, 9-11.

Laurin, L. & Dhaliwal, H., 2017. Life cycle environmental impact assessment.

Lehtinen, H., Saarentaus, A., Rouhiainen, J., Pitts, M. & Azapagic, A., 2011. A review of LCA methods and tools and their suitability for SMEs. Europe Innova Eco-Innovation Bio Chem. Available at: http://www. biochem-project. eu/download/toolbox/sustainability/01/120321%20BIOCHEM% 20LCA_review. pdf. Accessed January, 17, 2014.

Li, J., Xiao, F., Zhang, L. & Amirkhanian, S. N., 2019. Life cycle assessment and life cycle cost analysis of recycled solid waste materials in highway pavement: A review. *Journal of Cleaner Production,* 233**,** 1182-1206.

Mahayuddin, S., Pereira, J., Badaruzzaman, W. & Mokhtar, M., 2008. Construction waste management in a developing country: case study of Ipoh, Malaysia. *WIT Transactions on Ecology and the Environment,* 109**,** 481-489.

Malešev, M., Radonjanin, V. & Broćeta, G., 2014. Properties of recycled aggregate concrete. *Contemporary Materials,* 5**,** 239-249.

Mälkki, H., 2011. Life Cycle Assessment (LCA). Available at: https://lpmc.lv/uploads/media/Life_Cycle_Assesment.pdf

Marinković, S., Ignjatović, I. & Radonjanin, V., 2013. Life-cycle assessment (LCA) of concrete with recycled aggregates (RAs). *Handbook of Recycled Concrete and Demolition Waste.* Elsevier.

Martinez-Arguelles, G., Acosta, M. P., Dugarte, M. & Fuentes, L., 2019. Life Cycle Assessment of Natural and Recycled Concrete Aggregate Production for Road Pavements Applications in the Northern Region of Colombia: Case Study. *Transportation Research Record,* 2673**,** 397-406.

Meininger, R. C. & Stokowski, S. J., 2011. Wherefore art thou aggregate resources for highways? *Public roads,* 75.

Menoufi, K. A. I., 2011. Life cycle analysis and life cyle impact assessment methodologies: a state of the art.

Mishra, G., 2019. Types of Pavements. Available at: https://theconstructor.org/transportation/types-of-pavement-flexible-and-rigid-pavement/9570/#:~:text=A%20rigid%20pavement%20is%20constructed,resists%20the%20loads%20from%20traffic.

Mitchell, C. Aggregate carbon demand: the hunt for low carbon aggregate. 16th extractive industry geology conference, Portsmouth, England, 2012.

MPA, 2017. Long-term aggregates demand & supply scenarios, 2016-30. Available at:https://www.openlca.org/wp-content/uploads/2017/11/openLCA1.7_User_Manual_v1.1.pdf (Accessed: 27 March)

Mroueh, U.-M., Eskola, P., Laine-Ylijoki, J., Wellman, K., Mäkelä, E., Juvankoski, M. & Ruotoistenmäki, A., 2000. Life cycle assessment of road construction. *Analysis*.

Noi, C. D., Ciroth, D. A. & Srocka, M., 2017. openLCA 1.7 [Online]. Germany: GreenDelta GmbH. Available: https://www.openlca.org/wp-content/uploads/2017/11/openLCA1.7_User_Manual_v1.1.pdf [Accessed 27 March 2019].

Nwanosike, A., Akande, W., A, O., M.O, J. & G, F., 2015. Assessment of the Geotechnical Properties of Lateritic Soils in Minna, North Central Nigeria for Road design and Construction. *American Journal of Mining and Metallurgy,* 3**,** 15-20.

Phummiphan, I., Horpibulsuk, S., Rachan, R., Arulrajah, A., Shen, S.-L. & Chindaprasirt, P., 2018. High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material. *Journal of hazardous materials,* 341**,** 257-267.

Ponsioen, T., 2019. Finding your way in multifunctional processes and recycling. *PRé Sustain*.

Prasittisopin, L., Hirunlabh, J. & Sereewatthanawut, I. Life cycle assessment of solid pavement system of recycle concrete aggregate in Thailand. The 6th International Conference on Sustainable Energy and Green Architecture Smart Buildings and Eco Innovation, 2017. 30-31.

Praticò, F. G., Giunta, M., Mistretta, M. & Gulotta, T. M., 2020. Energy and Environmental Life Cycle Assessment of Sustainable Pavement Materials and Technologies for Urban Roads. *Sustainability,* 12**,** 704.

