University of Southern Queensland

School of Engineering

Lifecycle Emissions of Different Pavement Types

A dissertation submitted by

Matthew Targett

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University of Southern Queensland

School of Engineering

ENP4111 Dissertation Project

(This is a 2-unit research project in Bachelor of Engineering Honours Program)

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CERTIFICATION

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Student Name: Matthew Targett
Student Number: [redacted]

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ABSTRACT

This project is on the comparison of lifecycle pavement emissions from different pavement types and aims to produce options to help reduce the greenhouse gas emissions (GHG) during the design phase of a road construction project. This study is broken down into three categories of roads: high traffic volume motorways, medium traffic volume regional highways and low traffic volume local roads.

The core objective of this research is to assess and compare the quantities of emissions produced by different pavement types when employed on high traffic volume motorways, medium traffic volume regional highways and low traffic volume local roads. Specifically, the research aims to:

1. Designing common pavements for the three different road categories across a range of traffic volumes. These categories are:
    a. Motorways: Concrete vs Asphalt Pavements
    b. Rural Highway: Asphalt vs Spray Sealed Granular Pavement
    c. Local Roads: Spray Sealed Granular vs Unsealed Granular Pavements
2. Determining the required maintenance for each pavement type.
3. Quantify the lifetime GHG emissions associated with the various pavement materials and construction machinery.
4. Substitute regular pavement construction materials with sustainable alternatives, which include:
    a. Geopolymer concrete
    b. Bio-bitumen
    c. Eco Asphalt
5. Identify the most environmentally sustainable pavement solutions for each road category.

This report includes a thorough review of available literature in the areas of road pavement design, construction materials, embodied emissions of materials and sustainable alternative materials used in road construction.

This project aims to identify major areas of potential emissions saving during the design phases of road construction projects without sacrificing pavement strength, design life or value for money.

Two case studies were also examined in this report and looked at and found that emissions could be reduced by up to 37% if more sustainable pavement designs were chosen.

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Chapter 1 INTRODUCTION

Australia possesses the 9th largest road network in the world, with over 817,000 kilometres from motorways to minor tracks. Approximately 355,000 kilometres of road are sealed roads, 257,000 kilometres are improved gravel surfaces, and the remaining 205,000 kilometres are low quality gravel tracks (Phillips, 2024). Road maintenance is usually managed by the relevant Federal, State or Local Government Agencies. Life cycle cost analysis of road pavements is a highly researched area that Government Agencies have been using to provide the best value to taxpayers.

The Australian Government has adopted a goal to reduce emissions by 43% on 2005 levels by 2030 and to reach net zero by 2050. The Department of Infrastructure, Transport, Regional Development, Communications and the Arts (2024, p. 2) reported that the Transport Sector is the third largest source of greenhouse gas emissions in Australia, totalling 21% of Australia's greenhouse gas emissions in 2023. The Australian Government has been considering alternatives to reduce emissions in the transport sector, including the construction of more alternate forms of transport such as rail, pedestrian and cyclist infrastructure. Another way to reduce emissions in the transport sector is to make informed decisions for the selection of the road pavement with the lowest life cycle emissions.

1.1 Climate Change

Climate change is caused by the gradual warming of the planet due to the increasing levels of greenhouse gases in the atmosphere. These greenhouse gases, such as CO_2, absorb the incoming energy from the sun consequently raising the surface temperature of the Earth.
The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BOM) (2022, p. 2) states that Australia's climate has warmed by an average of 1.47 ± 0.24°C since records began in 1910.

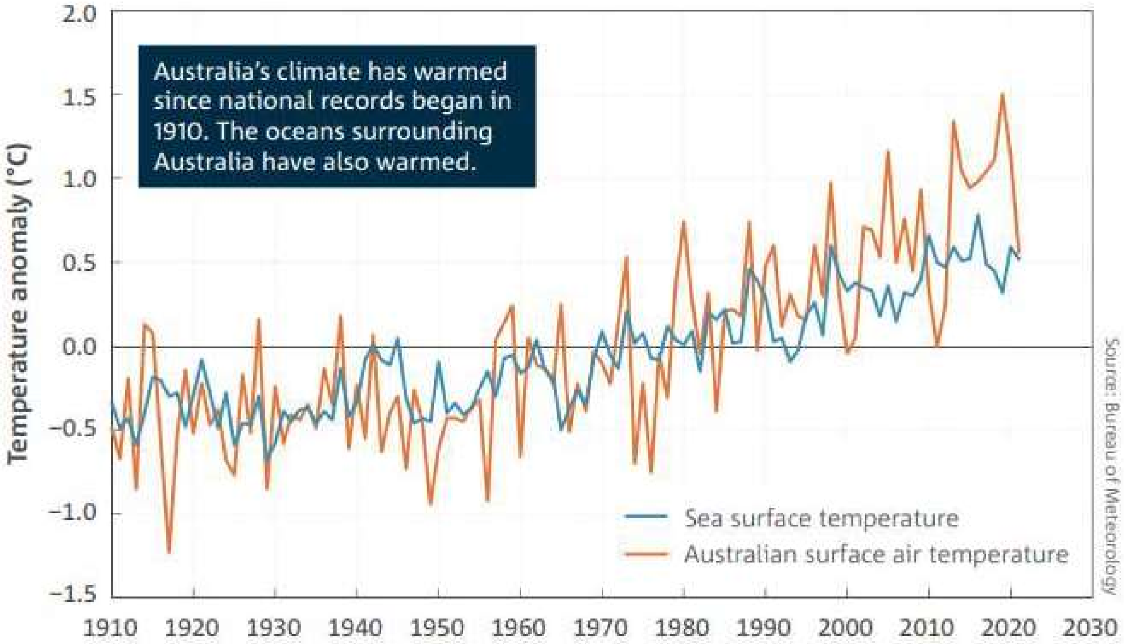


Figure 1.1 - anomalies in annual mean sea surface temperature, and temperature over land in Australia. (Source: Commonwealth Scientific and Industrial Research Organisation & Bureau of Meteorology 2022)

1.2 Road Pavements

The purpose of road pavements is to permit the simple transportation of people and goods to where they need to go. The pavement must maintain a good ride quality to ensure pleasant travel for all of the road's users. The road pavement must also have adequate skid resistance, drainage and delineation. In terms of structural performance, Austroads (2023) states the pavement must be of sufficient thickness, and be composed of materials of sufficient quality, to be able to withstand the various loads that are applied to it by heavy vehicles. The surface must also be capable of resisting both vertical and horizontal surface stresses in order to maintain its integrity. If the surface is lost, or cracked, then ride comfort is affected and water can enter the underlying base layers. It must also be capable of withstanding environmental loads, including oxidation of bituminous binders.

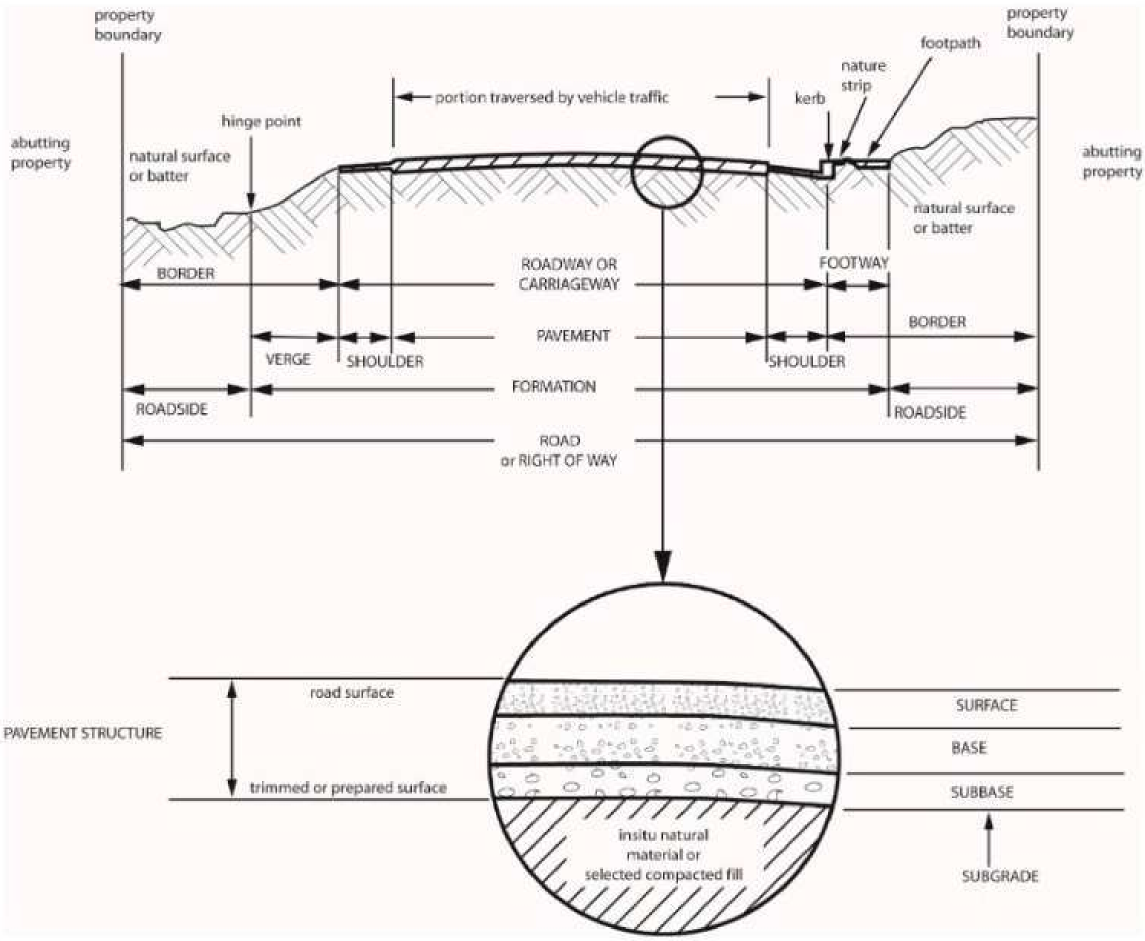


Figure 1.2 - Typical Road Pavement Structure (Source: Austroads 2023)

1.2.1 Rigid Pavement

Rigid pavements are constructed using concrete and were first used in Australia prior to 1930. Around 2% of the Australian road network is constructed using concrete and that consists of mostly major highways that require heavy duty pavements due to the high traffic usage. Concrete pavements can either be steel reinforced (continuously reinforced concrete pavement) or unreinforced (plain concrete pavement).

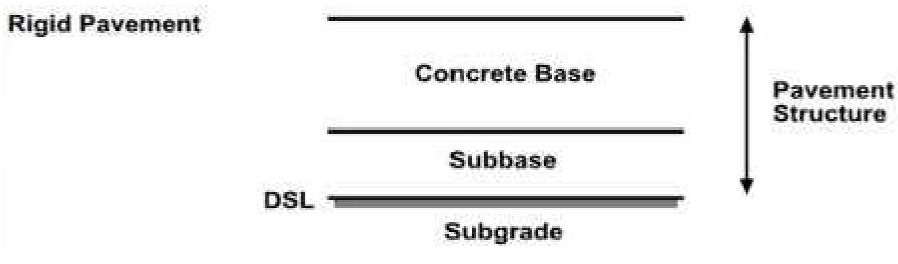


Figure 1.3 - Components of rigid road pavement structure (Source: Austroads 2023)

1.2.2 Flexible Pavement

The term flexible pavement refers to all other types other than rigid pavements. These can either be unbound granular pavements or bound (asphalt and stabilised) pavements. The wearing surface can either be asphalt, thin bituminous surfacing or unsealed gravel.

Flexible pavements work by distributing the traffic loads over multiple pavement layers, which relies on the flexibility of the materials to dissipate the stresses.

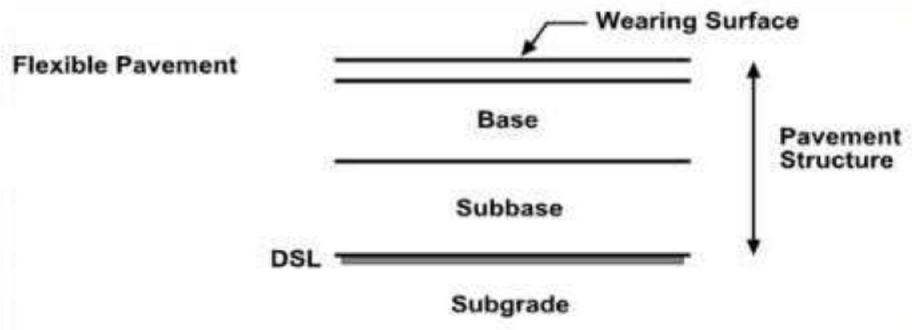


Figure 1.4 - Components of flexible road pavement structure (Source: Austroads 2023)

Full Depth Asphalt Pavement

Asphalt is a blend of bituminous binder and various, typically single sized aggregate. It is applied and compacted while hot to create a pavement layer. Although the binder is generally conventional bitumen, it can be modified with specific polymers for specialised applications.
Open graded asphalt can also be used as a wearing course that has a high skid resistance and drains some water to help prevent aquaplaning.

Spray Sealed Granular Pavement

Spray sealed granular pavements typically consist of a thin bituminous wearing surface that does not provide any structural support, over a bound or unbound compacted granular base and sub base. A bound/modified pavement is stabilised by mechanically mixing in a binder to improve the strength of the material. The binders that can be used include: quicklime, hydrated lime, cement and foamed bitumen.

Unsealed Granular Pavement

The quality and maintenance of unsealed roads vary greatly across the network, primarily based on daily traffic volume, traffic composition (such as road trains), and factors like accessibility and remoteness. Pavement designs range from two-lane roads with multiple granular layers and shoulders over the subgrade to single-lane roads shaped from the subgrade itself. Most are all-weather, formed pavements with some drainage. Typically, two pavement layers are placed over the subgrade, and granular or modified materials may be used for the wearing course. Dust suppressants may also be included as part of the maintenance strategy.

1.3 Regular Materials In Road Construction

1.3.1 Concrete

Concrete is known for its high compressive strength making it an ideal material for high traffic volume motorways. Concrete's high durability means it has a high design life and only requires minimal maintenance, which is a great benefit as it greatly reduces traffic impacts. However, its construction cost is generally higher than flexible pavements like asphalt, and repairs can be more complex.

Concrete is made from cement, aggregates like sand and gravel, and water. Due to the abundance of these raw materials, concrete can be made at batching plants closer to where it is needed compared to asphalt, which requires harder to obtain crude oil byproducts. Industrial byproducts like fly ash and ground granulated blast furnace slag are often used as a supplementary cementitious material to reduce the cost of the mix.

1.3.2 Steel

Reinforcing steel is commonly used in concrete pavements to reduce the formation and propagation of cracks. Due to the energy intensive refining process of the steel the fact that a large proportion of Australia's steel is imported from Asia, it is a large contributor of greenhouse gas emissions.

1.3.3 Asphalt

Asphalt is a type of flexible pavement that is used widely throughout Australia. It is a mixture of coarse and fine aggregates which form up to 96% of the asphalt, a bituminous binder and fillers. (Austroads 2014, p. 14).
The bituminous binder is sourced as a by-product of the crude oil refining process. Austroads (2007, p. 9) states that the majority of Australia's bitumen is manufactured in Australia from Middle East derived crude oils but there is a growing proportion of bitumen that is being imported

from overseas. The aggregates are sourced from local quarries and usually consist of igneous rocks such as basalt, dolerite, andesite, and granite.

1.3.3 Bitumen Spray Seal

Similar to asphalt, spray seals use bitumen as a binder that is generally sprayed onto a compacted granular base and topped off with a layer of aggregate that is rolled into the bitumen.

1.3.4 Gravel

Low traffic volume, unsealed roads usually source gravel from the nearest gravel pit/quarry to reduce costs. Uncrushed gravel is often used for these roads due to lower costs and lower puncture risk to tyres.

Crushed gravel base is used to construct higher strength pavements and is usually sealed with a bitumen wearing course.

1.4 Sustainable Alternative Construction Materials

1.4.1 Geopolymer Concrete

Typical concrete usually consists of a mixture of portland cement, coarse aggregates, fine aggregates and water, however geopolymer concrete replaces the portland cement with fly ash. Fly ash is already commonly used as a beneficial additive in regular concrete mixes but geopolymer concrete makes it the main active binding ingredient.

1.4.2 ECO Asphalt

ECO Asphalt has been developed as a more sustainable alternative to regular asphalt. It incorporates recycled asphalt pavement (RAP), recycled crushed glass, crumbed rubber and bio-bitumen. It is also produced as warm mix asphalt, instead of a traditional hot mix asphalt therefore reducing heating requirements.

1.4.3 Bio-Bitumen

Bio-bitumen is usually partially substituted with regular bitumen in asphalt mixes and can be used in spray seal applications. Bio-bitumen is a renewable resource that can be created from many different biological sources, compared to traditional crude oil based bitumen.

1.5 Embodied Greenhouse Gas Emissions

The term embodied carbon refers to the total amount of carbon released from the extraction and manufacturing of a material.

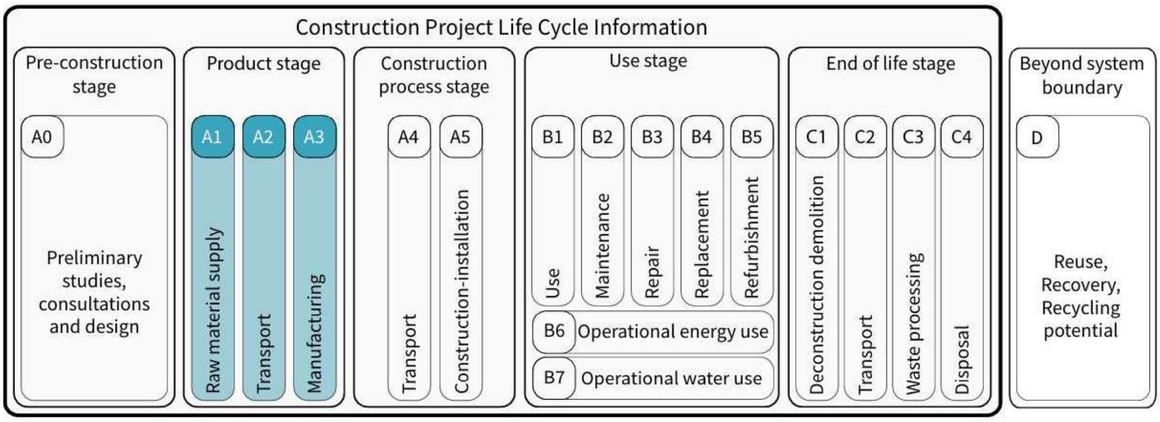


Figure 1.5 - Construction project lifecycle stages

Carbon dioxide equivalent (CO_2e) is used as the main unit of measure for embodied carbon emissions of material.

1.6 Problems

The Australian Transport sector is the third largest producer of greenhouse gas emissions. Current road construction practices often prioritise cost and performance without considering emission related environmental implications. Recently some road authorities have started including the level of construction emissions as a criteria for some larger projects but this only takes into account one stage of the lifecycle of these pavements. As a result, there is a lack of comprehensive data on the lifecycle emissions associated with different pavement types, especially the impacts of utilising sustainable alternatives. This knowledge gap hinders informed decision making and sustainable road construction. The main areas of focus are:

1.6.1 State Roads

Transport for NSW operates and maintains the state road network in NSW, which includes most high volume arterial roads. There are many new major highways and motorways in New South Wales that are at various stages of development or construction, including: the Coffs Harbour Bypass, Singleton Bypass, M1 to Raymond Terrace and the Rankin Park to Jesmond Inner City Bypass Extension. Multi criteria analyses are used to determine the appropriate pavement designs, with criterias such as: cost, construction timeframe, design life and maintenance requirements, however the lifecycle emissions are mostly overlooked.

1.6.2 Local Roads

Local Council's are the principal road authority for local roads in Australia and are expected to operate and maintain their road networks on a minimal budget. These councils are often seeking to seal as much of their unsealed road networks as possible, as it can reduce the lifecycle costs due to the reduction in maintenance. However, it is unknown the effects this has on the emissions from their road networks.

1.7 Aim

The primary aim of this project is to investigate and compare the lifecycle emissions associated with rigid and flexible pavement systems used in road construction. Furthering our knowledge on this area will help road authorities continue to reduce the emissions from managing their road networks and ultimately reduce the Australian Transport sector's climate impact.

1.8 Objectives

The research aims to achieve the following objectives:

- Conduct a thorough literature review to establish existing knowledge on the environmental impact of rigid and flexible pavement systems.
- Develop a comprehensive methodology for conducting a life cycle assessment (LCA) of rigid and flexible pavements.
- Determine which pavement construction type emits the lowest emissions for each road scenario.
- Propose methods for road authorities to reduce the quantity of greenhouse gas emissions they generate.

1.9 Outcomes & Benefits

The expected outcomes and benefits of this project include:

- A comprehensive understanding of the environmental impact of rigid and flexible pavement systems.
- Data driven insights for decision makers in the road construction industry, enabling them to choose sustainable pavement options.
- Reduction of GHG emissions associated with road construction through informed choices.
- Improved environmental sustainability in the infrastructure sector.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

Road construction is a fundamental component of infrastructure development, critical for economic growth and social wellbeing. Yet, it is also a major source of greenhouse gas (GHG) emissions due to the energy intensive nature of the processes involved. A substantial body of research has been dedicated to understanding and quantifying these emissions in the context of road construction.

A key aspect of established knowledge is the identification of emissions sources in road construction. These emissions from the construction, maintenance and disposal of road pavements primarily emanate from two main areas: material production/transportation and machinery for construction operations.

2.1 Effects of Harmful Emissions

2.1.1 Greenhouse Gas Emissions

Greenhouse gases (GHGs) are gases that contribute to the greenhouse effect in the Earth's atmosphere. This effect is caused by greenhouse gases trapping the sunlight and preventing the normal heat loss into space, thus causing the surface temperature of the planet to rise.

- Carbon Dioxide (CO_2) is the primary emission produced from burning carbon based fuels including petrol and diesel. It is also the primary contributor to climate change
- Methane (CH_4) is another greenhouse gas produced during carbon based fuel combustion, and is usually generated due to incomplete combustion of fuels. Methane has a global warming potential (GWP) over twenty five times greater than carbon dioxide, however it is produced at much lower levels.
- Nitrous Oxide (N_2O) is the third largest greenhouse gas contributor. While less abundant than carbon dioxide and methane, these gases have global warming potentials 250 times higher than CO_2. Nitrous oxide is released from the catalytic converters in gasoline and diesel engines.

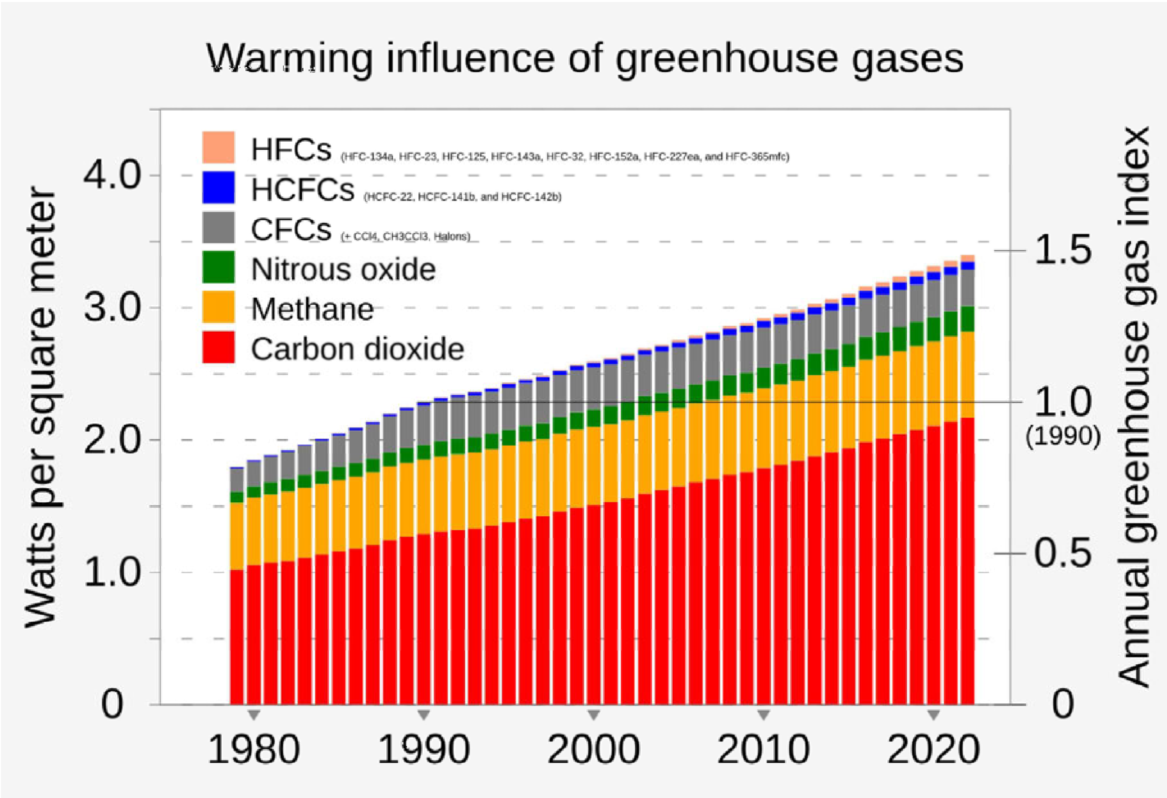


Figure 2.1 - Greenhouse Gas Index (Source: NOAA 2023)

2.1.2 Particulates

Particulates are microscopic solid or liquid particles suspended in the air. Internal combustion engine emissions,especially diesel engines, are a major non-natural producer of particulate matter. Particulate matter produced by the combustion of carbon-based fuels are often composed of black carbon (soot), unburnt fuel, sulphates, nitrates, iron, zinc and copper (Hodan & Barnard, 2004).

Approximately 99% of the world's population live in areas that do not meet the World Health Organisation’s air quality guidelines (World Health Organisation, 2022). Particulate matter is known to have significant and serious health impacts due to its ability to penetrate into the lungs. Coarse particles (PM10), those with a diameter of less than 10 micrometres, generally settle in the upper respiratory tract, causing irritation and aggravating conditions like asthma and bronchitis (Pope, 2000). Fine particles (PM2.5) are those with a diameter of less than 2.5 micrometres and are especially dangerous as they can infiltrate deep into the lungs and even enter the bloodstream. Long term exposure to PM2.5 is associated with a wide range of health issues, including respiratory infections, cardiovascular diseases such as heart attacks and strokes and the exacerbation of chronic respiratory diseases like chronic obstructive pulmonary disease (Hodan &

Barnard, 2004; Pope & Dockery, 2006). Children are particularly vulnerable to particulate expires, as it can lead to stunted lung development, increased respiratory infections and other long-term respiratory issues that persist into adulthood (Gong et al., 2014).

In addition to the cardiac and respiratory risks, recent studies suggest that exposure to particulate matter may have neurological consequences. Fine particles can cross the blood-brain barrier, the highly selective and semi permeable barrier that separates the circulatory system with the central nervous system that is intended to prevent harmful substances from reaching the brain. This could potentially lead to cognitive decline and an increased risk of neurodegenerative diseases, including Alzheimer's (Kim et al., 2015: Calderón-Garcidueñas et al., 2008).

Vehicle type		Carbon dioxide	Methane	Nitrous oxide	Particulate matter
		CO2	CH4	N20	PM10
Passenger cars					
Petrol	Post-08	2282	0.33	0.069	0.012
	06-08	2282	0.43	0.081	0.018
	04-05	2282	0.5	0.112	0.025
	98-03	2282	0.9	0.273	0.048
	86-97	2282	1.29	0.284	0.131
	76-85	2282	1.48	0.097	0.175
	Pre-76	2282	1.78	0.07	0.258
LPG	Post-08	1561.5	0.29	0.05	0.008
	06-08	1561.5	0.45	0.065	0.01
	04-05	1561.5	0.59	0.162	0.018
	98-03	1561.5	0.67	0.287	0.023
	86-97	1561.5	0.59	0.05	0.233
	76-85	1561.5	0.62	0.04	0.37
	Pre-76	1561.5	0.71	0.02	0.414
Diesel	Post-08	2671.2	0.01	0.116	0.201
	06-08	2671.2	0.01	0.116	0.383
	04-05	2671.2	0.02	0.058	0.422
	98-03	2671.2	0.05	0.027	0.643
	86-97	2671.2	0.06	0.027	0.808
	76-85	2671.2	0.07	0.027	1.282
	Pre-76	2671.2	0.14	0.01	2.66

Light commercial vehicles					
Petrol	Post-08	2282	0.53	0.104	0.024
	06-08	2282	0.69	0.122	0.037
	04-05	2282	0.8	0.167	0.049
	98-03	2282	1.43	0.409	0.095
	86-97	2282	2.06	0.426	0.262
	76-85	2282	2.37	0.145	0.349
	Pre-76	2282	2.85	0.105	0.516
LPG	Post-08	1561.5	0.35	0.075	0.009
	06-08	1561.5	0.54	0.097	0.011
	04-05	1561.5	0.71	0.243	0.019
	98-03	1561.5	0.81	0.431	0.026
	86-97	1561.5	0.7	0.075	0.256
	76-85	1561.5	0.74	0.06	0.407
	Pre-76	1561.5	0.85	0.03	0.456
Diesel	Post-08	2671.2	0.01	0.116	0.261
	06-08	2671.2	0.01	0.116	0.498
	04-05	2671.2	0.04	0.058	0.549
	98-03	2671.2	0.1	0.027	0.836
	86-97	2671.2	0.11	0.027	1.051
	76-85	2671.2	0.12	0.027	1.666
	Pre-76	2671.2	0.25	0.01	3.458
Medium trucks					
	CNG	2282	0.61	0.032	0.185
Diesel	post 08	2671.2	0.01	0.036	0.139
	03-08	2671.2	0.06	0.036	0.348
	96-02	2671.2	0.1	0.036	1.57
	pre 96	2671.2	0.2	0.036	3.059
Heavy trucks					
Diesel	post 08	2671.2	0.01	0.033	0.107
	03-08	2671.2	0.02	0.033	0.294
	96-02	2671.2	0.04	0.033	0.898
	pre 96	2671.2	0.08	0.033	1.626

Table 2.1 - Conversion ratios fuel (L) to emissions (g/L) (Source: Department of Infrastructure 2016)

2.2 Regulatory Measures and Mitigation

Many governments have established air quality standards to limit particulate matter emissions from vehicles. Australia will adopt the Euro 6d emissions standards by the end of 2028, which the Department of Climate Change, Energy, the Environment and Water expected to reduce greenhouse gas emissions in the transport sector by 18 million tonnes by 2050 (DCCEEW, 2023). DCCEEW also expects this to save $6.1 billion in health and fuel costs by 2040.

2.2.2 Diesel Exhaust Fluid (DEF)

Diesel Exhaust Fluid (DEF) is a solution used in vehicles equipped with Selective Catalytic Reduction (SCR) systems to reduce nitrogen oxide (NOx) emissions from diesel engines. DEF is a mixture of urea (32.5%) and deionized water (67.5%), which is injected into the exhaust stream of a diesel engine. When heated, the urea in DEF breaks down into ammonia, which reacts with NOx in the SCR catalyst to produce nitrogen and water vapour, both of which are harmless (Majewski 2005).

2.3 Embodied Emissions

The emissions released by the extraction and manufacture of materials commonly form the majority of the total lifecycle emissions of the constructed infrastructure .

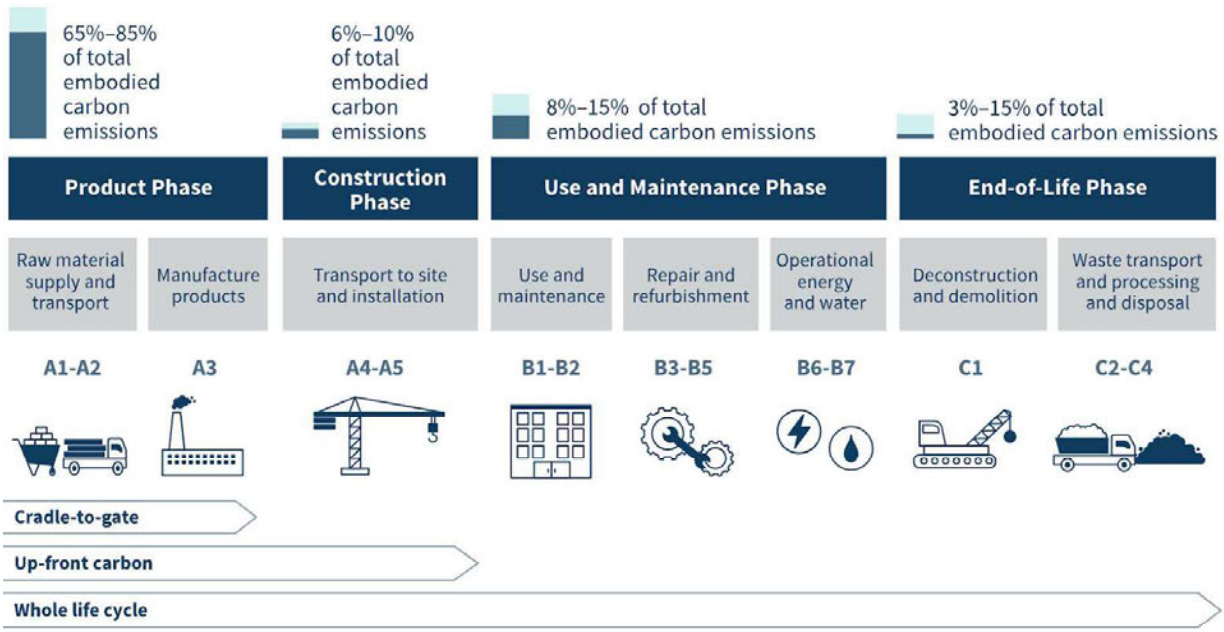


Figure 2.2 - percentage emissions at each stage of infrastructures life

The University of Melbourne in collaboration with the Federal Government's Australian Research Council, has developed a database of embodied carbon for the most commonly used materials in construction.

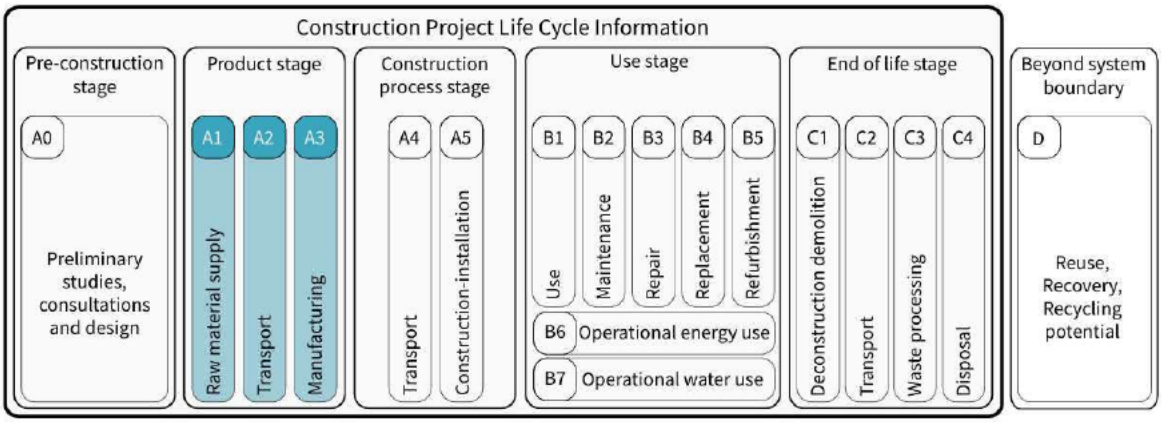


Figure 2.3 - '*Cradle-to-gate'* embodied carbon from the Environmental Performance in Construction (EPiC) Database (Source: Crawford, Stephan & Prideaux 2024, p. 28)

2.4 Global Warming Potential of Greenhouse Gases

Embodied emissions of materials are measured in carbon dioxide equivalent (CO_2e). CO_2e is the measurement of all greenhouse gas emissions emitted, not just carbon dioxide. Different greenhouse gases have different levels of global warming potential, for example the Australian Government's Clean Energy Regulator (2024) provides the following values for the most common greenhouse gases:

Greenhouse Gas	**Global Warming Potential**
Carbon Dioxide	1
Methane	28
Nitrous Oxide	265
Perfluoromethane (tetrafluoromethane)	6,630
Perfluoromethane (hexafluoromethane)	11,100
Sulphur Hexafluoride	23,500

Table 2.2 - global warming potential of major greenhouse gases

2.5 Rigid Pavements

The EPiC database, created by Crawford, R.H., Stephan, A. and Prideaux, F. (2024), provides estimates for the embodied energy in Megajoules, the embodied water in litres, and the embodied greenhouse gas emissions in kilograms of CO_2 equivalent of concrete per cubic metre at different compressive strengths and for percentage additions of fly ash and ground granulated blast furnace slag. TfNSW/Austroads recommends a compressive strength of between 40 and 45 MPa for rigid pavement construction. An extract from the database is shown below for the values of 40 MPa concrete with different percentages of fly ash and GGBFS.

Material	Functional unit	Embodied Energy (MJ)	Embodied Water (L)	Embodied Greenhouse Gas Emissions ($kgCO_2e$)
Concrete 40 MPa	m^3	3476	4355	497
Concrete 40 MPa - 10% fly ash	m^3	3304	4286	457
Concrete 40 MPa - 20% fly ash	m^3	3087	4195	415
Concrete 40 MPa - 30% fly ash	m^3	2854	4075	373
Concrete 40 MPa - 40% fly ash	m^3	2652	3995	332
Concrete 40 MPa - 50% fly ash	m^3	2436	3909	290
Concrete 40 MPa - 60% fly ash	m^3	2220	3823	248
Concrete 40 MPa - 10% GGBFS	m^3	3380	4294	462
Concrete 40 MPa - 20% GGBFS	m^3	3257	4223	428
Concrete 40 MPa - 30% GGBFS	m^3	3106	4120	392
Concrete 40 MPa - 40% GGBFS	m^3	3016	4052	358
Concrete 40 MPa - 50% GGBFS	m^3	2895	3984	324
Concrete 40 MPa - 60% GGBFS	m^3	2772	3915	289

Table 2.3 - embodied emissions of various concrete mix designs

TfNSW and Austroads (2021, p.19) have established a minimum and maximum percentage of fly ash and GGBFS as shown below:

Supplementary Cementitious Material	Alkali-Aggregate Reactivity Class	Limits	
Fly Ash (FA)	Non-reactive	15 - (0.5 x GGBFS%)	40 - (0.5 x GGBFS%)
	Slowly reactive / Reactive	20 - (0.5 x GGBFS%)	
Ground Granulated Blast Furnace Slag (GGBFS)	Non-reactive	10 - (2.0 x FA%)	65 - (2.0 x FA%)
	Slowly reactive / Reactive	40 - (2.0 x FA%)	

Table 2.4 - Range of supplementary cementitious material permitted in base concrete (Source: TfNSW 2021, p.19)

Where:

FA% = Percentage of fly ash by mass of total cementitious material

GGBFS% = Percentage of ground granulated blast furnace slag by mass of total cementitious material

2.6 Design Life/Typical Pavement Design

The design life of road pavements refers to the expected period during which a pavement structure is designed to perform satisfactorily under anticipated traffic and environmental conditions. It's an essential consideration in pavement design as it influences decisions related to materials selection, construction methods, and maintenance strategies.

2.6.1 Asphalt

A typical full depth asphalt pavement consists of multiple layers of different asphalt types usually topped with a 40mm wearing course. The design life of asphalt pavements ranges from 10 to 20 years but can be up to 40 years for heavy duty pavements, depending on factors such as traffic volume, climate, and maintenance practices. They offer flexibility, smoothness, and excellent ride quality. Asphalt pavements are relatively quick and cost effective to construct and repair but this can depend heavily on the location of the nearest asphalt plant.

2.6.2 Concrete

Rigid pavements typically consist of a compacted granular subbase over the subgrade topped with a concrete base course. Table 1 and 2 show the minimum subbase and base thickness layers using the amount of heavy vehicle axle groups.

Table 9.1: Minimum subbase requirements for rigid pavements

Design traffic (HVAG)	Subbase type
Up to 10^6	125 mm bound
Up to 5×10^6	150 mm bound or 125 mm LCS
Up to 1×10^7	170 mm bound or 125 mm LCS
Greater than 1×10^7	150 mm LCS[1]

Table 2.5 - Minimum sub base requirements for rigid pavements (Source: Austroads 2019)

Table 9.7: Minimum base thickness

Pavement type (base)	Design traffic		
	$1 \times 10^6 \leq$ HVAG $< 1 \times 10^7$	$1 \times 10^7 \leq$ HVAG $< 5 \times 10^7$	HVAG $\geq 5 \times 10^7$
Plain concrete	150	200	250
Jointed reinforced and dowelled	150	180	230
Steel fibre reinforced concrete	125	180	230
Continuously reinforced concrete	150	180	230

Table 2.6 - Minimum base thickness (Source: Austroads 2019)

Concrete pavements are designed to have a longer design life compared to asphalt pavements, typically ranging from 20 to 40 years or more. Rigid pavements are constructed using portland cement concrete and are known for their durability, strength, and resistance to heavy loads and harsh environmental conditions. They offer excellent long term performance with minimal maintenance requirements. However, they can be more expensive and time-consuming to construct compared to asphalt pavements and also do not offer the same ride quality and sound qualities as asphalt.

2.6.3 Sealed Granular

Sealed granular pavements are typically composed of a compacted granular subgrade, subbase and base layer topped with a thin surface layer of bituminous seal coat. Figure 1 shows the required minimum base thickness for different subgrade CBR and design equivalent standard axles.

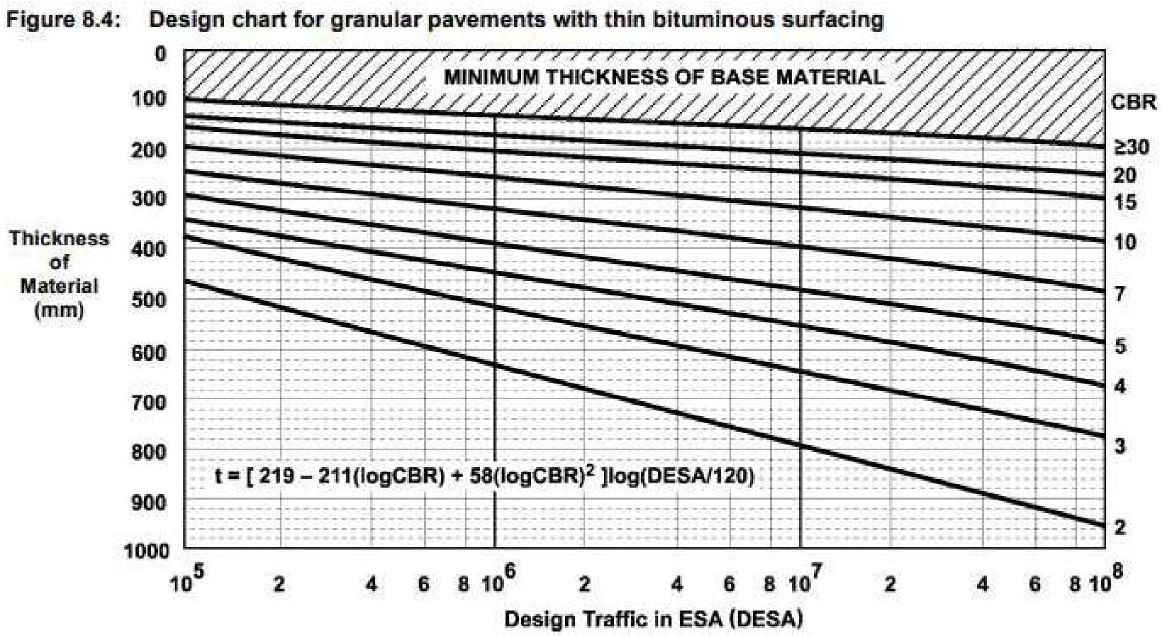


Figure 2.4 - Design chart for granular pavements with thin bituminous surfacing (Source: Austroads 2019)

Sealed granular pavements typically have a design life ranging from 10 to 20 years before they require resealing and potentially heavy patching. With this regular maintenance the pavement can reach upwards of 50 years before requiring a full pavement rehabilitation. They provide a durable and dust-free driving surface suitable for low to moderate traffic volumes. Sealed granular pavements are cost effective and relatively easy to maintain compared to asphalt and concrete pavements.

2.6.4 Unsealed

Unsealed pavements are typically constructed using a nearby source of uncrushed gravel to reduce handling and transport costs. They usually consist of a minimum 100mm compacted gravel layer that also acts as the wearing course.

Unsealed pavements generally have a shorter design life compared to sealed pavements, typically ranging from 5 to 15 years before requiring resheeting with more gravel. They are commonly used in rural and low-traffic areas where pavement surfacing is not economically justified. Unsealed pavements are relatively inexpensive to construct but require regular maintenance, including maintenance grading, gravel resheeting and drainage works, to mitigate erosion, rutting, and potholing.