Purdue University, 2011. Concrete recycling may cut highway construction cost, landfill use. Available at: purdue.edu/newsroom/research/2011/110421OlekConcrete.html

Rodriguez, J., 2019. Subbase or Subgrade: Improving Soil Conditions. Available at: https://www.thebalancesmb.com/what-is-a-subbase-or-subgrade-844583#:~:text=A%20solid%20subbase%20is%20a%20key%20to%20a%20successful%20building%20project.&text=A%20subbase%20will%20go%20on,prevent%20cracking%20and%20concrete%20spalling.

Roesler, J. R., Lange, D., Salas, A., Brand, A. S. & Arboleda, C., 2013. Properties of Recycled Concrete Aggregates for Airfield Rigid Pavements.

Rosado, L. P., Vitale, P., Penteado, C. S. G. & Arena, U., 2017. Life cycle assessment of natural and mixed recycled aggregate production in Brazil. *Journal of cleaner production,* 151**,** 634-642.

Sagoe-Crentsil, K. K., Brown, T. & Taylor, A. H., 2001. Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and concrete research,* 31**,** 707-712.

Sandrolini, F. & Franzoni, E., 2001. Waste wash water recycling in ready-mixed concrete plants. *Cement and concrete research,* 31**,** 485-489.

Santero, N., 2010. Life cycle assessment of pavements: a critical review of existing literature and research.

Shah, A., Mumaz, H., Qazi, E. & Naseer, S., 2012. *Reuse of municipal construction wastes as aggregates in concrete.*

Sharkawi, A. E.-D. M., Almofty, S. E.-D. M. & Abbass, E. S. M., 2016. Performance of Green Aggregate Produced by Recycling Demolition Construction Wastes (Case Study of Tanta City). *Engineering,* 8**,** 52-59.

Shi, X., Mukhopadhyay, A., Zollinger, D. & Grasley, Z., 2019. Economic input-output life cycle assessment of concrete pavement containing recycled concrete aggregate. *Journal of cleaner production,* 225**,** 414-425.

Snyder, M. B., 2018. Using Recycled Concrete Aggregate in Pavement Base Products. Available at: https://intrans.iastate.edu/app/uploads/2018/12/MAPbriefJul2018.pdf

Stajanča, M. & Eštoková, A., 2012. Environmental impacts of cement production. Available at: http://ena.lp.edu.ua:8080/bitstream/ntb/16692/1/55-Stajanca-296-302.pdf

Stripple, H., 2001. Life cycle assessment of road: a pilot study for inventory analysis. *IVL RAPPORT.*

Taffese, W. Z., 2018. Suitability investigation of recycled concrete aggregates for concrete production: an experimental case study. *Advances in Civil Engineering,* 2018.

The Concrete Society, 2019. Environmental Impact of Aggregates. Available at: http://www.concrete.org.uk/fingertips- nuggets.asp?cmd=display&id=148

Tojo, S. & Hirasawa, T., 2014. *Research approaches to sustainable biomass systems*, Academic Press.

Treloar, G., Love, P. & Smith, J. Streamlined Life Cycle Assessment: a method for considering environmental impact of road construction. 15th Annual Conference of the Association of Researchers in Construction Management (ARCOM), Liverpool, UK, 1999.

Treloar, G. J., Love, P. E. & Crawford, R. H., 2004. Hybrid life-cycle inventory for road construction and use. *Journal of construction engineering and management,* 130**,** 43-49.

Uhlmeyer, J. S. & Russell, M., 2018. Use of Recycled Concrete Aggregate in PCCP: Literature Search.

Vázquez, E., 2016. Recycled aggregates for concrete: problems and possible solutions. *International Journal of Earth & Environmental Sciences,* 2016.

Verian, K. P., Whiting, N. M., Olek, J., Jain, J. & Snyder, M. B., 2013. Using recycled concrete as aggregate in concrete pavements to reduce materials cost.

Verian, K. P., Whiting, N. M., Olek, J., Jain, J. & Snyder, M. B., 2013. Using recycled concrete as aggregate in concrete pavements to reduce materials cost. Purdue University. Joint Transportation Research Program.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. & Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment,* 21**,** 1218-1230.

WRAP, 2013. Aggregates from inert waste: End of waste criteria for the production of aggregates from inert waste. Available at: https://mineralproducts.org/documents/aggregates_quality_protocol.pdf