2.7 Common Defects & Lifecycle Maintenance

2.7.1 Flexible Pavements (Asphalt/Sealed Granular)

Austroads (2019) states that the defects of flexible pavements can be broadly separated into five categories:

- Potholes
- Edge defects
- Surface defects
- Shape correction
- Pavement cleaning

Periodic preventative maintenance will greatly reduce the amount of defects that occur, this maintenance can include:

- Resealing
- Crack sealing
- Hydroblasting flushed pavements
- Drainage clearing
- Surface sweeping

2.7.2 Rigid Pavements (Concrete)

Austroads (2019) states that concrete pavement defects are usually caused by movement in the subgrade, and the most common defects in concrete pavements are:

- Subsidence of all or part of a slab
- Sharing/bending of dowels at joints due to differential settlements in the slabs
- Water ingress into open joints
- Flexing of the slab due to traffic loading causing the loss of fines in the subgrade
- Impact of traffic on pavement edge causing spalling or cracking
- Ingress of water into pavements cracks causing settlement
- Development of a slippery surface

Preventative maintenance of concrete pavements is much more limited and usually only consists of crack sealing and minor joint maintenance. Surface grinding is usually performed once or twice during the lifecycle of a concrete pavement, this will improve surface traction.

2.7.3 Unsealed

Unsealed roads are typically much more maintenance intensive but will greatly depend on weather conditions, traffic volumes, material quality and construction quality. Maintenance grading is usually performed multiple times a year, gravel pothole patching and drainage clearing is also performed as required.

2.8 Material Sourcing

All of the pavement types use the same or similar materials, mainly: varying types of gravel/aggregates, bitumen binder and portland cement. The extraction, production and transportation of each of these materials will have their own Greenhouse Gas Emissions.

2.8.1 Gravel/Aggregates

Aggregates and gravel are by far the most common materials in road construction, whether they are used as part of a concrete mix, in asphalt, in sprayed seals and as part of granular pavement layers. The extraction and processing of gravel and aggregates usually include the drilling and blasting of rock and then the crushing down of this material into the required components. Due to the large quantity of material required, and the subsequent transport of to site, this can be one of the highest greenhouse gas contributors in road construction.

2.8.2 Bitumen

Bitumen is a viscous black liquid obtained from crude oil refining. It serves as the glue that binds the aggregate together in spray seals and asphalt pavements. The production of bitumen involves energy intensive refining processes that are usually completed overseas before being transported to Australia. Australia has become evermore reliant on overseas bitumen as the local crude oil extraction and refineries have been closed down. Due to this, the emissions from the transport can contribute quite heavily to the total lifecycle greenhouse gas emissions. Although bitumen does have a high embodied carbon, it can be recycled in-situ without any major degradation in material quality.

2.8.3 Portland Cement

Portland cement is one of the main ingredients in concrete pavements and the binding properties necessary for strength and durability. The production of Portland cement is an energy intensive process that is manufactured by burning and grinding a mixture of limestone and clay and releases significant amounts of greenhouse gasses during this process.

2.9 Sustainable Construction Materials

2.9.1 Geopolymer Concrete

Geopolymer concrete is an alternative to traditional portland cement concrete that utilises other materials such as fly ash and ground granulated blast furnace slag in the place of cement. Due to the energy intensive portland cement being replaced with the byproducts of other processes, geopolymer concrete is a more environmentally friendly option.
Austroads (2018) states that geopolymer concrete can reduce carbon dioxide equivalent emissions by approximately 30% without a substantial reduction in material quality.

2.9.2 ECO Asphalt

ECO Asphalt is a new asphalt blend that has been designed as a more sustainable option to traditional asphalt. Transport for NSW (2024) states that this will reduce greenhouse gas emissions by approximately 30% compared to conventional asphalt. Colas' ECO5 asphalt blend incorporates between 25% and 40% recycled material, including: recycled asphalt pavements (RAP), recycled glass and recycled rubber. An ECO5 AC14 mix typically consists of:

- 2.5% recycled crushed glass as a sand replacement
- 20% recycled asphalt pavement as a binder and aggregate replacement
- A15E binder with 10% crumb rubber as a bitumen and polymer replacement

This mix design meets Transport for NSW's R116 Heavy Duty Dense Graded Asphalt specification, and according to COLAS, has an improved rutting resistance, fatigue resistance and tensile strength when compared to a typical heavy duty asphalt (COLAS, 2021).

Property	Test Method	COLAS Heavy Duty Typical Value	COLAS ECO5 Asphalt Typical Value	Requirement for TfNSW Roads
Wheel Tracking 10,000 passes @ 60°C (rut depth mm)	AGPT/T231	3.1	2.6	Report
Resillient Modulus @ 25°C (MPa)	AS2981.13.1	6800	5900	Report
Beam Fatigue 400 microstrain @ 20°C (cycles to failure)	AGPT/T233	108,649	360,807	Report
Moisture Sensitivity (TSR %)	T640	95	87	≥ 80
Average Tensile Strength (kPa)	T640	800	1070	> 600

Figure 2.5 - comparison of performance properties of ECO5 against a typical heavy duty asphalt (The COLAS Group 2021)

ECO5 is also designed as a warm mix asphalt, so it is therefore produced at a lower temperature than a traditional hot mix asphalt. This reduces energy consumption and emissions and can improve workability in low temperatures.

2.9.3 Bio-Bitumen

Bio-bitumen includes any bitumen products that derive partially or fully from biological sources including vegetable and plant oils compared to traditional crude oil based bitumen. SAMIGreen Polymer Modified Binder and SAMIBioPrime are examples of bio-bitumens that are produced by SAMI Bitumen Technologies. Both use a vegetable oil derived alternative as a partial substitute to traditional bitumen.

The SAMIGreen Polymer Modified Binder can be used in spray seal applications and will reduce greenhouse gas emissions by approximately 65% (SAMI). It meets all requirements of AustRoads Technical Specification 3110 - Supply of Polymer Modified Binders.

Property	Unit	Test Method	TYPICAL VALUES (A10E grade)	ATS 3110 specification (A10E)
Softening Point	°C	AGPT/T131	105	88-110
Consistency 6% at 60°C,	Pa.s	AGPT/T121	1683	Min. 1000
Stiffness at 25°C,	kPa	AGPT/T121	23.8	Max. 30
Torsional Recovery at 25°C,	%	AGPT/T122	66	60-86
Viscosity at 165°C	Pa.s	AGPT/T111	0.8	Max. 1.1

Figure 2.6 - technical properties of SAMIGreen Polymer Modified Binder (SAMI)

2.10 Knowledge Gap

While there is a substantial amount of knowledge regarding GHG emissions in road construction, there are significant gaps that require further investigation.

Although researchers have made progress in understanding emissions associated with construction processes, comprehensive life cycle assessments are needed to evaluate the full environmental impact of road construction, including both construction and maintenance phases. Current research tends to focus on specific stages rather than the entire lifecycle. Examples of such research are:

1. A study on GHG emissions for construction of various pavement types. (Chehovits & Galehouse 2010)
2. A study on lifecycle emissions of maintaining asphalt pavements. (Ma et al. 2021)
3. A study comparing pavement construction emissions in China. (Huang et al. 2016)
4. A study on lifecycle emissions of asphalt pavement. (Wang & Gangaram 2014)

2.10.1 Geography

Many studies are focused on areas in Asia or Europe. There is likely to be major differences in emissions compared to road construction in Australia. For example, Australia is not a major producer of crude oil and needs to source it from overseas for use in creating bitumen. Also, due to the low population density of Australia, the majority of roads are low traffic volume, unsealed roads (Austroads 2019).

2.10.2 Data Availability

A critical gap in the existing literature is the lack of comprehensive data on lifecycle emissions from road construction projects. Obtaining accurate and consistent data for various construction processes, materials, and phases of construction remains a challenge. There is a large amount of data for the raw materials, as these are used in a variety of other industries however and this can be applied to road pavements. Details on the performance qualities of the sustainable alternatives is also lacking.

2.10.3 Policy and Regulation

Australia does not have its own set emissions standards for the vehicles and machinery and instead relies on both American and Euro emission standards. Clear and standardised policies are necessary to encourage the adoption of sustainable practices. Research is needed to assess the effectiveness of existing policies and identify areas where new regulations may be needed. The Department of Climate Change, Energy, the Environment and Water conducted a report into the emissions of non-road diesel engines (DCCEEW 2020) detailing how changes in emission policies will affect the emissions of non-road based diesel engines.

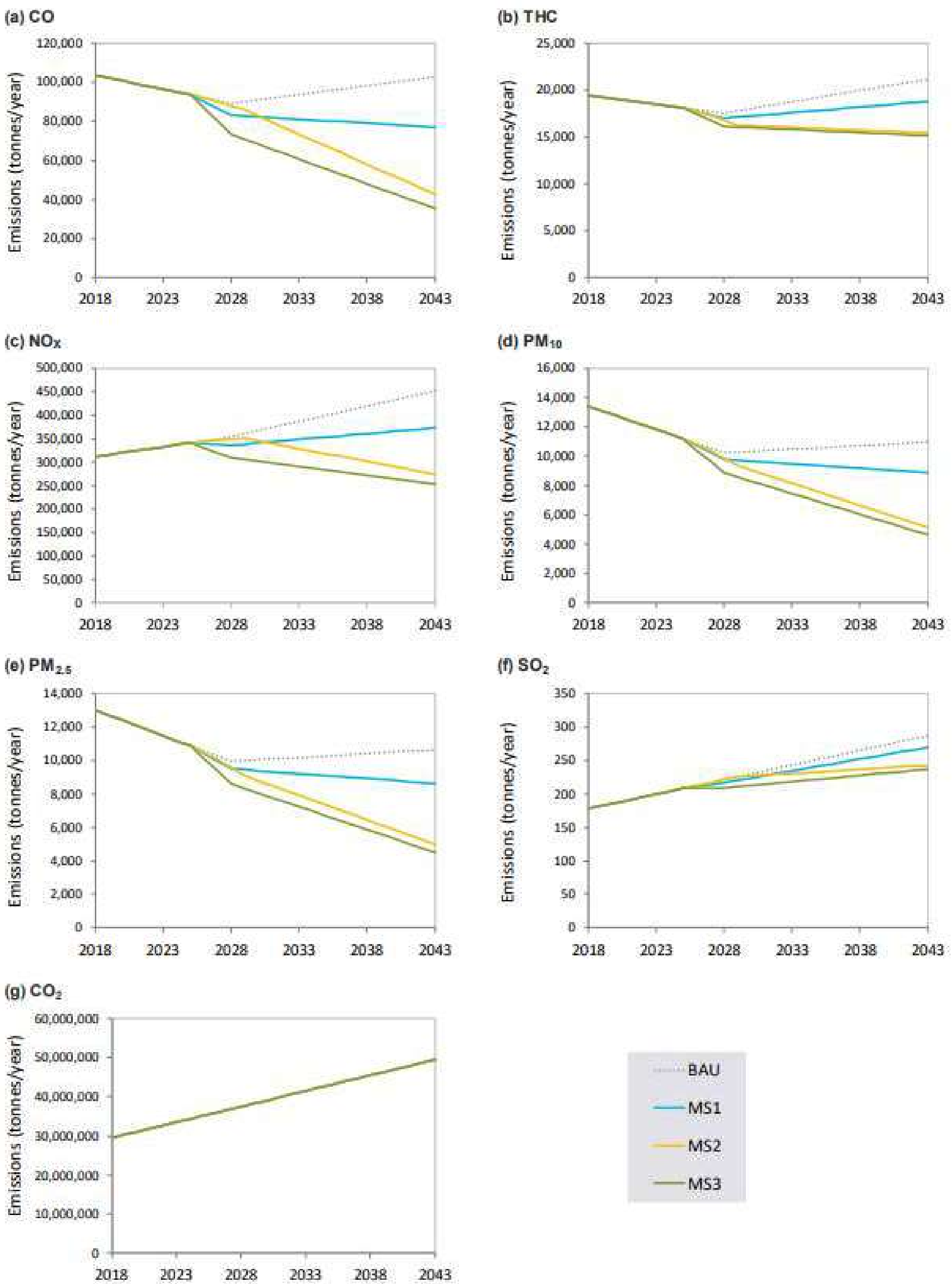


Figure 2.7 - Effects of management scenarios on national non-road diesel emissions (DCCEEW 2020)

2.10.4 Economic Considerations

The costs associated with adopting emission-reduction strategies can be a barrier to implementation. Further research should address the economic feasibility of sustainable road construction practices and explore potential incentives or funding mechanisms to support these practices.

CHAPTER 3 METHODOLOGY

3.1 Introduction

The preceding literature review and background has been completed to determine the amount of existing knowledge in regards to the lifecycle management of roads and the relevant greenhouse gas emissions. There is a large quantity of research that examines emissions from road construction at different stages and in varying geographic regions.

Whilst there has been much research into emissions from road construction, a thorough lifecycle analysis has been identified as a knowledge gap especially focussing on the Eastern Australian region. The literature review has also identified that there is a lack of lifecycle emission comparisons between different pavement designs.

To increase the body of knowledge relating to the emissions from road pavements, this project will examine and compare the lifecycle greenhouse gas emissions of different pavement types. With the world placing a large focus on fighting climate change and to assist Australia to meet its Paris Agreement targets, this research project will assist road agencies to choose the best pavement designs for the environment.

This research project will focus on recent road construction projects in Northern NSW. Both rigid and flexible pavement systems used in the region will be analysed. The three focus areas are:

- Motorways
  - Continuously Reinforced Concrete pavement
  - Plain Concrete Pavement
  - Full Depth Asphalt Pavement
- Rural Highways
  - Full Depth Asphalt Pavement
  - Bitumen Spray Sealed Granular Pavement
- Local Roads
  - Bitumen Spray Sealed Granular Pavement
  - Unsealed Granular Pavement

3.2 Overall Lifecycle Analysis Methodology

The sources of carbon dioxide emissions from construction are placed into two main categories, the embodied carbon of the materials and the emissions from machinery and equipment used in the construction.

The aim of this study is to determine the difference in lifecycle emissions between different pavement types, and will therefore focus primarily on the material differences as the emissions from the different machinery used will not have a great impact on the results. However for the local roads, where material emissions are far lower, the machinery emissions will have an impact on the results so will therefore be estimated.

Infrastructure assets including road pavements go through three major life stages: Construction, service and disposal. The aim of this lifecycle analysis is to comprehensively assess all three stages of a road pavement’s life.

To calculate emissions during the construction phase the pavement designs will be created using Circly 7.0 for a number of traffic volumes on each pavement type. The idea is to assess each pavement type for a range of traffic volumes that are relevant to each particular pavement type. A number of road agencies are now including some form of greenhouse gas emission data in the road designs, which can be used to compare to the calculations and help validate the results but these often include the emissions for ancillary items such as shared pathways and drainage structures.

The next stage is to review Transport for NSW’s previous maintenance data for a larger section of road network to determine the average maintenance per kilometre for each of the different pavement types. Local Government Asset Management Plans will provide these maintenance requirements for the local roads. This information along with the average design life will allow the calculation of the lifetime maintenance GHG emissions per kilometre.

The final stage of the road's lifecycle is the disposal of the asset which depending on the pavement design could mean the removal of material or the recycling of material which would then reduce the amount of material needed for the road’s reconstruction thus reducing GHG emissions.

3.3 Construction Stage

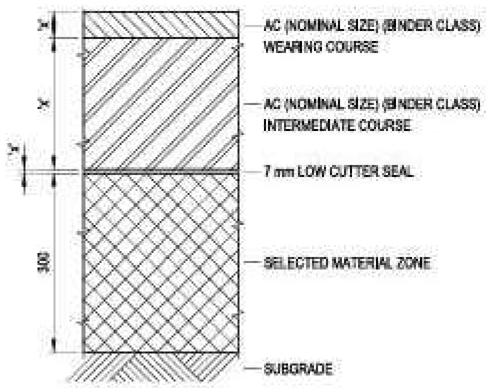
3.3.1 Pavement Design

The initial pavement designs were taken from the typical pavement profiles provided by Transport for NSW. These pavement profiles gave the required pavement layers and Circly 7.0 was used to determine the appropriate layer/pavement thickness for the four different pavement types (continuously reinforced concrete, plain concrete, full depth asphalt, sealed granular and unsealed granular) for three different traffic volumes.

The traffic load distributions were given by Austroads and Transport for NSW's presumptive urban and rural data. The pavement layer thicknesses were calculated at a range of different traffic volumes using Austroads pavement design method from 2017.

<u>**Full Depth Asphalt**</u>

Figure 3.1 provides the general layout for a full depth asphalt pavement. This typically consists of an AC14 wearing course over an AC20 base layer with a total asphalt thickness of up to 350mm. It also has a 7mm spray seal separating the base layer and the selected material zone. The subgrade CBR has been assumed as 3%.



FULL DEPTH ASPHALT

Figure 3.1 - Typical pavement profile of a full depth flexible asphalt pavement (Source: TfNSW, 2021)

Rigid Pavement

Figure 3.2 indicates the pavement profile for an average rigid pavement used in New South Wales. The continuously reinforced concrete pavement is used where extra tensile strength and crack control is required such as areas with a weak subgrade, corners, and steep hills.

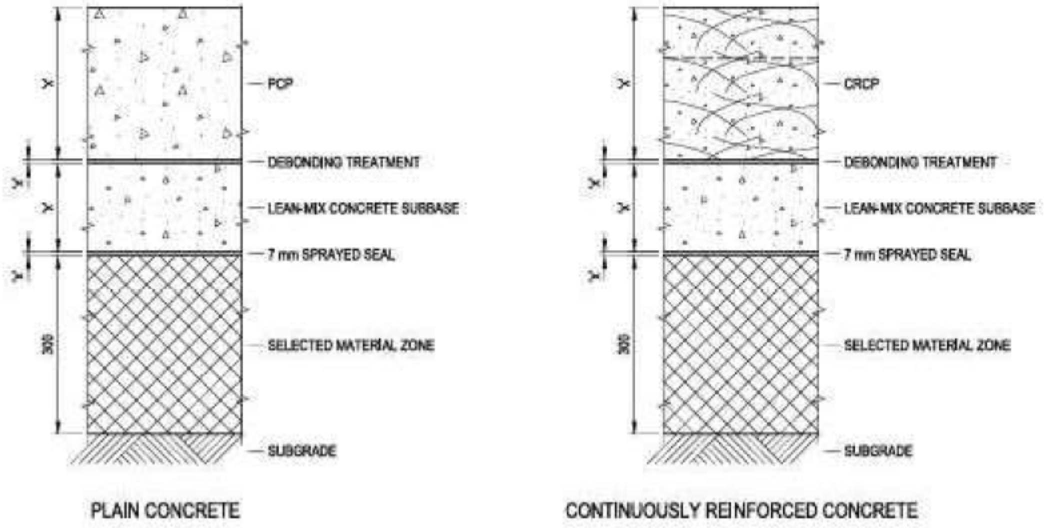


Figure 3.2 - Typical pavement profile of a full depth rigid concrete pavement with and without reinforcing steel (Source: TfNSW, 2021)

Sealed Granular Pavement

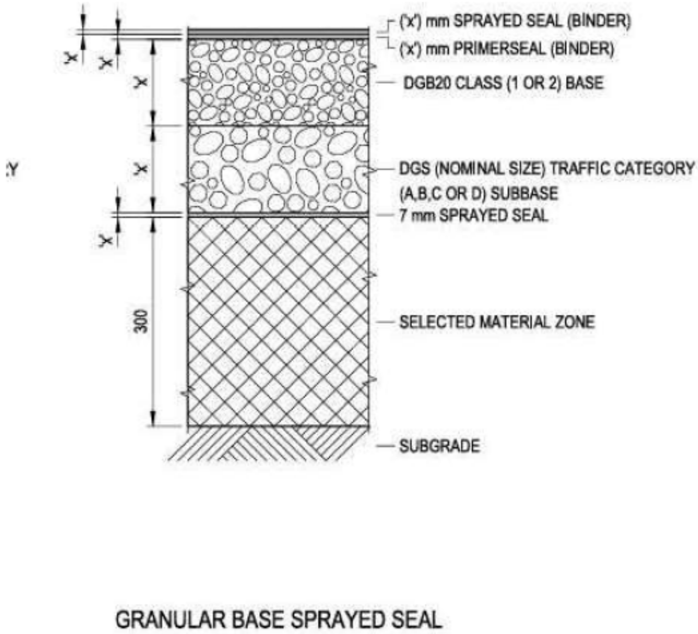


Figure 3.3 - Typical pavement profile of a granular pavement with a bitumen sprayed seal (Source: TfNSW, 2021)

Unsealed Granular Pavement

The unsealed granular pavement consists of the same DGB20 base layer thickness as the sealed granular pavement topped with a 75 millimetre uncrushed granular wearing course.

Design Traffic

Multiple traffic volumes were taken for each road category (Motorway, Rural Highway and Local Road) to get a relevant range of results

.

The three example locations for the motorway are: the Cahill Expressway near the Sydney Harbour Bridge, the Pacific Motorway near the Central Coast and the Pacific Motorway near Kempsey. These represent the highest traffic volume road in NSW, an average Motorway traffic volume and one of the lowest traffic volume motorways in NSW respectively.

Example Location	Road Classification	AADT	%HV	N_i	Annual Growth	Design Period	CGF	N_{hv}	N_{hvag}	HVAG
A1 Kempsey	Motorway	12000	28.0%	1680	1%	40	48.9	3.0E+07	2.8	8.4E+07
M1 Mount White	Motorway	74408	9.9%	3683	1%	40	48.9	6.6E+07	2.5	1.6E+08
Sydney Harbour Bridge	Motorway	200000	9.8%	9800	1%	40	48.9	1.7E+08	2.5	4.4E+08

Table 3.1 - example locations for a range of traffic volumes on Motorways in NSW

Similarly, three example locations were chosen of rural highways within New South Wales that represent a range of traffic volumes. The three locations are: the New England Highway at Bendemeer, the Newell Highway at Forbes and the Gwydir Highway at Inverell.

Example Location	Road Classification	AADT	%HV	N_i	Annual Growth	Design Period	CGF	N_{hv}	N_{hvag}	HVAG
New England Highway Bendemeer	Rural Highway	4268	22.0%	469	1	40	48.9	8.4E+06	2.5	2.1E+07
Newell Highway Forbes	Rural Highway	2325	38.0%	442	1	40	48.9	7.9E+06	2.5	2.0E+07
Gwydir Highway Inverell	Rural Highway	1343	21.0%	141	1	40	48.9	2.5E+06	2.5	6.3E+06

Table 3.2 - example locations for a range of traffic volumes on Rural Highways in NSW

Finally, due to the lack of accurate traffic data for local roads three relevant traffic volumes were chosen: 200, 100 and 50 average annual daily traffic.

Road Classification	AADT	%HV	N_i	Annual Growth	Design Period	CGF	N_{hv}	N_{hvag}	HVAG
Local Road	200	25.0%	25	1	40	48.9	4.5E+05	2.5	1.1E+06
Local Road	100	25.0%	13	1	40	48.9	2.2E+05	2.5	5.6E+05
Local Road	50	25.0%	6	1	40	48.9	1.1E+05	2.5	2.8E+05

Table 3.3 - example traffic volumes on Local Roads in NSW

3.3.2 Material Production

The production of materials like concrete, asphalt, gravel, bitumen and aggregates are energy intensive processes and are required in large quantities. A large amount of research has been done in this field by many public and private organisations in many regions of the World. The Australian Department of Climate Change, Energy, the Environment and Water (DCCEEW) and the Australian Life Cycle Assessment Society (ALCAS) are two such groups that have determined the GHG emission factors from many different resources and processes. These values are inclusive of the extraction of the raw resource, transport and any required processing. The relevant emissions factors for this study are shown in Table 3.4.

Material	Unit	Construction sector subcategory	$kgCO_2e$/unit
Gravel, crushed	kg	Gravel	0.01045
Gravel, uncrushed	kg	Gravel	0.00419
Sand	kg	Sand	0.00419
Bitumen sealing	kg	Bitumen	1.22011
general purpose cement	kg	Cementitious material	0.91796
Concrete 40 MPa 30% GGBFS	m3	Concrete	378.23
Reinforcing steel	kg	Ferro	1.50
Asphalt, standard hot mix	kg	Asphalt	0.07

Table 3.4 - embodied carbon by unit for most common pavement materials (Sources: DCCEEW, 2024 & ALCAS, 2023)

3.3.3 Material Transport

Transportation of the required materials to site is another energy intensive process that will differ greatly between materials. For example, much of Australia's steel and cement clinkers are imported from countries in Asia. Infrastructure NSW has developed an average transportation distance per tonne for most commonly used construction materials and the relevant materials are shown in Table 3.5.

Material	Transport (km)		
	Truck	Rail	Sea
Cement	324	10	704
Gravel, crushed	36	4	0
Gravel, uncrushed	36	4	0
Concrete 40 MPa 30% GGBFS	104	2	117
Reinforcing steel	911	15	2600
asphalt, standard hot mix	57	0	0
Bitumen sealing	57	0	0
Lean-mix concrete	104	2	117

Table 3.5 - average transport distance for common construction materials (Source: Infrastructure NSW, 2024)

Infrastructure NSW has also developed a set of average emissions per tonne for various transport modes shown in Table 3.6.

Transport Mode	Quantity	Unit
Articulated Truck	0.00007	tonnes CO_2e/km
Concrete Agitator Truck	0.00013	tonnes CO_2e/km
Light Commercial Vehicles	0.00120	tonnes CO_2e/km
Rail, Bulk Transport	0.00002	tonnes CO_2e/km
Rigid Truck	0.00022	tonnes CO_2e/km
Shipping	0.00001	tonnes CO2e/km

Table 3.6 - default emission factors for the transport stage of construction materials (Source: Infrastructure NSW, 2024)

3.3.4 Construction Process

For most medium to high volume traffic roads the embodied emissions of the materials far outweighs the emissions from the construction machinery. Also, the difference in the emissions from the machinery used is going to be relatively similar, therefore these have not been included in the calculations.

Local Roads are the exception, where the material emissions are comparatively very low so the machinery emissions will have a greater effect. The machinery emissions have been estimated by taking the average fuel consumption of the required plant and multiplying by the standard carbon dioxide emissions from diesel of 2.671 kilograms per litre of diesel.

Machinery emissions for the maintenance activities were also estimated using the same method.

3.3.5 Construction Stage Summary

Once the pavement design has been completed, this will give the quantities of materials required, which can then be multiplied by their relevant emissions factor thus giving the total construction project GHG emissions. Transport for NSW have recently started including these calculations in some major projects, which could be used to verify that this project's estimates are reasonable.

3.4 Maintenance Stage

3.4.1 Maintenance Completed

The total maintenance required for motorways and rural highways is taken from Transport for NSW's steady state requirements and shown in table 3.7. The maintenance required for local roads has been taken from the road asset management plans of multiple councils to find average figures.

Maintenance Activity	Amount per year	Unit
Renew Wearing Surface (reseal)	100	Linear m/km
Renew Wearing Surface (asphalt resurfacing)	200	Linear m/km
Repair Pothole	1.24	per km
Repair Pavement Edge	2.715	Linear m/km
Minor Pavement Patching	0.74	m^2/km
Seal Pavement Crack	19.58	m^2/km
Cross-stitch Crack	5.25	Linear m/km
Slab Jacking	13.23	m^2/km

Table 3.7 - average maintenance required on roads in northern New South Wales

3.4.2 Maintenance Stage Summary

These calculations will incorporate the same methods for the construction phase but for the maintenance identified as above. The projected useful life of the pavement is determined during the design phase of a project and is used to determine how many years the pavement will be in service and therefore requiring maintenance.

Maintenance Activity	Material $kgCO_2e/m2$	Machinery $kgCO_2e/m2$	Total $kgCO_2e/m2$
Renew Wearing Surface (reseal)	1.5	0.06	1.54
Renew Wearing Surface (asphalt resurfacing)	8.1	0.06	8.123
Repair Pothole	1.6	10.6	12.2
Repair Pavement Edge	9.7	29.0	38.7
Minor Pavement Patching	22.6	17.8	40.5
Seal Pavement Crack	24.0	83.7	107.7
Cross-stitch crack and joint	0.0013	0.0633	0.0645
Slab Jacking	0.0028	0.0797	0.0826

Table 3.8 - approximate emissions per square metre for each maintenance activity

3.5 End of Life Stage

The end of life stage of a road pavement will vary greatly depending on the design and could involve, demolition, material removal, disposal and restoration of the surface. Infrastructure NSW provides a set rate of 200 $kgCO_2e$/tonne for the treatment of construction waste. However most pavement materials can be reused on site on other jobs and therefore does not require any waste treatment, Infrastructure NSW provides recycling and landfill rates for many building materials. The relevant recycling and landfill rates are shown in table 3.9. These values have been incorporated into the overall material embodied emissions.

Waste Type	Recycling Rate (%)	Landfill Rate (%)
Aggregate	90	10
Asphalts	100	0
Bitumen Binders	100	0
Concretes	90	10
Steel Reinforcement	90	10

Table 3.9- Recycling and landfill rates of common materials used in pavements (Source: Infrastructure NSW, 2024)

3.6 Overall Material Emissions Factors

The overall emissions for each material is shown in table 3.9 inclusive of all necessary extraction, processing, transportation to site, disposal of material in landfill and a percentage wastage rate as defined by Infrastructure NSW.

Material	Unit	Production Emissions	Transport to Site Emissions	Wastage (%)	Landfill (%)	Landfill Emissions	Total Emissions
Gravel, crushed	Tonne	10.5	2.60	5	0	0	13.7
Gravel, uncrushed	Tonne	4.2	2.60	5	0	0	7.1
Concrete 40 MPa 30% GGBFS	Tonne	157.6	8.46	5	10	20	195.4
Reinforcing steel	Tonne	1500.3	90.07	5	10	20	1690.8
Asphalt, standard hot mix	Tonne	70.6	3.99	6	0	0	79.1
Bitumen	Tonne	1220.1	3.99	6	0	0	1297.5
Lean-mix concrete	Tonne	106.5	8.46	5	10	20	141.7

Table 3.10 - total emissions factors for each traditional pavement component per tonne

3.7 Sustainable Alternative Materials Emissions

Exact greenhouse gas emissions figures have not been released for any of the sustainable alternatives, however suppliers have indicated a percentage reduction figure compared to the traditional materials. These reduction percentages have been applied to the production emissions of the relevant traditional material in order to determine the production emissions for the sustainable alternative. All of the other components including the transport emissions, wastage and disposal emissions remain the same.

Material	Unit	Production Emissions	Transport to Site Emissions	Wastage (%)	Landfill (%)	Landfill Emissions	Total Emissions
ECO5 High Performance Sustainable Asphalt	Tonne	49.4	3.99	6	0	0	56.6
Geopolymer Concrete	Tonne	88.3	8.46	5	10	20	122.6
Bio-bitumen	Tonne	427.0	3.99	6	0	0	456.9

Table 3.11 - total emissions factors for each sustainable alternative pavement component per tonne

3.8 Lifecycle Emissions

Utilising the pavement design to calculate the required quantities of materials along with their relevant emissions factories gives the total construction emissions. Combining this with the required maintenance for each pavement type multiplied by the design life of the pavement, gives the total lifetime emissions of the chosen pavement.
Substituting the sustainable alternative materials will provide a figure for the potential lifetime greenhouse gas emissions savings that could be achieved.

3.9 Limitations

This study does not calculate the total emissions for a section of road as it does not include ancillary items such as: culverts, kerb and gutters, bike lanes, signs etc. This study is purely designed to compare the emissions of different pavement types.

There is a potential that the maintenance data analysed is not representative of a typical period of time, especially given that northern New South Wales has been hit hard by many heavy rainfall events that can cause the quick deterioration of road pavements.

This study does not take into account economical factors so even though one pavement type might have significantly lower lifecycle emissions than the alternative, it still might be cost prohibitive for Road Authorities. This research project should therefore be used to advise and assist in making pavement selections at the design stage.

Due to this project focusing on projects in Northern New South Wales, it may not be representative for all of Australia due to regional differences in design specifications, construction processes and material availability.

Due to many of the sustainable alternatives only being developed recently, there is a lack of performance data, especially long term data to compare with traditional pavements. The rate of emissions savings was chosen conservatively to ensure that build quality and design life is not tangibly affected. Once further data becomes available for these materials the emissions savings could increase substantially.

Chapter 4 Case Study 1: Hexham Straight Widening Project

Transport for NSW is the road authority for the classified state road network in New South Wales. State Roads are primarily medium to high traffic volume arterial roads in and between major urban areas and also carry the majority of traffic and freight around NSW.

TfNSW is an agency of the NSW State Government and funds the construction and maintenance of State Roads. As a government agency, TfNSW has a responsibility to get as much value for money for road works whilst helping Australia to meet its climate targets by reducing carbon emissions.

One of the roads mostly managed by TfNSW is the Pacific Highway. The Pacific Highway is a 970 km long major transport route that runs along the east coast of Australia, connecting Brisbane at the Northern end to Sydney at the Southern end. Sections of the Pacific Highway are some of the highest trafficked roads in NSW outside of Sydney with up 75,000 annual average daily traffic volume (AADT). Due to the high traffic loadings, there is a requirement for heavy duty pavement designs which mostly consist of full depth asphalt or concrete pavements. Concrete pavements are favoured on the highest traffic section of the route, between Sydney and Newcastle, due to the unfavourable terrain conditions and high traffic volumes making maintenance work both risky and expensive. One major project that is underway at the moment is the Hexham Straight Widening works, which involves the widening of the motorway in both directions at Hexham near Newcastle.

Figure 4.1 - Hexham Straight Widening project map

This project is a six kilometre stretch of road that currently consists of 4.4 kilometres of full depth asphalt pavement and 1.6 kilometres of continuously reinforced concrete pavement. The existing pavement will be rehabilitated and an extra lane added in each direction. The new lanes will be approximately 3.5 metres wide with an additional 3 metres of shoulder in each direction. Therefore the total width of both carriageways will be approximately 27 metres on average.

The 1.4 kilometre rigid section on the Western side will follow the pavement design shown in Figure 4.1. The design indicates a subgrade CBR of 3% and consists of a 300 millimetre select material zone, a bitumen spray seal separating the granular layer from the concrete, a 150 millimetre lean mix concrete subbase with a wax emulsion debonding layer, and a 210 millimetre steel fibre reinforced concrete base.

Layer	Comments
Base	210mm (nominal) Steel Fibre Reinforced Concrete (SFCP-R) with SL82 Mesh 70 ± 10mm top cover and 80 ± 20mm cover to joints and edges (HSWA R83)
Debonding	Wax emulsion (HSWA R82)
Subbase	150mm Lean Mix Concrete (LMC) Subbase (HSWA R82)
Seal	7mm Spray Seal C170 Binder (HSWA R106)
Select	300mm SMZ
Subgrade	Subgrade CBR ≥ 3%

Table 4.1 - Hexham Straight Widening project rigid pavement profile

Using these materials and layer thicknesses, the amount of kilograms of carbon dioxide equivalent per square metre can be calculated. Multiplying this by the rigid pavement section length of 1.4 kilometre by the approximate pavement width of 27 metres. This was calculated by multiplying the lane thickness of 3.5 metres by the total amount of lanes and adding 3 metres of shoulder in each direction.

Layer	Material	Thickness (mm)	Weight (tonnes)	Emissions ($kgCO_2e/m2$)
Base	Concrete 40 MPa 30% GGBFS	210	0.504	93.8
Base	Steel Reinforcement	-	0.052	83.7
Subbase	Lean-mix concrete	150	0.360	48.6
Seal	Single C170/C240 Spray Seal	-	-	1.5
Select	Select Material Zone	300	0.540	7.0
Subgrade	Existing CBR = 3%	-	-	-
Total ($kgCO_2e/m^2$)				**234.6**
Approximate Rigid Pavement Area (m^2)				**43,200**
Approximate Rigid Pavement Emissions (tCO_2e)				**10,135**

Table 4.2 - Hexham Straight Widening project rigid pavement layer emissions

The Hexham Straight Widening project uses heavy duty pavements with a design life of 40 years. The amount of maintenance required was provided by Transport for NSW.

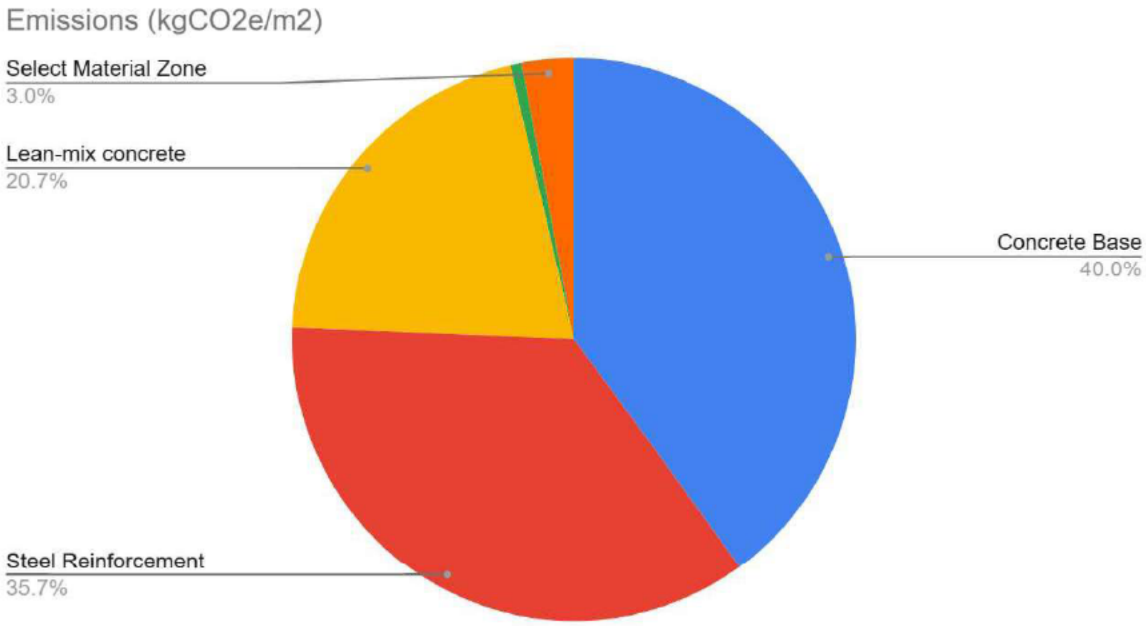


Figure 4.2 - breakdown of emissions by pavement component

Maintenance Activity	Amount per year	Unit	$kgCO_2e/m2$ Per Year			Design Life	$kgCO_2e/m2$ Lifetime
			Material	Machinery	Total		
Cross-stitch crack and joint	5.25	m / km	0.0013	0.0633	0.0645	40	2.5812

Slab Jacking	13.23	m2 / km	0.0028	0.0797	0.0826	40	3.3022
Total Lifetime Emissions (kgCO_2e/m^2)							**5.9**

Table 4.3 - Hexham Straight Widening project rigid section lifetime maintenance emissions

Layer	Comments
Wearing Course	45mm AC14 A15E Binder (HSWA R116)
Intermediate Course	360mm AC20 C450 Binder (HSWA R116)
Seal	7mm Spray Seal C170 Binder (HSWA R106)
Select	300mm SMZ (HSWA R44 and HSWA R106)
Subgrade	Subgrade CBR ≥ 3%

Table 4.4 - Hexham Straight Widening project flexible pavement profile

Layer	Material / Sustainable Alternative	Thickness (mm)	Weight (tonnes)	Emissions (kgCO_2e/m2)	Alternative Emissions (kgCO_2e/m2)
Wearing Course	Asphalt, standard hot mix / ECO5 Asphalt	45	0.108	8.1	6.1
Intermediate Course	Asphalt, standard hot mix / ECO5 Asphalt	360	0.864	64.5	48.9
Seal	Single C170/C240 Spray Seal	-	-	1.5	1.5
Select	Select Material Zone	300	0.540	7.0	7.4
Subgrade	Existing CBR = 3%	-	-	-	-
Total (kgCO_2e/m^2)				**81.1**	**63.9**
Approximate Flexible Pavement Area (m^2)				**118,800**	
Approximate Flexible Pavement Emissions (tCO_2e)				**9,632**	**7,592**

Table 4.5 - Hexham Straight Widening project flexible pavement layer emissions

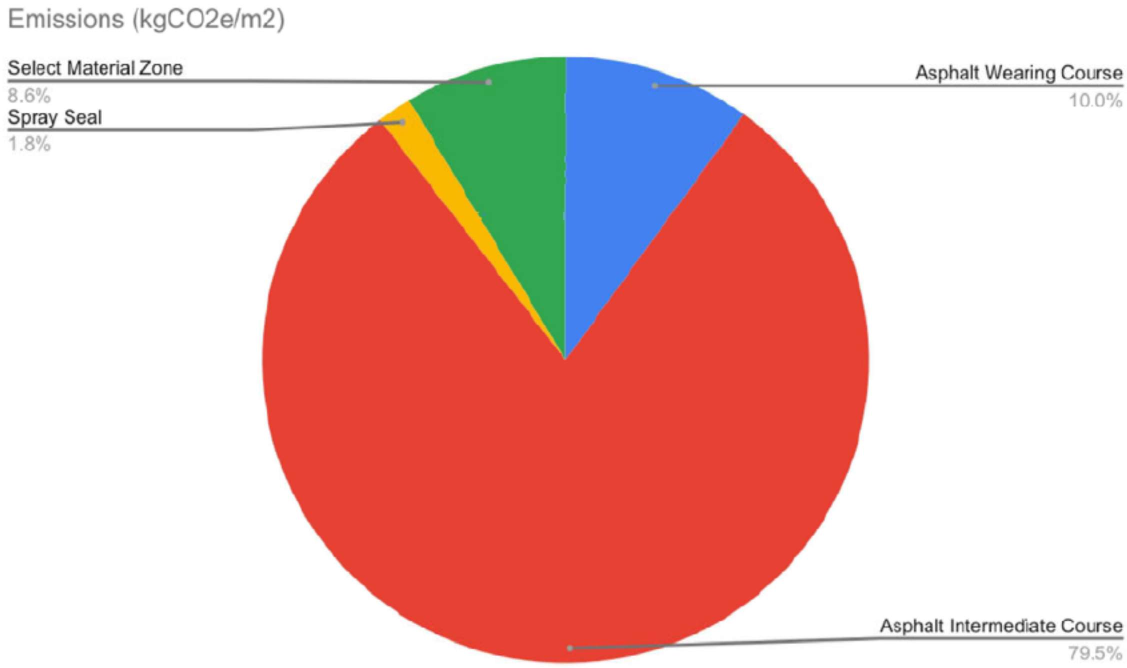


Figure 4.3 - breakdown of emissions by pavement component

Maintenance Activity	Amount per year	Unit	kgCO₂e/m2 Per Year			Design Life	kgCO₂e/m2 Lifetime
			Material	Machinery	Total		
Asphalt Resurfacing			8.1	0.06	8.123	20	16.25
Repair Pothole	1.24	per km	0.000078	0.000530	0.000608	40	0.024
Repair Pavement Edge	2.715	m / km	0.000486	0.001450	0.001937	40	0.077
Minor Pavement Patching	0.74	m2 / km	0.001132	0.000892	0.002023	40	0.081
Seal Pavement Crack	19.58	m2 / km	0.001198	0.004184	0.005383	40	0.215
Total Lifetime Emissions ($kgCO_2e/m^2$)							**16.6**

Table 4.6 - Hexham Straight Widening project flexible section lifetime maintenance emissions

	Rigid Pavement	Flexible Pavement
Construction Emissions ($kgCO_2e/m2$)	234.6	81.1
Maintenance Emissions ($kgCO_2e/m2$)	5.88	16.64
Lifetime Emissions ($kgCO_2e/m2$)	240.50	97.72

Table 4.7 - Hexham Straight Widening project lifetime emissions per square metre

	Rigid Pavement	Flexible Pavement
Design Life (years)	40	40
Area (m2)	43,200	118,800
Total Construction Emissions (tCO_2e)	10,135	9,632
Total Maintenance Emissions (tCO_2e)	254	1,977
Total Lifetime Emissions (tCO_2e)	10,389	11,609
Total Lifetime Project Emissions (tCO_2e)		**21,998**

Table 4.8 - Hexham Straight Widening project total lifetime emissions

The Hexham Straight Widening project has a mix of flexible and rigid pavement designs mainly due to desire to match the existing pavement. If the designs had maintained the same pavement for the entire length of the project, the emissions could be vastly different, as shown in Table 4.9.

	Rigid Pavement	Flexible Pavement
Total Construction Emissions (tCO_2e)	38,007	13,134
Total Maintenance Emissions (tCO_2e)	953	2,696
Total Lifetime Emissions (tCO_2e)	38,960	15,831

Table 4.9 - Hexham Straight Widening project total lifetime emissions comparison

Sustainable Material Substitution

If sustainable options had been taken into account during the design phase of this project there could have been large reductions in the greenhouse gas emissions produced. The effects of choosing sustainable materials such as geopolymer concrete and ECO5 Asphalt as well as changing from a continually reinforced concrete to a plain concrete pavement have been tabulated below.

Design Consideration	Construction Emissions Saved per m^2 ($kgCO_2e/m^2$)	Lifetime Project Emissions Saved (tCO_2e)
Geopolymer Concrete Substitution	30.6	1,321
ECO5 Asphalt Substitution	17.5	2,081

Change to Plain Concrete Pavement	83.7	3,617
Total	131.8	7,019

Table 4.10 - total potential greenhouse gas emissions savings

Discussion

As expected, the rigid pavement has much higher emissions from the construction phase, around three times higher than the flexible pavement. Even when removing the reinforcing steel mesh from the concrete pavement it is still almost two times higher than flexible. As predicted, the flexible pavements emissions from the maintenance phase were higher than rigid, primarily due to the requirement to renew the wearing surface half way through the design life.

Although the rigid pavement requires much less overall maintenance, the works that are required are much more time and resource intensive. Therefore, the difference in maintenance emissions between flexible and rigid pavements was a lot closer than expected.

Overall, the total lifetime emissions from the pavement were approximately 21,998 tonnes of carbon dioxide equivalent which is greater than the annual emissions of 1,000 Australian households.

If more sustainable options are selected during the design of this project, including: substituting geopolymer concrete, substituting ECO5 Asphalt and changing to a plain concrete pavement, there is a potential reduction in emissions of 7,019 tonnes of carbon dioxide equivalent. This is a 32% reduction in the overall lifetime emissions which is equivalent to the annual emissions of over 400 Australian households. This would also likely not have a tangible impact on the maintenance requirements and the design life.

Chapter 5 Case Study 2: Warrumbungle Shire Local Road Network

The Warrumbungle Shire is a local government area in central New South Wales that maintains a road network consisting of approximately 1,986 kilometres of local roads as shown in Table 5.1.

Category	Sealed Length (km)	Unsealed Length (km)	Total Length (km)
Arterial Roads	200	21	221
Distributor Roads	208	526	734
Collector Roads	64	532	596
Access Roads	7	398	405
Unformed Roads	-	30	30
Total Local Roads	479	1,507	1,986

Table 5.1 - Warrumbungle Shire Council's Road Asset Inventory

5.1 Unsealed Road Network

The unsealed road network requires two major maintenance activities to keep the road at a satisfactory condition indefinitely. The emissions from the two maintenance activities per square metre are estimated in table 5.2.

Maintenance Activity	Material Emissions ($kgCO_2e/m2$)	Machinery Emissions ($kgCO_2e/m2$)	Total Emissions ($kgCO_2e/m2$)
Maintenance Grading		0.099	0.099
Gravel Resheeting	0.754	0.305	1.059

Table 5.2 - material, machinery and total emissions per maintenance activity for unsealed roads

Warrumbungle Shire Council defines their technical levels of service and maintenance requirements for the unsealed road network as shown in table 5.3.

Road Hierarchy	KM	Technical Level of Services	
		Maintenance Grading	Gravel Resheeting
Arterial	21	Once every 15 months	Once every 15 years
Distributor	526	Once every 15 months	Once every 15 years
Collector	532	Once every 3 years	Once every 20 years
Access	398	Once every 5 years	Once every 25 years

Table 5.3 - Warrumbungle Shire Council's technical levels of service for unsealed roads

Using the emissions for each maintenance activity per square metre and the frequencies for each road hierarchy, the average yearly emissions is shown in table 5.4.

Road Hierarchy	Maintenance Grading Frequency	Gravel Resheeting Frequency	Yearly Emissions ($kgCO_2e/m2$)
Arterial	0.8	0.0667	0.150
Distributor	0.8	0.0667	0.150
Collector	0.3333	0.05	0.086
Access	0.2	0.04	0.062

Table 5.4 - maintenance yearly frequencies and average yearly emissions for each road hierarchy

5.2 Sealed Road Network

The sealed road network requires two major maintenance activities to keep the road at a satisfactory condition. The emissions from the two maintenance activities per square metre are estimated in table 5.5.

Activity	Material Emissions ($kgCO_2e/m2$)	Machinery Emissions ($kgCO_2e/m2$)	Total Emissions ($kgCO_2e/m2$)
Initial Construction / Pavement Rehabilitation	12.444	0.825	13.269
Reseal	2.698	0.206	2.904

Table 5.5 - material, machinery and total emissions per maintenance activity for sealed roads

Warrumbungle Shire Council defines their technical levels of service and maintenance requirements for the unsealed road network as shown in table 5.6.

Road Hierarchy	KM	Technical Level of Services	
		Reseals	Pavement Rehabilitation
Arterial Roads	200	25 Years	80 Years
Distributor Roads	208	25 Years	100 Years
Collector Roads	64	25 Years	100 Years
Access Roads	7	25 Years	100 Years

Table 5.6 - Warrumbungle Shire Council's technical levels of service for sealed roads

Using the emissions for each maintenance activity per square metre and the frequencies for each road hierarchy, the average yearly emissions is shown in table 5.4.

Road Hierarchy	Reseals	Pavement Rehabilitation	Yearly Emissions ($kgCO_2e/m2$)
Arterial	0.04	0.0125	0.282
Distributor	0.04	0.01	0.249
Collector	0.04	0.01	0.249
Access	0.04	0.01	0.249

Table 5.7 - maintenance yearly frequencies and average yearly emissions for each road hierarchy

5.3 Potential Emissions Savings

The only area for potential savings in the amount of greenhouse gas emissions produced is substituting the bitumen with bio-bitumen.

Activity	Material Emissions Savings ($kgCO_2e/m2$)	Reduction (%)
Initial Construction / Pavement	3.507	26.4%

Rehabilitation		
Reseal	1.754	60.4%

Table 5.8 - potential greenhouse gas emissions savings using bio-bitumen

Discussion

As expected, the lifetime carbon dioxide emissions released from sealed pavement is greater than unsealed roads. However, as the traffic volumes increase and more maintenance is required for unsealed roads, the gap between the two decreases and it is expected that eventually unsealed roads will likely overtake sealed roads in lifetime pavement emissions. Utilising bio-bitumen will reduce sealed emissions by approximately 30% which brings it much closer to the emissions of unsealed pavements.

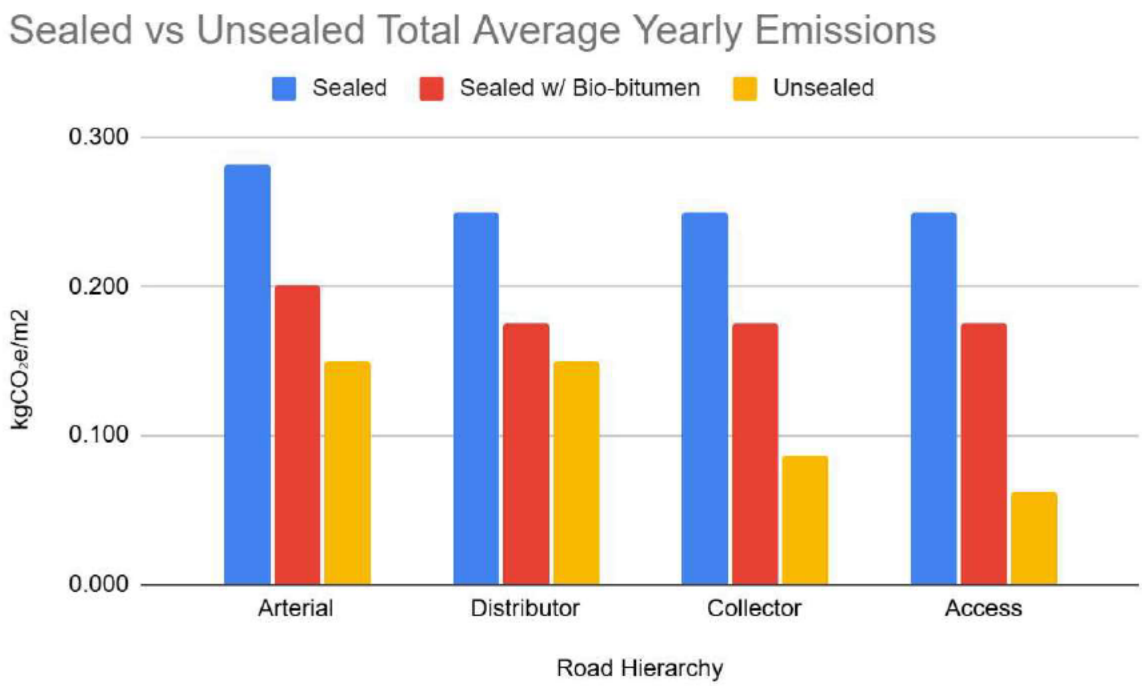


Figure 5.1 - comparing the average yearly emissions of sealed and unsealed pavements per road hierarchy

Chapter 6 RESULTS

6.1 Motorways

A thorough review of the three chosen motorway pavement types has been conducted. The effects of substituting sustainable materials has also been quantified.

6.1.1 Plain Concrete Pavement

Taking the designed pavement profiles for each of the traffic volumes and applying the embodied emission for each gives the following total greenhouse gas emissions per square metre for the construction of a plain concrete pavement. Due to the minimum base and subbase thicknesses stated in the Austroads specifications, the emissions are the same for each traffic volume.

Plain Concrete Pavement							
		High		Medium		Low	
Layer	Material	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$
Base	Concrete 40 MPa 30% GGBFS	250	111.64	250	111.64	250	111.64
Subbase	Lean-mix concrete	150	48.57	150	48.57	150	48.57
Select	Select Material	300	7.05	300	7.05	300	7.05
	Total		**167.26**		**167.26**		**167.26**

Table 6.1 - total construction emissions of a plain concrete pavement across three different traffic volumes

Table 6.2 provides the results for the greenhouse gas emissions from the maintenance of plain concrete pavements over the 40 year design life.

	High	Medium	Low
Maintenance	Lifetime $kgCO_2e/m2$	Lifetime $kgCO_2e/m2$	Lifetime $kgCO_2e/m2$
Cross-stitch crack and joint	2.58	2.58	2.58
Slab Jacking	3.30	3.30	3.30
Total	**5.88**	**5.88**	**5.88**

Table 6.2 - total maintenance emissions of a plain concrete pavement across three different traffic volumes

Summing the construction and maintenance emissions provides the values for the total lifetime emissions of plain concrete pavements, and dividing by the design life provides the square metre emissions per year.

	High	Medium	Low
	Lifetime $kgCO_2e/m2$	Lifetime $kgCO_2e/m2$	Lifetime $kgCO_2e/m2$
Construction	167.26	167.26	167.26
Maintenance	5.88	5.88	5.88
Total Lifetime Emissions	173.14	173.14	173.14
Design life	40 Years	40 Years	40 Years
Total Emissions per year	**4.33**	**4.33**	**4.33**

Table 6.3 - total emissions of a plain concrete pavement across three different traffic volumes

Table 6.4 identifies the quantity of emissions savings that are expected if sustainable choices are made during the design phase of a road construction project.

		Reduction		
Area	**Sustainable Alternative**	**High**	**Medium**	**Low**
Base	Geopolymer Concrete	-38.10	-38.10	-38.10
Subbase	Geopolymer Concrete	-4.46	-4.46	-4.46
	Total	**-42.56**	**-42.56**	**-42.56**
	Percentage Reduction	**25.4%**	**25.4%**	**25.4%**

Table 6.4 - potential reduction in greenhouse gas emissions for plain concrete pavement

6.1.2 Continuously Reinforced Concrete Pavement

Taking the designed pavement profiles for each of the traffic volumes and applying the embodied emission for each gives the following total greenhouse gas emissions per square metre for the construction of a continuously reinforced concrete pavement. Similar to the plain concrete pavement, continuously reinforced concrete pavements have a minimum base and subbase thicknesses required by Austroads specifications, therefore the emissions are the same for each traffic volume.

Continuously Reinforced Concrete Pavement							
		High		Medium		Low	
Layer	Material	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$
Base	Concrete 40 MPa 30% GGBFS	230	102.7	230	102.7	230	102.7
Base	Reinforcing steel	SL82 (52kg)	83.74	SL82 (52kg)	83.74	SL82 (52kg)	83.74
subbase	Lean-mix concrete	150	48.57	150	48.57	150	48.57
Select	Select Material	300	7.05	300	7.05	300	7.05
		Total	**242.07**		**242.07**		**242.07**

Table 6.5 - total construction emissions of a continuously reinforced concrete pavement across three different traffic volumes

Table 6.6 provides the results for the greenhouse gas emissions from the maintenance of continuously reinforced concrete pavements over the 40 year design life.

	High	Medium	Low
Maintenance	**Lifetime $kgCO_2e/m2$**	**Lifetime $kgCO_2e/m2$**	**Lifetime $kgCO_2e/m2$**
Cross-stitch crack and joint	2.58	2.58	2.58
Slab Jacking	3.30	3.30	3.30
Total	**5.88**	**5.88**	**5.88**

Table 6.6 - total maintenance emissions of a continuously reinforced concrete pavement across three different traffic volumes

Summing the construction and maintenance emissions provides the values for the total lifetime emissions of continuously reinforced concrete pavements, and dividing by the design life provides the square metre emissions per year.

	High	Medium	Low
	$kgCO_2e/m2$	**$kgCO_2e/m2$**	**$kgCO_2e/m2$**
Construction	242.07	242.07	242.07
Maintenance	5.88	5.88	5.88
Total Lifetime Emissions	247.95	247.95	247.95
Design life	40 Years	40 Years	40 Years
Total Emissions per year	**6.20**	**6.20**	**6.20**

Table 6.7 - total emissions of a continuously reinforced concrete pavement across three different traffic volumes

Table 6.8 identifies the quantity of emissions savings that are expected if sustainable choices are made during the design phase of a road construction project.

Area	Sustainable Alternative	Reduction		
		High	Medium	Low
Base	Geopolymer Concrete	-35.06	-35.06	-35.06
Subbase	Geopolymer Concrete	-4.46	-4.46	-4.46
Extra	Remove Steel Reinforcement	-83.74	-83.74	-83.74
	Total	**-123.25**	**-123.25**	**-123.25**
	Percentage Reduction	50.9%	50.9%	50.9%

Table 6.8 - potential reduction in greenhouse gas emissions for continuously reinforced concrete pavement

6.1.3 Full Depth Asphalt Pavement

Taking the designed pavement profiles for each of the traffic volumes and applying the embodied emission for each gives the following total greenhouse gas emissions per square metre for the construction of a plain concrete pavement. Unlike the rigid concrete pavement, asphalt can be designed for a larger range of thicknesses. This prevents design thicknesses being too excessive for the given traffic volume.

Full Depth Asphalt Pavement							
		High		Medium		Low	
Layer	Material	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$
Wearing Course	Asphalt, Standard Hot Mix	50	8.96	50	8.96	50	8.96
Base	Asphalt, Standard Hot Mix	370	66.28	320	57.32	290	51.95
Select	Select Material	300	7.05	300	7.05	300	7.05
		Total	**82.29**		**73.33**		**67.95**

Table 6.9 - total construction emissions of a full depth asphalt pavement across three different traffic volumes

Table 6.10 provides the results for the greenhouse gas emissions from the maintenance of full depth asphalt pavements over the 40 year design life.

	High	Medium	Low
Maintenance	**Lifetime kgCO_2e/m2**	**Lifetime kgCO_2e/m2**	**Lifetime kgCO_2e/m2**
Renew Wearing Surface (Asphalt Resurfacing)	16.246	14.621	13.159
Repair Pothole	0.024	0.022	0.020
Repair Pavement Edge	0.077	0.070	0.063
Minor Pavement Cracking	0.081	0.073	0.066
Seal Pavement Crack	0.215	0.194	0.174
Total	**16.64**	**14.98**	**13.48**

Table 6.10 - total maintenance emissions of a full depth asphalt pavement across three different traffic volumes

Summing the construction and maintenance emissions provides the values for the total lifetime emissions of full depth asphalt pavements, and dividing by the design life provides the square metre emissions per year.

	High	Medium	Low
	Lifetime kgCO_2e/m2	**Lifetime kgCO_2e/m2**	**Lifetime kgCO_2e/m2**
Construction	82.29	73.33	67.95
Maintenance	16.64	14.98	13.48
Total Lifetime Emissions	98.93	88.31	81.43
Design life	40 Years	40 Years	40 Years
Total Emissions per year	**2.47**	**2.21**	**2.04**

Table 6.11 - total emissions of a full depth asphalt pavement across three different traffic volumes

Table 6.12 identifies the quantity of emissions savings that are expected if sustainable choices are made during the design phase of a road construction project.

		Reduction		
Area	**Sustainable Alternative**	**High**	**Medium**	**Low**
Wearing Course	ECO5 Asphalt	-2.16	-2.16	-2.16
Base	ECO5 Asphalt	-16.01	-13.84	-12.55
Resurfacing	ECO5 Asphalt	-4.87	-4.39	-3.95

Total	**-23.04**	**-20.39**	**-18.66**
Percentage Reduction	28.0%	27.8%	27.5%

Table 6.12 - potential reduction in greenhouse gas emissions for full depth asphalt pavements

6.1.4 Motorway Summary

Analysing the total emissions from the three different pavement types, the plain concrete and continuously reinforced concrete pavements were much higher than a full depth asphalt pavement. However, as shown in Figure 6.1, as the traffic volume increases the gap between the different pavements reduces. This is due to the minimum thickness requirements for the concrete layers.

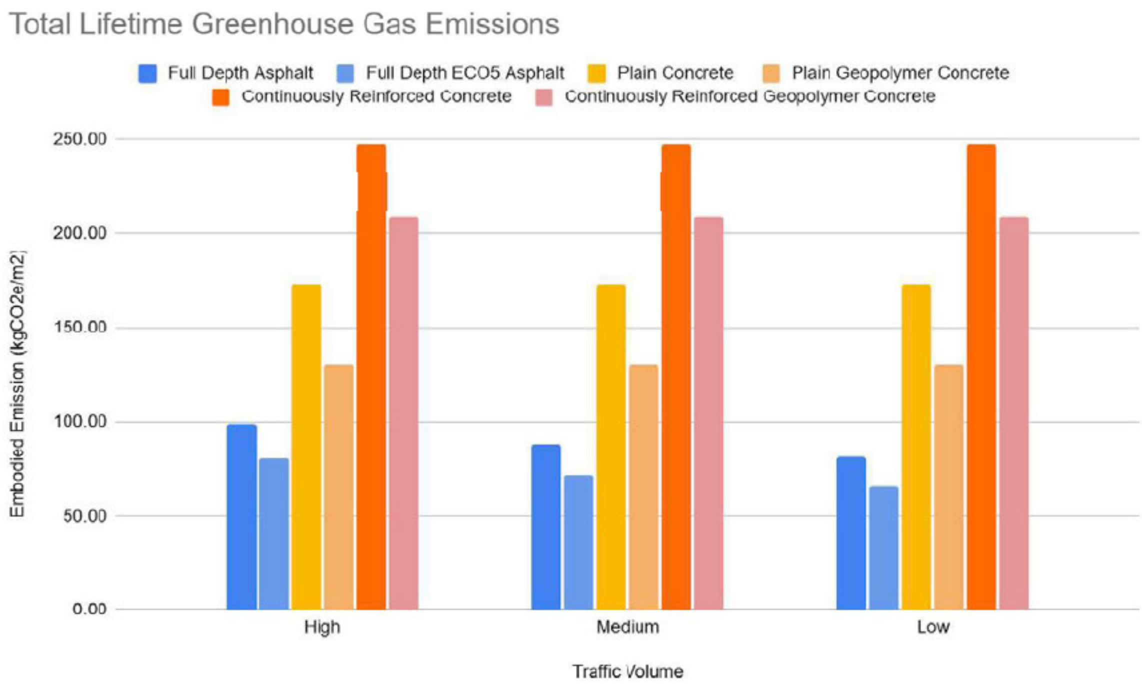


Figure 6.1 - total lifetime emissions of different pavement types for motorways

The emissions from maintenance across the two rigid pavement designs only accounted for approximately 3-4% of the total lifetime emissions, in contrast to the asphalt pavement where the maintenance makes up around 20%. This higher portion of maintenance is due to the requirement to renew the asphalt wearing surface which can take a lot of material.

6.2 Rural Highways

A thorough review of the two chosen rural highway pavement types has been conducted. The effects of substituting sustainable materials has also been quantified.

6.2.1 Full Depth Asphalt Pavement

Taking the designed pavement profiles for each of the traffic volumes and applying the embodied emission for each gives the following total greenhouse gas emissions per square metre for the construction of a full depth asphalt pavement.

Full Depth Asphalt Pavement							
		High		Medium		Low	
Layer	Material	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$
Wearing Course	asphalt, standard hot mix, 5.5% virgin bitumen	50	8.96	50	8.96	50	8.96
Base	asphalt, standard hot mix, 5.5% virgin bitumen	230	41.20	225	40.31	185	33.14
Select	Select Material	300	7.05	300	7.05	300	7.05
		Total	**57.21**		**56.31**		**49.15**

Table 6.13 - total construction emissions of a full depth asphalt pavement across three different traffic volumes

Table 6.14 provides the results for the greenhouse gas emissions from the maintenance of full depth asphalt pavements over the 40 year design life.

	High	Medium	Low
Maintenance	Lifetime $kgCO_2e/m2$	Lifetime $kgCO_2e/m2$	Lifetime $kgCO_2e/m2$
Renew Wearing Surface (Asphalt Resurfacing)	12.184	10.966	9.869
Repair Pothole	0.018	0.016	0.015
Repair Pavement Edge	0.058	0.052	0.047
Minor Pavement Cracking	0.061	0.055	0.049

Seal Pavement Crack	0.161	0.145	0.131
Total	**12.48**	**11.23**	**10.11**

Table 6.14 - total maintenance emissions of a full depth asphalt pavement across three different traffic volumes

Summing the construction and maintenance emissions provides the values for the total lifetime emissions of full depth asphalt pavements, and dividing by the design life provides the square metre emissions per year.

	High	**Medium**	**Low**
	Lifetime kgCO_2e/m2	**Lifetime kgCO_2e/m2**	**Lifetime kgCO_2e/m2**
Construction	57.21	56.31	49.15
Maintenance	12.48	11.23	10.11
Total Lifetime Emissions	69.69	67.55	59.26
Design life	40 Years	40 Years	40 Years
Total Emissions per year	**1.74**	**1.69**	**1.48**

Table 6.15 - total emissions of a full depth asphalt pavement across three different traffic volumes

Table 6.16 identifies the quantity of emissions savings that are expected if sustainable choices are made during the design phase of a road construction project.

Area	Sustainable Alternative	Reduction		
		High	Medium	Low
Wearing Course	ECO5 Asphalt	-2.16	-2.16	-2.16
Base	ECO5 Asphalt	-9.95	-9.73	-8.00
Resurfacing	ECO5 Asphalt	-4.87	-3.66	-3.29
	Total	**-16.99**	**-15.55**	**-13.46**
	Percentage Reduction	29.7%	27.6%	27.4%

Table 6.16 - potential reduction in greenhouse gas emissions for full depth asphalt pavements

6.2.2 Spray Sealed Granular Pavement

Taking the designed pavement profiles for each of the traffic volumes and applying the embodied emission for each gives the following total greenhouse gas emissions per square metre for the construction of a spray sealed granular pavement.

Spray Sealed Granular Pavement							
		High		Medium		Low	
Layer	Material	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$	Thickness (mm)	$kgCO_2e/m2$
Wearing Course	Bitumen Spray Seal	-	5.40	-	5.40	-	5.40
Base	DGB20	200	4.70	200	4.70	200	4.70
Subbase	DGS40	205	4.82	200	4.70	155	3.64
Select	Select Material	300	7.05	300	7.05	300	7.05
		Total	**21.96**		**21.84**		**20.79**

Table 6.17 - total construction emissions of a spray sealed granular pavement across three different traffic volumes

Table 6.18 provides the results for the greenhouse gas emissions from the maintenance of full depth asphalt pavements over the 40 year design life.

	High	Medium	Low
Maintenance	**Lifetime $kgCO_2e/m2$**	**Lifetime $kgCO_2e/m2$**	**Lifetime $kgCO_2e/m2$**
Renew Wearing Surface (Reseal)	10.764	8.073	7.266
Repair Pothole	0.024	0.018	0.016
Repair Pavement Edge	0.077	0.058	0.052
Minor Pavement Cracking	0.081	0.061	0.055
Seal Pavement Crack	0.215	0.161	0.145
Total	**11.162**	**8.372**	**7.535**

Table 6.18 - total maintenance emissions of a spray sealed granular pavement across three different traffic volumes

Summing the construction and maintenance emissions provides the values for the total lifetime emissions of spray sealed granular pavements, and dividing by the design life provides the square metre emissions per year.

	High	Medium	Low
	$kgCO_2e/m2$	**$kgCO_2e/m2$**	**$kgCO_2e/m2$**
Construction	21.96	21.84	20.79

Maintenance	11.162	8.372	7.535
Total Lifetime Emissions	33.123	30.215	28.320
Design life	40 Years	40 Years	40 Years
Total Emissions per year	**0.828**	**0.755**	**0.708**

Table 6.19 - total emissions of a spray sealed granular concrete pavement across three different traffic volumes

Table 6.20 identifies the quantity of emissions savings that are expected if sustainable choices are made during the design phase of a road construction project.

Area	Sustainable Alternative	Reduction		
		High	**Medium**	**Low**
Wearing Course	Bio-Bitumen Spray Seal	-3.51	-3.51	-3.51
Reseal	Bio-Bitumen Spray Seal	-3.77	-2.83	-2.54
	Total	**-7.28**	**-6.34**	**-6.05**
	Percentage Reduction	33.1%	29.0%	29.1%

Table 6.20 - potential reduction in greenhouse gas emissions for a spray sealed granular pavement

6.2.3 Rural Highway Summary

Analysing the total emissions from the two pavement types, the asphalt is far greater than the spray sealed pavement but the use of ECO5 asphalt reduces the gap by almost 50%. Therefore the bitumen spray sealed granular pavement is the more environmentally friendly option. The reduction of emissions from the use of bio-bitumen was not as great as the ECO5 asphalt reduction however it is still a significant amount.

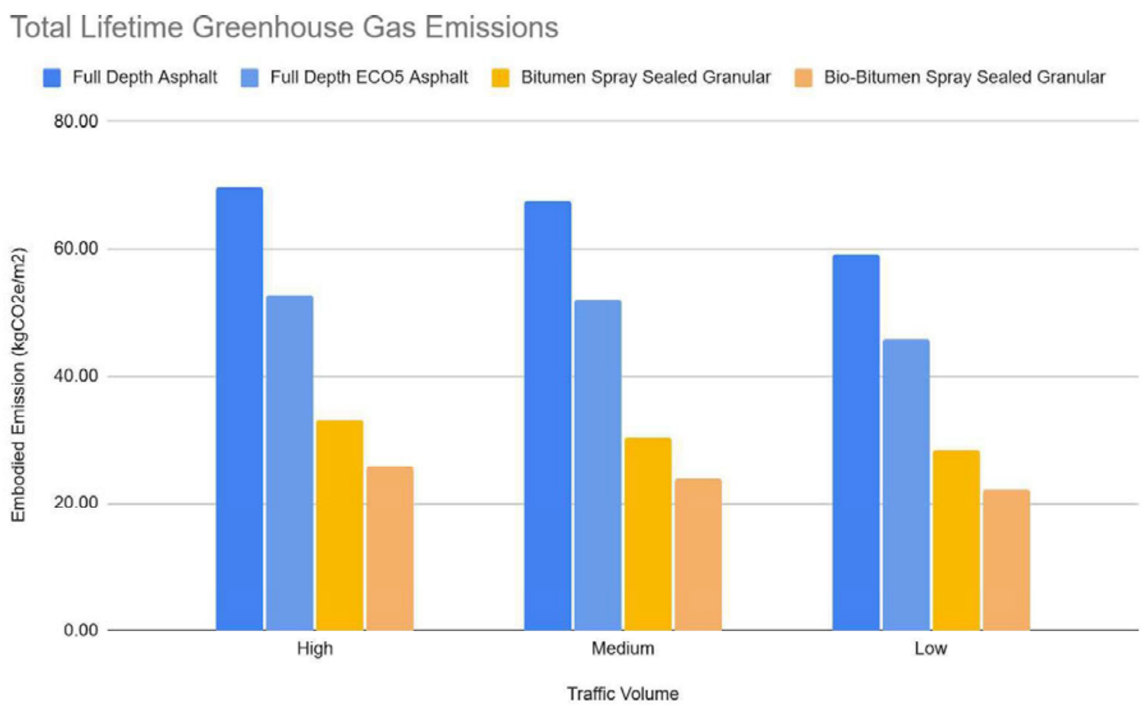


Figure 6.2 - total lifetime emissions of different pavement types for rural highways

6.3 Local Roads

The final road category for review is of the two chosen local road pavement types. The effects of substituting sustainable materials has also been quantified for the spray sealed pavement but no such sustainable alternative is available for unsealed roads. As there is no major initial construction or rehabilitation works required on unsealed roads, this local road section results are provided as the average yearly emissions instead of the lifetime emissions.

6.3.1 Spray Sealed Granular Pavement

As can be seen in Table 6.21, the initial construction/pavement rehabilitation and reseals are the two main contributors to greenhouse gas emissions.

Activity	Material Emissions ($kgCO_2e/m2$)	Machinery Emissions ($kgCO_2e/m2$)	Total Emissions ($kgCO_2e/m2$)
Initial Construction / Pavement Rehabilitation	12.444	0.825	13.269
Reseal	2.698	0.206	2.904
Repair Pothole	0.002	0.011	0.012
Repair Pavement Edge	0.010	0.029	0.039
Minor Pavement Patching	0.023	0.018	0.040
Seal Pavement Crack	0.024	0.084	0.108

Table 6.21- material, machinery and total emissions per activity for sealed roads

Local governments typically try to get as much life out of a pavement as possible due to the high upfront cost of rehabilitation. This can impact the ride quality of the road but can save substantial cost and greenhouse gas emissions.

AADT	Pavement Rehabilitation	Reseals	Repair Pothole	Repair Pavement Edge	Minor Pavement Patching	Seal Pavement Crack
50	80 Years	25 Years	1.24 per km	2.715 m/km	0.74 m^2/km	19.58 m^2/km
100	100 Years	25 Years	1.24 per km	2.715 m/km	0.74 m^2/km	19.58 m^2/km
200	100 Years	25 Years	1.24 per km	2.715 m/km	0.74 m^2/km	19.58 m^2/km

Table 6.22 - typical local government's sealed maintenance targets

Table 6.23 highlights the proportion of a pavement's emissions that come from the production and transportation of the construction materials compared to the much lower machinery emissions.

AADT	Pavement Rehabilitation ($kgCO_2e/m2$)	Reseals ($kgCO_2e/m2$)	Other Maintenance ($kgCO_2e/m2$)	Total Emissions ($kgCO_2e/m2$)
50	0.13269	0.11615	0.00043	0.24927
100	0.13269	0.11615	0.00043	0.24927
200	0.16586	0.11615	0.00043	0.28244

Table 6.23 - maintenance yearly frequencies and average yearly emissions for each road hierarchy

Table 6.24 identifies the quantity of emissions savings that are expected if bio-bitumen is utilised in the road design and again highlights the effects of material selection in reducing emissions.

Area	Sustainable Alternative	Reduction		
		AADT 200	AADT 100	AADT 50
Wearing Course	Bio-Bitumen Spray Seal	-0.044	-0.035	-0.035
Reseal	Bio-Bitumen Spray Seal	-0.070	-0.070	-0.070
	Total	**-0.114**	**-0.105**	**-0.105**
	Percentage Reduction	40.4%	42.2%	42.2%

Table 6.24 - potential reduction in greenhouse gas emissions for a spray sealed granular pavement

6.3.2 Unsealed Granular Pavement

There are only two main maintenance activities that are conducted on unsealed roads and they are shown in Table 6.25.

Maintenance Activity	Material Emissions ($kgCO_2e/m2$)	Machinery Emissions ($kgCO_2e/m2$)	Total Emissions ($kgCO_2e/m2$)
Maintenance Grading		0.099	0.099
Gravel Resheeting	0.754	0.305	1.059

Table 6.25 - material, machinery and total emissions per maintenance activity for unsealed roads

Unsealed roads typically require much more frequent maintenance compared to any other pavement.

AADT	Maintenance Grading	Gravel Resheeting
50	Once every 15 months	Once every 15 years
100	Once every 15 months	Once every 15 years
200	Once every 3 years	Once every 20 years

Table 6.26 - typical local government unsealed maintenance targets

The total average yearly emissions for maintaining an unsealed road is shown in Table 6.27.

AADT	Maintenance Grading Frequency	Grading Emissions ($kgCO_2e/m2$)	Gravel Resheeting Frequency	Resheeting Emissions ($kgCO_2e/m2$)	Yearly Emissions ($kgCO_2e/m2$)
50	0.3333	0.099	0.05	1.059	0.086
100	0.8	0.099	0.0667	1.059	0.150
200	0.8	0.099	0.0667	1.059	0.150

Table 6.27 - maintenance yearly frequencies and average yearly emissions for each road hierarchy

6.3.3 Local Road Summary

As expected, the bitumen spray sealed granular pavement produces the most emissions, however changing to bio-bitumen brings the value down in line with unsealed pavements. However, as can be seen in Figure 6.3, the unsealed emissions drop significantly at lower traffic volumes, while the sealed pavements do not see a major decrease.

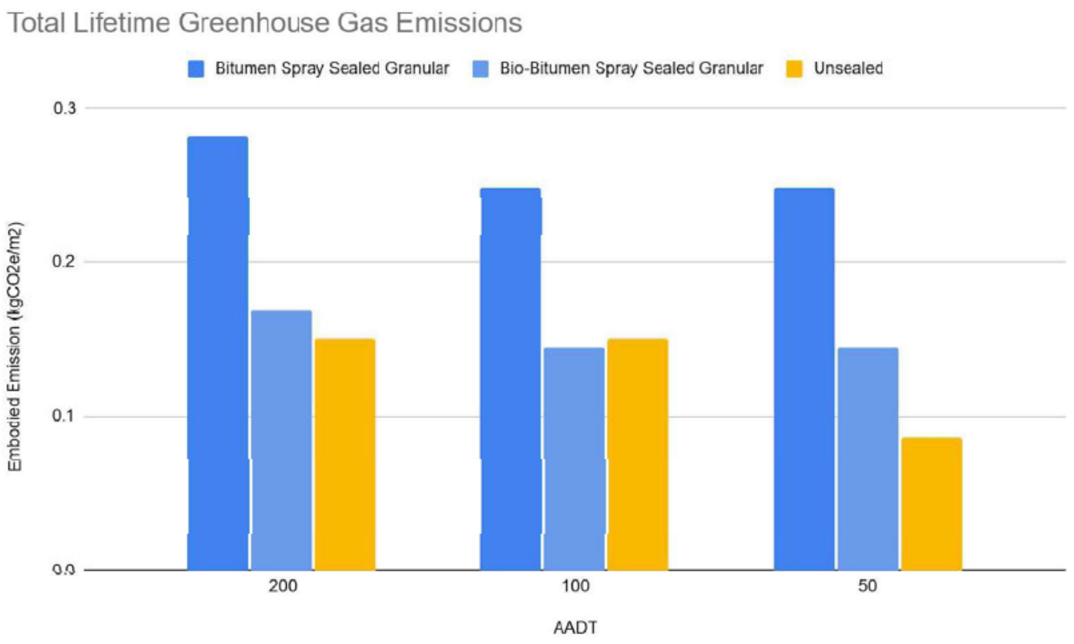


Figure 6.3 - total lifetime emissions of different pavement types for local roads

CHAPTER 7 DISCUSSION

The discussion focuses on comparing the results of the lifecycle greenhouse gas emissions of different pavement types, with a particular emphasis on the environmental impact of using sustainable materials in road construction. The resultant calculations show that rigid pavements, especially continuously reinforced concrete, exhibit far higher carbon emissions during the construction phase compared to flexible pavements, such as full depth asphalt. This is primarily due to the high production and transportation emissions of cement and steel. Also, This is partly due to the requirement under Austroads Guide to Pavement Technology Part 2: Pavement Structural Design that there is a minimum concrete base thickness of 250 millimetres for plain concrete and 230 millimetres for continuously reinforced concrete when the design traffic is over 5×10^7 heavy vehicle axle groups, which are required in order to reduce cracking in the pavement. In contrast, asphalt pavements have lower initial emissions but have higher maintenance emissions over their lifespan mainly due to the need for regular resurfacing.

The substitution of geopolymer concrete, ECO5 asphalt and bio-bitumen as sustainable alternatives, presents an opportunity to substantially reduce the overall embodied emissions. The results show that geopolymer concrete, which replaces Portland cement with industrial byproducts like fly ash and ground granulated blast furnace slag, can reduce the emissions of rigid pavements by around 25%. This reduction is significant considering the high carbon intensity of traditional concrete pavements but is still much higher than the embodied emissions of traditional asphalt pavement. Similarly, the use of ECO5 asphalt, which incorporates recycled materials like reclaimed asphalt pavement (RAP), recycled glass, and rubber, can lead to a 28% reduction in emissions over the traditional full depth asphalt pavement.

For the rural highway scenario, the results show that the asphalt pavements produce over double the amount of embodied emissions compared with the spray sealed pavement. Over the three traffic volumes that were calculated, the full depth asphalt saw a larger emissions decrease when compared with the spray sealed pavements. When ECO5 and bio-bitumen are substituted into the pavements, there is an approximately 30% reduction in embodied emissions for both.

In the local road scenario, the results found that the embodied emissions of spray seals was 2 to 4 times higher than an unsealed pavement depending on traffic volumes. Similarly to the rural highway, when bio-bitumen is substituted in, the emissions reduce by approximately 30% which brings it much closer to the unsealed pavements on the higher traffic volume roads. The emissions from the spray sealed pavements don't reduce much when the traffic volume is lower, this is due to the degradation of the spray seals and need for rejuvenation even without any traffic damage. This is mainly caused by the oxidation of the bitumen due to the ultraviolet light and exposure to oxygen. However, unsealed roads don't suffer as much degradation from non traffic sources.

The results show that the production and transportation of the construction materials is by far the largest contributor of greenhouse gas emissions. For rigid pavements, maintenance accounts for only a small fraction of total emissions (3-4%), but for flexible pavements, the maintenance activities can account for nearly 20% of lifetime emissions. This difference shows the importance of selecting the appropriate pavement materials for the design of a road construction project.

CHAPTER 8 CONCLUSION

The lifecycle pavement emissions calculated in this study really underlines the potential reduction in greenhouse gases that can be achieved when sustainable materials are utilised. The findings indicate that rigid pavements generate the highest emissions for motorway pavements, asphalt the highest for rural highways and spray sealed pavements the highest for local roads.

The high embodied carbon emissions of concrete comes primarily from the cement component, mainly due the production of cement being very energy intensive. It is also due to the fact that Australia does not produce enough cement clinkers to satisfy domestic demand and relies heavily on imports from Asian countries The partial substitution of cement with 30% fly ash or 30% ground granulated blast furnace slag can reduce the embodied carbon of concrete by approximately 27% and 20% respectively. Another factor in the embodied carbon of concrete is the compressive strength, where an increase from 32 MPa to 40 MPa will see a 21% increase in embodied carbon.

Although reinforcing steel is necessary in certain situations within rigid pavements usually due to poor subgrade conditions, on curves or on hills, it should be used sparingly due to its very high embodied carbon per kilogram.

With Australia's net zero carbon emissions target by 2050 and the ongoing shift away from utilising fossil fuels, there will be a reduction in the supply of bitumen in the future. This will cause a major increase in price which could potentially push road construction projects towards using rigid pavements, therefore increasing emissions.

There are limitations to this project, namely the lack of long term performance data for the sustainable materials. This introduces uncertainty regarding the durability and effectiveness over the typical lifespan of road pavements. The trial sites of geopolymer concrete, bio-bitumen seals and ECO5 asphalt will need to be continually assessed in the future to determine the longevity of the products compared to the traditional materials. Also, due to how diverse Australia is and the remoteness of much of the road network, material and machinery availability may affect these findings, particularly for road authorities operating in regions with different environmental and economic conditions.

Furthermore, as a lot of these sustainable products are still in the testing and development phase, the true cost is not yet known. However, given all of the sustainable materials either use recycled materials, byproducts or commonly used production techniques, the cost will likely not be significantly higher than the traditional materials. Also, as global and national climate goals continue to prioritise emissions reduction, it is expected that there will likely be incentives to utilise these sustainable materials.

In conclusion, this project has shown a number of possible sustainable alternative materials that will substantially reduce the emissions generated by the transport sector in order to meet Australia's net zero by 2050 goal.

REFERENCES

References

Phillips 2024, *Australia's Road Network: Navigating the Continent with Precision,* Transvirtual, Melbourne, Victoria, viewed 11th August 2024 <https://www.transvirtual.com/blog/australias-road-network-navigating-the-continent-with-precision/#:~:text=Australia%27s%20expansive%20road%20network%20stretches,355%2C000%20kilometres%20of%20sealed%20roads>

Department of Infrastructure, Transport, Regional Development, Communications and the Arts 2024, *Transport and Infrastructure Net Zero Consultation Roadmap*, DITRDCA, Canberra

Commonwealth Scientific and Industrial Research Organisation & Bureau of Meteorology 2022, *State of the Climate 2022*, 7th edition, CSIRO & BOM, Canberra

Austroads 2023, *Guide to Pavement Technology Part 1: Introduction to Pavement Technology*, Austroads Ltd, Level 9, 287 Elizabeth Street Sydney NSW 2000 Australia.

Austroads 2017, *Guide to Pavement Technology Part 4c: Materials for Concrete Road Pavements*, Austroads Ltd, Level 9, 287 Elizabeth Street Sydney NSW 2000 Australia.

Austroads 2014, *Guide to Pavement Technology Part 4b: Asphalt*, Austroads Ltd, Level 9, 287 Elizabeth Street Sydney NSW 2000 Australia.

Austroads 2007, *The Durability of Australian Bitumens 1956-2004*, Austroads Ltd, Level 9, 287 Elizabeth Street Sydney NSW 2000 Australia.

Australian Transport Assessment and Planning Steering Committee 2016, *Australian Transport Assessment and Planning Guidelines: PV2 Road Parameter Values*, Commonwealth Department of Infrastructure, GPO Box 594 Canberra ACT 2601 Australia.

National Oceanic and Atmospheric Administration Global Monitoring Laboratory 2023, *The NOAA Annual Greenhouse Gas Index (AGGI)*, National Oceanic and Atmospheric Administration,<NOAA Global Monitoring Laboratory - THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI)>

Calderón-Garcidueñas, L, Franco-Lira, M, Torres-Jardón, R, Henríquez-Roldán, C, Barragán-Mejía, G, Valencia-Salazar, G et al. 2008, 'Early Alzheimer's and neural hyperinflammation in urban children', *Journal of Alzheimer's Disease*, vol. 15, no. 4, p. 529-544. <https://doi.org/10.3233/JAD-2008-15409>

Gong, J, Zhu, T, Kipen, H, Wang, G, Hu, M, Guo, Q et al. 2014, 'Comparisons of ultrafine and fine particles in their associations with biomarkers reflecting physiological pathways', *Environmental Science & Technology*, vol. 48, no. 9, p. 5264-5273. <https://doi.org/10.1021/es5006018>

Hodan, WM & Barnard, WR 2004, *Evaluating the contribution of PM2.5 precursor emissions and atmospheric processes to the complexities of managing PM2.5 air quality*, U.S. Environmental Protection Agency. <https://www3.epa.gov/ttnchie1/conference/ei13/mobile/hodan.pdf>

Kim, JY, Lee, JS & Lee, SW 2015, 'Impact of air pollution on neurological disorders: The link between particulate matter and Alzheimer's disease', *Environmental Health Perspectives*, vol. 123, no. 1, p. 32-38. <https://doi.org/10.1289/ehp.1408213>

Pope, CA 2000, 'Epidemiology of fine particulate air pollution and human health: biological mechanisms and who's at risk?', *Environmental Health Perspectives*, vol. 108, suppl. 4, p. 713-723. <https://pubmed.ncbi.nlm.nih.gov/11667958/>

Pope, CA & Dockery, DW 2006, 'Health effects of fine particulate air pollution: lines that connect', *Journal of the Air & Waste Management Association*, vol. 56, no. 6, pp. 709-742. <https://doi.org/10.1080/10473289.2006.10464485>

World Health Organization 2018, *Ambient air pollution: Health impacts*, WHO, Geneva. <https://www.who.int/airpollution/ambient/health-impacts/en/>

Department of Climate Change, Energy, the Environment and Water 2023, *New Fuel Efficiency Standards to Improve Public Health,* DCCEEW, Canberra, ACT, viewed 11th August 2024 <https://www.dcceew.gov.au/about/news/new-fuel-quality-standards-improve-public-health#:~:text=Noxious%20vehicle%20emissions%20contributed%20to,Australian%20market%20from%20December%202025>

Crawford, R.H., Stephan, A. and Prideaux, F. 2024 *Environmental Performance in Construction (EPiC) Database*, The University of Melbourne, Melbourne.

Weir, M., Rempher, A. and Esau, R. 2023 '*Embodied Carbon 101: Building Materials',* Rocky Mountain Institute, Basalt, Colorado USA, viewed 20th August 2024 <https://rmi.org/embodied-carbon-101/>

Transport for New South Wales 2024, *Specification D&C TS 0.3323.2 (3211) Cementitious Materials, Binders and Fillers*, TfNSW, <https://standards.transport.nsw.gov.au/search-standard-specific/?id=TBA%20-%200006403:2024>

Hanson, C, Noland, R 2015, *Greenhouse gas emissions from road construction: An assessment of alternative staging approaches,* 40, Elsevier, viewed 7 Oct 2023, <https://www.sciencedirect.com/science/article/abs/pii/S1361920915001066#preview-section-cited-by>

Chehovits, J. & Galehouse, L., 2010, *Energy usage and greenhouse gas emissions of pavement preservation processes for asphalt concrete pavements*, Proceedings on the 1st International conference of pavement preservation

Huang, Y., Ning, Y., Zhang, T. & Wu, J., 2016. Measuring carbon emissions of pavement construction in China. *Sustainability*, *8*(8), p.723.

Ma, F., Dong, W., Fu, Z., Wang, R., Huang, Y. and Liu, J., 2021. Life cycle assessment of greenhouse gas emissions from asphalt pavement maintenance: A case study in China. *Journal of Cleaner Production*, *288*, p.125595.

Huang, Y., Bird, R. and Bell, M., 2009. A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. *Transportation Research Part D: Transport and Environment*.

Wang, H. and Gangaram, R., 2014. *Life Cycle Assessment of Asphalt Pavement Maintenance* (No. CAIT-UTC-013). Rutgers University. Center for Advanced Infrastructure and Transportation.

Lee, D.I., Park, J., Shin, M., Lee, J. and Park, S., 2022. Characteristics of real-world gaseous emissions from construction machinery. *Energies*

El Sheikh, S 2022 *CO2 emissions from buildings and construction hit new high, leaving sector off track to decarbonize by 2050: UN*, UN Environment Programme. Viewed 11 Feb 2024, <https://www.unep.org/news-and-stories/press-release/co2-emissions-buildings-and-construction-hit-new-high-leaving-sector>

United Nations Environment Programme, 2022 *2022 Global Status Report for Buildings and Construction*, Viewed 11 Feb 2024, <https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction>

Austroads 2019, *Guide to Pavement Technology Part 7: Pavement Maintenance*, Austroads Ltd., Level 9, 287 Elizabeth Street Sydney NSW 2000 Australia.

Austroads 2017, *Guide to Pavement Technology Part 2: Pavement Structural Design*, Austroads Ltd., Level 9, 287 Elizabeth Street Sydney NSW 2000 Australia.

Australian Life Cycle Assessment Society 2023, *The Australian Life Cycle Inventory Database Initiative*, ALCAS, Australia Viewed 30 Aug 2024, <https://www.auslci.com.au/index.php/EmissionFactors>

Transport for New South Wales 2021, *Pavement Standard Drawings: Typical Pavement Profiles*, TfNSW, Viewed 28 June 2024 <https://standards.transport.nsw.gov.au/search-standard-specific/?id=TBA%20-%200003840:2022>

The COLAS Group 2021, *ECO5 - High Performance Sustainable Asphalt*, The Colas Group, Viewed 30 Sept 2024, <https://www.colas.com.au/313/wp-content/uploads/2021/02/ECO5.pdf>

Transport for New South Wales 2024, *Bio-bitumen trial removing the roadblock for a greener future*, TfNSW, Viewed 30 Sept 2024, <https://www.transport.nsw.gov.au/system/files/media/documents/2024/Media_release_Bio_bitumen_trial_Aitchison.pdf>

Clean Energy Regulator 2024, *Global Warming Potential,* CER, Viewed 30 Sept 2024, <https://cer.gov.au/schemes/national-greenhouse-and-energy-reporting-scheme/about-emissions-and-energy-data/global-warming-potential>

APPENDIX A - Project Specification

ENP4111

Project Specification

For: Matthew Targett

Title: Lifecycle Emissions of Different Pavement Types

Major: Civil

Supervisors: Dr Saya Ramakrishnan

Enrollment: ENP4111

Project Aims:

The primary aim of this research proposal is to investigate and compare the lifecycle emissions associated with rigid and flexible pavement systems used in road construction. Furthering our knowledge on this area will help road authorities continue to reduce the emissions from managing their road networks.

The research aims to achieve the following objectives:

- Conduct a thorough literature review to establish existing knowledge on the environmental impact of rigid and flexible pavement systems.
- Identify the knowledge gap in current research and determine the study's justification.
- Develop a comprehensive methodology for conducting a life cycle assessment (LCA) of rigid and flexible pavements.
- Determine which pavement construction type emits the lowest emissions for each road scenario.

Expected Outcomes:

The expected outcomes and benefits of this research include:

- A comprehensive understanding of the environmental impact of rigid and flexible pavement systems.
- Data-driven insights for decision-makers in the road construction industry, enabling them to choose sustainable pavement options.
- Reduction of GHG emissions associated with road construction through informed choices.
- Improved environmental sustainability in the infrastructure sector.

APPENDIX B - Risk Assessment

UNIVERSITY OF SOUTHERN QUEENSLAND

Offline Vers

USQ Safety Risk Management System

Note: This is the offline version of the Safety Risk Management System (SRMS) Risk Management Plan (RMP) and is only to be used for planning an drafting sessions, and when working in remote areas or on field activities. It must be transferred to the online SRMS at the first opportunity.

Safety Risk Management Plan – Offline Version			
Assessment Title:	BENH Thesis - Lifecycle Emissions of Different Pavement Types	Assessment Date:	10/10/2023
Workplace (Division/Faculty/Section):	School of Engineering	Review Date:(5 Years Max)	10/10/2028
Context			
Description:			
What is the task/event/purchase/project/procedure?	Researching the Lifecycle Greenhouse Gas Emissions of Different Pavement Types		
Why is it being conducted?	For completion of Bachelor of Engineering		
Where is it being conducted?			
Course code (if applicable)	ENG4110	Chemical name (if applicable)	
What other nominal conditions?			
Personnel involved	Matthew Targett		
Equipment	Desk, chair, computer, phone		
Environment	Home office		
Other			
Briefly explain the procedure/process	Calculate emissions from available data		
Assessment Team - who is conducting the assessment?			

Assessor(s)	Dr Wahid Ferdous
Others consulted:	

Eg 1. Enter Consequence

Eg 2. Enter Probability

	Consequence				
Probability	Insignificant No Injury 0-$5K	Minor First Aid $5K-$50K	Moderate Med Treatment $50K-$100K	Major Serious Injuries $100K-$250K	Catastrophic Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1000	L	M	H	H	H
Unlikely 1 in 10 000	L	L	M	M	M
Rare 1 in 1 000 000	L	L	L	L	L

Eg 3. Find Action

Recommended Action Guide
E=Extreme Risk – Task ***MUST NOT*** proceed
H=High Risk – Special Procedures Required (See USQSafe)
M=Moderate Risk – Risk Management Plan/Work Method Statement Required
L=Low Risk – Use Routine Procedures

Step 1 (cont)	Step 2	Step 2a	Step 2b	Step 3			Step 4				
Hazards: From step 1 or more if identified	***The Risk:*** What can happen if exposed to the hazard without existing controls in place?	***Consequence:*** What is the harm that can be caused by the hazard without existing controls in place?	***Existing Controls:*** What are the existing controls that are already in place?	***Risk Assessment:*** Consequence x Probability = Risk Level			***Additional controls:*** Enter additional controls if required to reduce the risk level	***Risk assessment with additional controls:***			
				Probability	**Risk Level**	**ALARP? Yes/no**		**Consequence**	**Probability**	**Risk Level**	**ALARP? Yes/no**
Example											
Working in temperatures over 35° C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	catastrophic	Regular breaks, chilled water available, loose clothing, fatigue management policy.	possible	high	No	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
Sitting down all day	Injure hips, legs, back	Minor	Stretching, good office chair, posture	Likely	High	No	Break up the required work into smaller sections and take regular breaks	Mionr	Unlikely	Low	Yes
Traversing stairs	Tripping and injuring to body	Moderate	Ensuring you are free from distractions	Possible	High	No	Keeping stairs clean and clear of objects	Moderate	Unlikely	Medium	Yes

Step 5 - Action Plan (for controls not already in place)			
Additional controls:	*Resources:*	*Persons responsible:*	*Proposed implementation date:*
Schedule works into smaller sections to allow frequent breaks	Calendar application	Matthew Targett	10/10/2023
Keeping stairs clean and clear of objects	Vacuum and mop	Matthew Targett	10/10/2023

Step 6 - Approval			
Drafter's name:	Matthew Targett	Draft date:	10/10/2023
Drafter's comments:	N/A		
Approver's name:		Approver's title/position:	
Approver's comments:			
I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.			
Approver's signature:		Approval date:	Click here to enter a date.

APPENDIX C - CIRCLY Reports

Motorway - Rigid Pavement - High Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 4.40E+08

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load  Load                 Load                 Load             Radius    Pressure/    Exponent
   No.   ID                   Category             Type                       Ref. stress
    1    ESA750-Full          ESA750-Full          Vertical Force     92.1     0.75          0.00
    2    SAST53               SAST53               Vertical Force    102.4     0.80          0.00

   Load Locations:
   Location  Load                 Gear          X           Y      Scaling     Theta
   No.         ID                 No.                                Factor
    1          ESA750-Full         1         -165.0        0.0    1.00E+00      0.00
    2          ESA750-Full         1          165.0        0.0    1.00E+00      0.00
    3          ESA750-Full         1         1635.0        0.0    1.00E+00      0.00
    4          ESA750-Full         1         1965.0        0.0    1.00E+00      0.00
    1          SAST53              1            0.0        0.0    1.00E+00      0.00
    2          SAST53              1         2130.0        0.0    1.00E+00      0.00

Details of Layered System:

   ID: StandardRigid Title: Rigid Pavement

   Layer  Lower    Material              Isotropy   Modulus    P.Ratio
   No.    i/face   ID                               (or Ev)    (or vvh)  F          Eh         vh
    1     rough    Concrete              Iso.       2.80E+04   0.00
    2     rough    TfNSW LMC             Iso.       1.00E+04   0.20
    3     rough    subsltCB10            Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3              Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material              Component  Perform.   Perform.   Shift
   No.             ID                               Constant   Exponent   Factor
    3     top      subsltCB10            EZZ         0.009150    7.000
    4     top      Sub_CBR3              EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  1
   Minimum thickness:  250
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material              Axle       Unitless
   No.               ID                               Strain
    3      300.00    subsltCB10
                                           SADT(80): 4.895E-05
    4        0.00    Sub_CBR3
                                           SADT(80): 8.940E-05

Results:

   Layer  Thickness  Material              Axle       CDF
   No.               ID                    Group
    1      250.00    Concrete                                n/a

    2      150.00    TfNSW LMC                               n/a

    3      300.00    subsltCB10            Total:     5.894E-08

    4        0.00    Sub_CBR3              Total:     3.994E-06
```

Motorway - Rigid Pavement - Medium Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 1.60E+08

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                 Load                 Load            Radius    Pressure/    Exponent
   No.    ID                   Category             Type                      Ref. stress
    1     ESA750-Full          ESA750-Full          Vertical Force     92.1    0.75          0.00
    2     SAST53               SAST53               Vertical Force    102.4    0.80          0.00

   Load Locations:
   Location   Load                Gear         X          Y      Scaling     Theta
   No.        ID                  No.                            Factor
    1         ESA750-Full          1        -165.0       0.0   1.00E+00      0.00
    2         ESA750-Full          1         165.0       0.0   1.00E+00      0.00
    3         ESA750-Full          1        1635.0       0.0   1.00E+00      0.00
    4         ESA750-Full          1        1965.0       0.0   1.00E+00      0.00
    1         SAST53               1           0.0       0.0   1.00E+00      0.00
    2         SAST53               1        2130.0       0.0   1.00E+00      0.00

Details of Layered System:

   ID: StandardRigid Title: Rigid Pavement

   Layer  Lower    Material              Isotropy  Modulus    P.Ratio
   No.    i/face   ID                              (or Ev)    (or vvh)  F          Eh         vh
    1     rough    Concrete              Iso.      2.80E+04   0.00
    2     rough    TfNSW LMC             Iso.      1.00E+04   0.20
    3     rough    subsltCB10            Aniso.    8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3              Aniso.    3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material              Component Perform.   Perform.   Shift
   No.             ID                              Constant   Exponent   Factor
    3     top      subsltCB10            EZZ        0.009150    7.000
    4     top      Sub_CBR3              EZZ        0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor       Type
    3      1.00       Subgrade (Selected Material) (Austroads 2017)
    4      1.00       Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  1
   Minimum thickness:  250
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material              Axle       Unitless
   No.               ID                               Strain
    3       300.00   subsltCB10
                                          SADT(80): 4.895E-05
    4         0.00   Sub_CBR3
                                          SADT(80): 8.940E-05

Results:

   Layer  Thickness  Material              Axle       CDF
   No.               ID                    Group
    1       250.00   Concrete                              n/a

    2       150.00   TfNSW LMC                             n/a

    3       300.00   subsltCB10            Total:     2.143E-08

    4         0.00   Sub_CBR3              Total:     1.452E-06
```

Motorway - Rigid Pavement - Low Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 8.40E+07

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                 Load                 Load            Radius    Pressure/    Exponent
   No.    ID                   Category             Type                      Ref. stress
    1     ESA750-Full          ESA750-Full          Vertical Force     92.1    0.75          0.00
    2     SAST53               SAST53               Vertical Force    102.4    0.80          0.00

   Load Locations:
   Location   Load                 Gear          X          Y      Scaling     Theta
   No.        ID                   No.                             Factor
    1         ESA750-Full           1         -165.0       0.0    1.00E+00      0.00
    2         ESA750-Full           1          165.0       0.0    1.00E+00      0.00
    3         ESA750-Full           1         1635.0       0.0    1.00E+00      0.00
    4         ESA750-Full           1         1965.0       0.0    1.00E+00      0.00
    1         SAST53                1            0.0       0.0    1.00E+00      0.00
    2         SAST53                1         2130.0       0.0    1.00E+00      0.00

Details of Layered System:

   ID: StandardRigid Title: Rigid Pavement

   Layer  Lower    Material             Isotropy   Modulus    P.Ratio
   No.    i/face   ID                              (or Ev)    (or vvh)  F          Eh         vh
    1     rough    Concrete             Iso.       2.80E+04   0.00
    2     rough    TfNSW LMC            Iso.       1.00E+04   0.20
    3     rough    subsltCB10           Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3             Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material             Component  Perform.   Perform.   Shift
   No.             ID                              Constant   Exponent   Factor
    3     top      subsltCB10           EZZ         0.009150    7.000
    4     top      Sub_CBR3             EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  1
   Minimum thickness:  250
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material             Axle       Unitless
   No.               ID                              Strain
    3       300.00   subsltCB10
                                          SADT(80): 4.895E-05
    4         0.00   Sub_CBR3
                                          SADT(80): 8.940E-05

Results:

   Layer  Thickness  Material             Axle       CDF
   No.               ID                   Group
    1       250.00   Concrete                               n/a

    2       150.00   TfNSW LMC                              n/a

    3       300.00   subsltCB10           Total:     1.125E-08

    4         0.00   Sub_CBR3             Total:     7.625E-07
```

Motorway - Flexible Pavement - High Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  1 is INCLUDED in max. CDF calculation
   Layer no.  2 is INCLUDED in max. CDF calculation
   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 4.40E+08

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                 Load                 Load             Radius    Pressure/    Exponent
   No.    ID                   Category             Type                       Ref. stress
    1     ESA750-Full          ESA750-Full          Vertical Force     92.1     0.75          0.00
    2     SAST53               SAST53               Vertical Force    102.4     0.80          0.00

   Load Locations:
   Location   Load               Gear        X          Y     Scaling      Theta
   No.        ID                 No.                          Factor
    1         ESA750-Full         1       -165.0       0.0    1.00E+00      0.00
    2         ESA750-Full         1        165.0       0.0    1.00E+00      0.00
    3         ESA750-Full         1       1635.0       0.0    1.00E+00      0.00
    4         ESA750-Full         1       1965.0       0.0    1.00E+00      0.00
    1         SAST53              1          0.0       0.0    1.00E+00      0.00
    2         SAST53              1       2130.0       0.0    1.00E+00      0.00

Details of Layered System:

   ID: Asphalt Title: Full Depth Asphalt

   Layer  Lower    Material             Isotropy   Modulus    P.Ratio
   No.    i/face   ID                              (or Ev)    (or vvh)  F          Eh          vh
    1     rough    AC14                 Iso.       2.20E+03   0.40
    2     rough    AC20                 Iso.       2.50E+03   0.40
    3     rough    subsltCB10           Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01    0.45
    4     rough    Sub_CBR3             Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01    0.45

   Performance Relationships:
   Layer  Location Material             Component  Perform.   Perform.   Shift
   No.             ID                              Constant   Exponent   Factor
    1     bottom   AC14                 ETH         0.004705    5.000      6.0
    2     bottom   AC20                 ETH         0.004342    5.000      6.0
    3     top      subsltCB10           EZZ         0.009150    7.000
    4     top      Sub_CBR3             EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    1      6.00        Asphalt
    2      6.00        Asphalt
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material              Axle       Unitless
   No.               ID                               Strain
    1       50.00    AC14
                                           SADT(80):  3.812E-05
                                           SAST(53):  4.073E-05
    2      367.58    AC20
                                           SADT(80):  8.878E-05
                                           SAST(53):  6.196E-05
    3      300.00    subsltCB10
                                           SADT(80):  1.423E-04
    4        0.00    Sub_CBR3
                                           SADT(80):  2.157E-04

Results:

   Layer  Thickness  Material              Axle       CDF
   No.               ID                    Group
    1       50.00    AC14                  Total:     2.173E-02
                                           SAST:      1.296E-02
                                           SADT:      8.050E-04
                                           TAST:      7.212E-04
                                           TADT:      5.893E-03
                                           TRDT:      1.335E-03
```

Motorway - Flexible Pavement - Medium Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

    Layer no.  1 is INCLUDED in max. CDF calculation
    Layer no.  2 is INCLUDED in max. CDF calculation
    Layer no.  3 is INCLUDED in max. CDF calculation
    Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 1.60E+08

Traffic Load Distribution:

    ID: NSWPresumeRural
    Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
    ESA/HVAG: 1.068

Details of Load Groups:

    Load   Load                 Load                 Load             Radius    Pressure/    Exponent
    No.    ID                   Category             Type                       Ref. stress
     1     ESA750-Full          ESA750-Full          Vertical Force     92.1     0.75          0.00
     2     SAST53               SAST53               Vertical Force    102.4     0.80          0.00

    Load Locations:
    Location   Load                 Gear         X           Y      Scaling      Theta
    No.        ID                   No.                             Factor
     1         ESA750-Full           1        -165.0        0.0    1.00E+00      0.00
     2         ESA750-Full           1         165.0        0.0    1.00E+00      0.00
     3         ESA750-Full           1        1635.0        0.0    1.00E+00      0.00
     4         ESA750-Full           1        1965.0        0.0    1.00E+00      0.00
     1         SAST53                1           0.0        0.0    1.00E+00      0.00
     2         SAST53                1        2130.0        0.0    1.00E+00      0.00

Details of Layered System:

    ID: Asphalt Title: Full Depth Asphalt

    Layer  Lower    Material              Isotropy   Modulus    P.Ratio
    No.    i/face   ID                               (or Ev)    (or vvh)  F          Eh          vh
     1     rough    AC14                  Iso.       2.20E+03   0.40
     2     rough    AC20                  Iso.       2.50E+03   0.40
     3     rough    subsltCB10            Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
     4     rough    Sub_CBR3              Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

    Performance Relationships:
    Layer  Location Material              Component  Perform.   Perform.   Shift
    No.             ID                               Constant   Exponent   Factor
     1     bottom   AC14                  ETH         0.004705   5.000      6.0
     2     bottom   AC20                  ETH         0.004342   5.000      6.0
     3     top      subsltCB10            EZZ         0.009150   7.000
     4     top      Sub_CBR3              EZZ         0.009150   7.000

    Reliability Factors:
    Project Reliability: Austroads 95%
    Layer  Reliability  Material
     No.   Factor        Type
     1      6.00        Asphalt
     2      6.00        Asphalt
     3      1.00        Subgrade (Selected Material) (Austroads 2017)
     4      1.00        Subgrade (Austroads 2017)

    Details of Layers to be sublayered:
    Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
    Layer number to be designed:  2
    Minimum thickness:  0
    Maximum thickness:  5000

Strains:

    Layer  Thickness  Material               Axle       Unitless
    No.               ID                                Strain
     1       50.00    AC14
                                             SADT(80):  3.362E-05
                                             SAST(53):  3.489E-05
     2      315.52    AC20
                                             SADT(80):  1.085E-04
                                             SAST(53):  7.785E-05
     3      300.00    subsltCB10
                                             SADT(80):  1.743E-04
     4        0.00    Sub_CBR3
                                             SADT(80):  2.593E-04

Results:

    Layer  Thickness  Material               Axle       CDF
    No.               ID                     Group
     1       50.00    AC14                   Total:     3.857E-03
                                             SAST:      2.173E-03
                                             SADT:      1.564E-04
                                             TAST:      1.209E-04
                                             TADT:      1.145E-03
                                             TRDT:      2.593E-04
```

Motorway - Flexible Pavement - Low Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  1 is INCLUDED in max. CDF calculation
   Layer no.  2 is INCLUDED in max. CDF calculation
   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 8.40E+07

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                 Load                 Load              Radius    Pressure/    Exponent
   No.    ID                   Category             Type                        Ref. stress
    1     ESA750-Full          ESA750-Full          Vertical Force     92.1      0.75          0.00
    2     SAST53               SAST53               Vertical Force    102.4      0.80          0.00

   Load Locations:
   Location   Load                  Gear          X           Y      Scaling      Theta
   No.        ID                    No.                              Factor
    1         ESA750-Full            1         -165.0        0.0   1.00E+00      0.00
    2         ESA750-Full            1          165.0        0.0   1.00E+00      0.00
    3         ESA750-Full            1         1635.0        0.0   1.00E+00      0.00
    4         ESA750-Full            1         1965.0        0.0   1.00E+00      0.00
    1         SAST53                 1            0.0        0.0   1.00E+00      0.00
    2         SAST53                 1         2130.0        0.0   1.00E+00      0.00

Details of Layered System:

   ID: Asphalt Title: Full Depth Asphalt

   Layer  Lower    Material                Isotropy   Modulus    P.Ratio
   No.    i/face   ID                                 (or Ev)    (or vvh)  F          Eh         vh
    1     rough    AC14                    Iso.       2.20E+03   0.40
    2     rough    AC20                    Iso.       2.50E+03   0.40
    3     rough    subsltCB10              Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3                Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material                Component  Perform.   Perform.   Shift
   No.             ID                                 Constant   Exponent   Factor
    1     bottom   AC14                    ETH         0.004705    5.000      6.0
    2     bottom   AC20                    ETH         0.004342    5.000      6.0
    3     top      subsltCB10              EZZ         0.009150    7.000
    4     top      Sub_CBR3                EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    1      6.00        Asphalt
    2      6.00        Asphalt
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material                Axle       Unitless
   No.               ID                                 Strain
    1       50.00    AC14
                                             SADT(80):  3.059E-05
                                             SAST(53):  3.060E-05
    2      286.66    AC20
                                             SADT(80):  1.225E-04
                                             SAST(53):  8.960E-05
    3      300.00    subsltCB10
                                             SADT(80):  1.970E-04
    4        0.00    Sub_CBR3
                                             SADT(80):  2.902E-04

Results:

   Layer  Thickness  Material                Axle       CDF
   No.               ID                      Group
    1       50.00    AC14                    Total:     1.137E-03
                                             SAST:      5.924E-04
                                             SADT:      5.113E-05
                                             TAST:      3.297E-05
                                             TADT:      3.743E-04
                                             TRDT:      8.481E-05
```

Rural Highway - Asphalt - High Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  1 is INCLUDED in max. CDF calculation
   Layer no.  2 is INCLUDED in max. CDF calculation
   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 2.10E+07

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load  Load                 Load                 Load            Radius   Pressure/    Exponent
   No.   ID                   Category             Type                     Ref. stress
    1    ESA750-Full          ESA750-Full          Vertical Force    92.1    0.75          0.00
    2    SAST53               SAST53               Vertical Force   102.4    0.80          0.00

   Load Locations:
   Location   Load             Gear         X           Y      Scaling     Theta
   No.        ID               No.                             Factor
    1         ESA750-Full       1         -165.0        0.0   1.00E+00      0.00
    2         ESA750-Full       1          165.0        0.0   1.00E+00      0.00
    3         ESA750-Full       1         1635.0        0.0   1.00E+00      0.00
    4         ESA750-Full       1         1965.0        0.0   1.00E+00      0.00
    1         SAST53            1            0.0        0.0   1.00E+00      0.00
    2         SAST53            1         2130.0        0.0   1.00E+00      0.00

Details of Layered System:

   ID: Asphalt Title: Full Depth Asphalt

   Layer  Lower    Material             Isotropy  Modulus    P.Ratio
   No.    i/face   ID                             (or Ev)    (or vvh)  F          Eh          vh
    1     rough    AC14                 Iso.      2.20E+03   0.40
    2     rough    AC20                 Iso.      2.50E+03   0.40
    3     rough    subsltCB10           Aniso.    8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3             Aniso.    3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material             Component  Perform.   Perform.   Shift
   No.             ID                              Constant   Exponent   Factor
    1     bottom   AC14                 ETH        0.004705    5.000      6.0
    2     bottom   AC20                 ETH        0.004342    5.000      6.0
    3     top      subsltCB10           EZZ        0.009150    7.000
    4     top      Sub_CBR3             EZZ        0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    1      6.00        Asphalt
    2      6.00        Asphalt
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material             Axle       Unitless
   No.               ID                              Strain
    1       50.00    AC14
                                          SADT(80): 2.297E-05
                                          SAST(53): 1.888E-05
    2      229.48    AC20
                                          SADT(80): 1.599E-04
                                          SAST(53): 1.228E-04
    3      300.00    subsltCB10
                                          SADT(80): 2.620E-04
    4        0.00    Sub_CBR3
                                          SADT(80): 3.737E-04

Results:

   Layer  Thickness  Material             Axle       CDF
   No.               ID                   Group
    1       50.00    AC14                 Total:     4.446E-05
                                          SAST:      1.322E-05
                                          SADT:      3.050E-06
                                          TAST:      7.361E-07
                                          TADT:      2.233E-05
                                          TRDT:      5.059E-06
```

Rural Highway - Asphalt - Medium Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  1 is INCLUDED in max. CDF calculation
   Layer no.  2 is INCLUDED in max. CDF calculation
   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 2.00E+07

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                  Load                  Load            Radius    Pressure/    Exponent
   No.    ID                    Category              Type                      Ref. stress
    1     ESA750-Full           ESA750-Full           Vertical Force     92.1     0.75          0.00
    2     SAST53                SAST53                Vertical Force    102.4     0.80          0.00

   Load Locations:
   Location   Load                 Gear          X           Y      Scaling     Theta
   No.        ID                   No.                              Factor
    1         ESA750-Full           1         -165.0        0.0    1.00E+00     0.00
    2         ESA750-Full           1          165.0        0.0    1.00E+00     0.00
    3         ESA750-Full           1         1635.0        0.0    1.00E+00     0.00
    4         ESA750-Full           1         1965.0        0.0    1.00E+00     0.00
    1         SAST53                1            0.0        0.0    1.00E+00     0.00
    2         SAST53                1         2130.0        0.0    1.00E+00     0.00

Details of Layered System:

   ID: Asphalt Title: Full Depth Asphalt

   Layer  Lower    Material                Isotropy   Modulus    P.Ratio
   No.    i/face   ID                                 (or Ev)    (or vvh)  F          Eh         vh
    1     rough    AC14                    Iso.       2.20E+03   0.40
    2     rough    AC20                    Iso.       2.50E+03   0.40
    3     rough    subsltCB10              Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3                Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material                Component  Perform.   Perform.   Shift
   No.             ID                                 Constant   Exponent   Factor
    1     bottom   AC14                    ETH         0.004705    5.000      6.0
    2     bottom   AC20                    ETH         0.004342    5.000      6.0
    3     top      subsltCB10              EZZ         0.009150    7.000
    4     top      Sub_CBR3                EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    1      6.00        Asphalt
    2      6.00        Asphalt
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material                 Axle        Unitless
   No.               ID                                   Strain
    1       50.00    AC14
                                              SADT(80): 2.267E-05
                                              SAST(53): 1.841E-05
    2      227.69    AC20
                                              SADT(80): 1.614E-04
                                              SAST(53): 1.242E-04
    3      300.00    subsltCB10
                                              SADT(80): 2.648E-04
    4        0.00    Sub_CBR3
                                              SADT(80): 3.770E-04

Results:

   Layer  Thickness  Material                 Axle        CDF
   No.               ID                       Group
    1       50.00    AC14                     Total:      3.897E-05
                                              SAST:       1.110E-05
                                              SADT:       2.725E-06
                                              TAST:       6.180E-07
                                              TADT:       1.995E-05
                                              TRDT:       4.520E-06
```

Rural Highway - Asphalt - Low Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  1 is INCLUDED in max. CDF calculation
   Layer no.  2 is INCLUDED in max. CDF calculation
   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 6.30E+06

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                  Load                  Load             Radius    Pressure/    Exponent
   No.    ID                    Category              Type                       Ref. stress
    1     ESA750-Full           ESA750-Full           Vertical Force     92.1     0.75          0.00
    2     SAST53                SAST53                Vertical Force    102.4     0.80          0.00

   Load Locations:
   Location   Load                  Gear          X           Y      Scaling      Theta
   No.        ID                    No.                              Factor
    1         ESA750-Full            1         -165.0        0.0   1.00E+00      0.00
    2         ESA750-Full            1          165.0        0.0   1.00E+00      0.00
    3         ESA750-Full            1         1635.0        0.0   1.00E+00      0.00
    4         ESA750-Full            1         1965.0        0.0   1.00E+00      0.00
    1         SAST53                 1            0.0        0.0   1.00E+00      0.00
    2         SAST53                 1         2130.0        0.0   1.00E+00      0.00

Details of Layered System:

   ID: Asphalt Title: Full Depth Asphalt

   Layer  Lower    Material              Isotropy   Modulus    P.Ratio
   No.    i/face   ID                               (or Ev)    (or vvh)  F           Eh          vh
    1     rough    AC14                  Iso.       2.20E+03   0.40
    2     rough    AC20                  Iso.       2.50E+03   0.40
    3     rough    subsltCB10            Aniso.     8.00E+01   0.45      5.52E+01    4.00E+01    0.45
    4     rough    Sub_CBR3              Aniso.     3.00E+01   0.45      2.07E+01    1.50E+01    0.45

   Performance Relationships:
   Layer  Location Material              Component  Perform.   Perform.   Shift
   No.             ID                               Constant   Exponent   Factor
    1     bottom   AC14                  ETH         0.004705    5.000      6.0
    2     bottom   AC20                  ETH         0.004342    5.000      6.0
    3     top      subsltCB10            EZZ         0.009150    7.000
    4     top      Sub_CBR3              EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    1      6.00        Asphalt
    2      6.00        Asphalt
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material                Axle       Unitless
   No.               ID                                 Strain
    1       50.00    AC14
                                             SADT(80):  1.530E-05
                                             SAST(53):  6.044E-06

    2      186.02    AC20
                                             SADT(80):  2.012E-04
                                             SAST(53):  1.626E-04

    3      300.00    subsltCB10
                                             SADT(80):  3.437E-04

    4        0.00    Sub_CBR3
                                             SADT(80):  4.690E-04

Results:

   Layer  Thickness  Material                Axle       CDF
   No.               ID                      Group
    1       50.00    AC14                    Total:     1.214E-06
                                             SAST:      1.335E-08
                                             SADT:      1.200E-07
                                             TAST:      7.433E-10
                                             TADT:      8.788E-07
                                             TRDT:      1.991E-07
```

Rural Highway - Sealed - High Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 2.10E+07

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load  Load                  Load                  Load            Radius    Pressure/    Exponent
   No.   ID                    Category              Type                      Ref. stress
    1    ESA750-Full           ESA750-Full           Vertical Force     92.1    0.75         0.00
    2    SAST53                SAST53                Vertical Force    102.4    0.80         0.00

   Load Locations:
   Location   Load              Gear          X           Y       Scaling      Theta
   No.        ID                No.                               Factor
    1         ESA750-Full        1        -165.0        0.0    1.00E+00      0.00
    2         ESA750-Full        1         165.0        0.0    1.00E+00      0.00
    3         ESA750-Full        1        1635.0        0.0    1.00E+00      0.00
    4         ESA750-Full        1        1965.0        0.0    1.00E+00      0.00
    1         SAST53             1           0.0        0.0    1.00E+00      0.00
    2         SAST53             1        2130.0        0.0    1.00E+00      0.00

Details of Layered System:

   ID: Granular Title: Granular Pavement

   Layer  Lower    Material              Isotropy   Modulus    P.Ratio
   No.    i/face   ID                               (or Ev)    (or vvh)  F          Eh         vh
    1     rough    Gran_350              Aniso.     3.50E+02   0.35      2.59E+02   1.75E+02   0.35
    2     rough    Gran_250              Aniso.     2.50E+02   0.35      1.85E+02   1.25E+02   0.35
    3     rough    subsltCB10            Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3              Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material              Component  Perform.   Perform.   Shift
   No.             ID                               Constant   Exponent   Factor
    3     top      subsltCB10            EZZ         0.009150    7.000
    4     top      Sub_CBR3              EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  1:  Austroads (2004) sublayering
   Layer no.  2:  Austroads (2004) sublayering
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  100
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material              Axle       Unitless
   No.               ID                               Strain
    3      300.00    subsltCB10
                                           SADT(80): 8.141E-04
    4        0.00    Sub_CBR3
                                           SADT(80): 7.620E-04

Results:

   Layer  Thickness  Material              Axle       CDF
   No.               ID                    Group
    1      200.00    Gran_350                                n/a

    2      203.65    Gran_250                                n/a

    3      300.00    subsltCB10            Total:     9.900E-01

    4        0.00    Sub_CBR3              Total:     6.230E-01
```

Rural Highway - Sealed - Medium Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 2.00E+07

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                 Load                Load            Radius    Pressure/   Exponent
   No.    ID                   Category            Type                      Ref. stress
    1     ESA750-Full          ESA750-Full         Vertical Force     92.1    0.75         0.00
    2     SAST53               SAST53              Vertical Force    102.4    0.80         0.00

   Load Locations:
   Location    Load               Gear          X          Y      Scaling      Theta
   No.         ID                 No.                             Factor
    1          ESA750-Full         1         -165.0       0.0   1.00E+00      0.00
    2          ESA750-Full         1          165.0       0.0   1.00E+00      0.00
    3          ESA750-Full         1         1635.0       0.0   1.00E+00      0.00
    4          ESA750-Full         1         1965.0       0.0   1.00E+00      0.00
    1          SAST53              1            0.0       0.0   1.00E+00      0.00
    2          SAST53              1         2130.0       0.0   1.00E+00      0.00

Details of Layered System:

   ID: Granular Title: Granular Pavement

   Layer  Lower    Material             Isotropy   Modulus    P.Ratio
   No.    i/face   ID                              (or Ev)    (or vvh)  F          Eh         vh
    1     rough    Gran_350             Aniso.     3.50E+02   0.35      2.59E+02   1.75E+02   0.35
    2     rough    Gran_250             Aniso.     2.50E+02   0.35      1.85E+02   1.25E+02   0.35
    3     rough    subsltCB10           Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3             Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material             Component  Perform.   Perform.   Shift
   No.             ID                              Constant   Exponent   Factor
    3     top      subsltCB10           EZZ         0.009150    7.000
    4     top      Sub_CBR3             EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  1:  Austroads (2004) sublayering
   Layer no.  2:  Austroads (2004) sublayering
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  100
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material              Axle       Unitless
   No.               ID                               Strain
    3      300.00    subsltCB10
                                           SADT(80): 8.209E-04
    4        0.00    Sub_CBR3
                                           SADT(80): 7.676E-04

Results:

   Layer  Thickness  Material              Axle       CDF
   No.               ID                    Group
    1      200.00    Gran_350                                n/a

    2      201.35    Gran_250                                n/a

    3      300.00    subsltCB10            Total:     9.995E-01

    4        0.00    Sub_CBR3              Total:     6.245E-01
```

Rural Highway - Sealed - Low Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 6.30E+06

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                 Load                 Load           Radius    Pressure/    Exponent
   No.    ID                   Category             Type                     Ref. stress
    1     ESA750-Full          ESA750-Full          Vertical Force    92.1     0.75         0.00
    2     SAST53               SAST53               Vertical Force   102.4     0.80         0.00

   Load Locations:
   Location   Load             Gear        X          Y      Scaling     Theta
   No.        ID               No.                           Factor
    1         ESA750-Full       1        -165.0       0.0    1.00E+00     0.00
    2         ESA750-Full       1         165.0       0.0    1.00E+00     0.00
    3         ESA750-Full       1        1635.0       0.0    1.00E+00     0.00
    4         ESA750-Full       1        1965.0       0.0    1.00E+00     0.00
    1         SAST53            1           0.0       0.0    1.00E+00     0.00
    2         SAST53            1        2130.0       0.0    1.00E+00     0.00

Details of Layered System:

   ID: Granular Title: Granular Pavement

   Layer  Lower    Material              Isotropy   Modulus     P.Ratio
   No.    i/face   ID                               (or Ev)     (or vvh)  F          Eh         vh
    1     rough    Gran_350              Aniso.     3.50E+02    0.35      2.59E+02   1.75E+02   0.35
    2     rough    Gran_250              Aniso.     2.50E+02    0.35      1.85E+02   1.25E+02   0.35
    3     rough    subsltCB10            Aniso.     8.00E+01    0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3              Aniso.     3.00E+01    0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material              Component  Perform.    Perform.   Shift
   No.             ID                               Constant    Exponent   Factor
    3     top      subsltCB10            EZZ         0.009150    7.000
    4     top      Sub_CBR3              EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  1:  Austroads (2004) sublayering
   Layer no.  2:  Austroads (2004) sublayering
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  100
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material              Axle      Unitless
   No.               ID                              Strain
    3      300.00    subsltCB10
                                           SADT(80): 9.677E-04
    4        0.00    Sub_CBR3
                                           SADT(80): 8.916E-04

Results:

   Layer  Thickness  Material              Axle      CDF
   No.               ID                    Group
    1      200.00    Gran_350                               n/a

    2      154.78    Gran_250                               n/a

    3      300.00    subsltCB10            Total:    9.963E-01

    4        0.00    Sub_CBR3              Total:    5.612E-01
```

Local Road - Sealed - High Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 1.10E+06

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load   Load                  Load                  Load            Radius    Pressure/    Exponent
   No.    ID                    Category              Type                      Ref. stress
    1     ESA750-Full           ESA750-Full           Vertical Force    92.1     0.75         0.00
    2     SAST53                SAST53                Vertical Force   102.4     0.80         0.00

   Load Locations:
   Location    Load               Gear          X           Y       Scaling      Theta
   No.         ID                 No.                               Factor
    1          ESA750-Full         1         -165.0        0.0    1.00E+00      0.00
    2          ESA750-Full         1          165.0        0.0    1.00E+00      0.00
    3          ESA750-Full         1         1635.0        0.0    1.00E+00      0.00
    4          ESA750-Full         1         1965.0        0.0    1.00E+00      0.00
    1          SAST53              1            0.0        0.0    1.00E+00      0.00
    2          SAST53              1         2130.0        0.0    1.00E+00      0.00

Details of Layered System:

   ID: Granular Title: Granular Pavement

   Layer  Lower    Material                 Isotropy   Modulus    P.Ratio
   No.    i/face   ID                                  (or Ev)    (or vvh)  F          Eh         vh
    1     rough    Gran_350                 Aniso.     3.50E+02   0.35      2.59E+02   1.75E+02   0.35
    2     rough    Gran_250                 Aniso.     2.50E+02   0.35      1.85E+02   1.25E+02   0.35
    3     rough    subsltCB10               Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3                 Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material                 Component  Perform.   Perform.   Shift
   No.             ID                                  Constant   Exponent   Factor
    3     top      subsltCB10               EZZ         0.009150    7.000
    4     top      Sub_CBR3                 EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  1:  Austroads (2004) sublayering
   Layer no.  2:  Austroads (2004) sublayering
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material                 Axle       Unitless
   No.               ID                                  Strain
    3      300.00    subsltCB10
                                              SADT(80): 1.241E-03
    4        0.00    Sub_CBR3
                                              SADT(80): 1.115E-03

Results:

   Layer  Thickness  Material                 Axle       CDF
   No.               ID                       Group
    1      200.00    Gran_350                                n/a

    2       87.18    Gran_250                                n/a

    3      300.00    subsltCB10               Total:     9.942E-01

    4        0.00    Sub_CBR3                 Total:     4.692E-01
```

Local Road - Sealed - Medium Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 5.60E+05

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load  Load              Load              Load          Radius   Pressure/   Exponent
   No.   ID                Category          Type                   Ref. stress
    1    ESA750-Full       ESA750-Full       Vertical Force   92.1    0.75        0.00
    2    SAST53            SAST53            Vertical Force  102.4    0.80        0.00

   Load Locations:
   Location  Load            Gear       X          Y     Scaling    Theta
   No.       ID              No.                         Factor
    1        ESA750-Full      1       -165.0      0.0   1.00E+00    0.00
    2        ESA750-Full      1        165.0      0.0   1.00E+00    0.00
    3        ESA750-Full      1       1635.0      0.0   1.00E+00    0.00
    4        ESA750-Full      1       1965.0      0.0   1.00E+00    0.00
    1        SAST53           1          0.0      0.0   1.00E+00    0.00
    2        SAST53           1       2130.0      0.0   1.00E+00    0.00

Details of Layered System:

   ID: Granular Title: Granular Pavement

   Layer  Lower   Material           Isotropy  Modulus   P.Ratio
   No.    i/face  ID                           (or Ev)   (or vvh)  F         Eh        vh
    1     rough   Gran_350           Aniso.    3.50E+02  0.35      2.59E+02  1.75E+02  0.35
    2     rough   Gran_250           Aniso.    2.50E+02  0.35      1.85E+02  1.25E+02  0.35
    3     rough   subsltCB10         Aniso.    8.00E+01  0.45      5.52E+01  4.00E+01  0.45
    4     rough   Sub_CBR3           Aniso.    3.00E+01  0.45      2.07E+01  1.50E+01  0.45

   Performance Relationships:
   Layer  Location Material          Component Perform.  Perform.  Shift
   No.             ID                          Constant  Exponent  Factor
    3     top      subsltCB10        EZZ        0.009150   7.000
    4     top      Sub_CBR3          EZZ        0.009150   7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  1:  Austroads (2004) sublayering
   Layer no.  2:  Austroads (2004) sublayering
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material          Axle       Unitless
   No.               ID                           Strain
    3      300.00    subsltCB10
                                       SADT(80):  1.367E-03
    4        0.00    Sub_CBR3
                                       SADT(80):  1.186E-03

Results:

   Layer  Thickness  Material          Axle       CDF
   No.               ID                Group
    1      200.00    Gran_350                           n/a

    2       68.77    Gran_250                           n/a

    3      300.00    subsltCB10        Total:     9.949E-01

    4        0.00    Sub_CBR3          Total:     3.688E-01
```

Local Road - Sealed - Low Traffic

```
CIRCLY  - Version 7.0 (21 June 2024)

   Layer no.  3 is INCLUDED in max. CDF calculation
   Layer no.  4 is INCLUDED in max. CDF calculation
Job Title: SydHarBri

Design Method: Austroads 2017

NDT (cumulative heavy vehicle axle groups over design period): 2.80E+05

Traffic Load Distribution:

   ID: NSWPresumeRural
   Name: NSW RMS Aug 2018 - Rural Presumptive (Table 18)
   ESA/HVAG: 1.068

Details of Load Groups:

   Load  Load                  Load                  Load            Radius    Pressure/    Exponent
   No.   ID                    Category              Type                      Ref. stress
    1    ESA750-Full           ESA750-Full           Vertical Force    92.1     0.75         0.00
    2    SAST53                SAST53                Vertical Force   102.4     0.80         0.00

   Load Locations:
   Location   Load                   Gear         X          Y      Scaling     Theta
   No.        ID                     No.                            Factor
    1         ESA750-Full             1        -165.0        0.0    1.00E+00     0.00
    2         ESA750-Full             1         165.0        0.0    1.00E+00     0.00
    3         ESA750-Full             1        1635.0        0.0    1.00E+00     0.00
    4         ESA750-Full             1        1965.0        0.0    1.00E+00     0.00
    1         SAST53                  1           0.0        0.0    1.00E+00     0.00
    2         SAST53                  1        2130.0        0.0    1.00E+00     0.00

Details of Layered System:

   ID: Granular Title: Granular Pavement

   Layer  Lower    Material              Isotropy   Modulus    P.Ratio
   No.    i/face   ID                               (or Ev)    (or vvh)  F          Eh         vh
    1     rough    Gran_350              Aniso.     3.50E+02   0.35      2.59E+02   1.75E+02   0.35
    2     rough    Gran_250              Aniso.     2.50E+02   0.35      1.85E+02   1.25E+02   0.35
    3     rough    subsltCB10            Aniso.     8.00E+01   0.45      5.52E+01   4.00E+01   0.45
    4     rough    Sub_CBR3              Aniso.     3.00E+01   0.45      2.07E+01   1.50E+01   0.45

   Performance Relationships:
   Layer  Location Material              Component  Perform.   Perform.   Shift
   No.             ID                               Constant   Exponent   Factor
    3     top      subsltCB10            EZZ         0.009150    7.000
    4     top      Sub_CBR3              EZZ         0.009150    7.000

   Reliability Factors:
   Project Reliability: Austroads 95%
   Layer  Reliability  Material
    No.   Factor        Type
    3      1.00        Subgrade (Selected Material) (Austroads 2017)
    4      1.00        Subgrade (Austroads 2017)

   Details of Layers to be sublayered:
   Layer no.  1:  Austroads (2004) sublayering
   Layer no.  2:  Austroads (2004) sublayering
   Layer no.  3:  Austroads (2004) sublayering

Automatic layer thickness design:
   Layer number to be designed:  2
   Minimum thickness:  0
   Maximum thickness:  5000

Strains:

   Layer  Thickness  Material                Axle       Unitless
   No.               ID                                 Strain
    3      300.00    subsltCB10
                                             SADT(80): 1.509E-03
    4        0.00    Sub_CBR3
                                             SADT(80): 1.265E-03

Results:

   Layer  Thickness  Material                Axle       CDF
   No.               ID                      Group
    1      200.00    Gran_350                                 n/a

    2       52.96    Gran_250                                 n/a

    3      300.00    subsltCB10              Total:     9.908E-01

    4        0.00    Sub_CBR3                Total:     2.884E-01
```