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A Life Cycle Assessment of Three Department of Defense Airfield Paving Projects

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Abstract

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Following Executive Order (EO) 14008 *Tackling the Climate Crisis at Home and Abroad*, the Department of Defense (DOD) began implementing strategies to reduce greenhouse gas (GHG) emissions to net-zero by 2050. In support of these goals, this thesis uses life cycle assessment (LCA) to analyze one concrete and two asphalt airfield paving projects from three military installations, quantifying associated Global Warming Potential (GWP) contributions from materials, transportation, and construction (life cycle stages A1 through A5). LCA results were calculated using the openLCA software with input data from pavement material Environmental Product Declarations (EPD) and reported construction equipment use information. Material production (A1 – A3) was the most significant contributor to the project’s overall GWP for both pavements due to cement and asphalt binder manufacturing, followed by construction activities (A5) and transportation (A4). This thesis provides a baseline understanding of DOD airfield paving carbon emissions and presents recommendations for future research to substantiate the identified environmental impact observations. Ultimately, the methods outlined in this thesis could enable carbon emission tracking capabilities to achieve federal sustainability objectives.

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, the United States Army, the United States Navy, the United States Department of Defense, or the United States Government.

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1 Introduction

Presently, perhaps one of the most significant threats to our future on this planet is climate change. From rising sea levels to increasing natural disasters, negative environmental impacts from the human-induced climate crisis are being experienced globally at accelerating levels. In 2021, President Biden released two Executive Orders (EO), which were essential to establishing climate considerations as forerunners in U.S. foreign policy and national security planning: EO 14008 *Tackling the Climate Crisis at Home and Abroad* and EO 14057 *Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability*. To ensure climate considerations were central to federal policies, EO 14008 required government agencies to develop strategies and implementation plans for integrating climate considerations into their international operations including assessments of relevant impacts on infrastructure abroad and methods for addressing management in coordination with our allies (White House Council on Environmental Quality Jan 2021). Later that year, in an effort to re-establish the U.S. as a leader in environmental sustainability, EO 14057 established the federal government's long-term strategy to achieve a carbon pollution-free electricity sector by 2035, to reduce greenhouse gas (GHG) emissions to net-zero by 2050, to promote climate-resilient infrastructure, and to advance environmental justice, among several other goals (White House Council on Environmental Quality Dec 2021). These EOs were effectively the first step in propelling a nation-wide effort to set realistic goals and ways forward to address climate change from the federal level. In response to these proclamations, government entities began to release their own plans to counteract climate change, which will be addressed in section 1.1, as they pertain to this thesis.

This background information is the foundation for this research as heavy construction is one of the largest contributors to anthropogenic carbon emissions, primarily due to the material production (A1 – A3) process. Currently, cement, one of the main ingredients in concrete, is produced at a rate of 86 million tons per year in the U.S. and 4.1 billion tons world-wide, contributing approximately 8% of carbon dioxide emissions caused by human-related activities (Woodall 2021). These factors rank industry as the third largest source of anthropogenic carbon emissions, behind fossil fuels and land-use change, which cement production contributes to significantly (Dr. Singla et al. 2022). Comparatively, asphalt production in the U.S. is approximately 420 million tons per year, but the associated carbon emissions are 0.3% of the nation's total greenhouse gas (GHG) emissions and 1.3% of industrial emissions (Shacat et al. 2022). Carbon emissions from asphalt are comparatively smaller than cement because there is less asphalt present in infrastructure – it is used primarily for horizontal construction (pavements) while concrete is used for both horizontal and vertical construction (pavements and buildings). By promoting decarbonization of construction operations, our country can minimize the hazards associated with climate change while pursuing established net-zero goals.

1.1 Department of Defense (DOD) Climate Initiatives

Following the publication of EO 14008, the DOD released their draft *Climate Adaptation Plan* (CAP) in September 2021, which was refined and redistributed in 2024. Originally, CAP defined the climate crisis concerns faced by our armed forces and established a strategic framework to ensure the DOD can operate under changing climate conditions through five priority actions (Department of Defense 2021):

1. Climate-informed decision-making
2. Train and equip a climate-ready force
3. Resilient built and natural infrastructure
4. Supply chain resilience and innovation
5. Enhance adaptation and resilience through collaboration

Three years later, CAP was updated to include descriptions of climate resilience efforts, which have been incorporated across the DOD, and to provide a roadmap for the period of 2024 through 2027, building on previous climate progress reports (Department of Defense 2024). In response to CAP, each branch of service also authored their own approach to address climate change including the Department of the Air Force (DAF) *Climate Campaign Plan* (Department of the Air Force 2023), the Department of the Army (DA) *Climate Strategy* (Department of the Army 2022), and the Department of the Navy (DON) *Climate Action 2030* (Department of the Navy 2022). Between these three plans, the goals and methods for achieving them are similar (see Table 1). Construction is addressed in all of these strategies from a planning and procurement perspective to reduce embodied carbons globally, but they are lacking specific metrics for execution.

Table 1 – DOD Climate Change Goals by Department

GHG Reduction Goals	Department of the		
	Air Force	Army	Navy
Installation Milestones	50% reduction by 2033	50% reduction by 2030	65% reduction by 2030
Net-zero installations	100% reduction by 2046	100% reduction by 2045	100% reduction by 2050
Carbon-free electricity (CFE)	100% achieved by 2030	100% achieved by 2040	100% achieved by 2030
Electric vehicle (EV) fleet	100% acquired by 2035	100% acquired by 2035	100% acquired by 2035
Infrastructure emissions	100% reduction by 2046	50% reduction by 2032	50% reduction by 2032
Solid waste / construction debris	Not addressed	Not addressed	50% reduction by 2025

1.2 Research Question

In order to reach the target metrics established by the federal government, the DOD will need to measure GHG emissions from infrastructure projects to quantify and reduce those contributions. This can be achieved through using Life Cycle Assessment (LCA), as described in section 2.1, in combination with Environmental Product Declarations (EPDs), as described in section 2.2, to account for embodied carbons. This thesis attempts to establish a baseline for carbon emission quantification in DOD airfield construction by asking:

“What are the GHG emissions associated with material production (A1 – A3), transportation to the jobsite (A4), and construction operations (A5) for airfield paving on DOD installations?”

To answer this question, this research examines one concrete and two asphalt projects from three different DOD installations, using LCA to quantify GHG emissions from the demolition and construction of airfield pavements (stages A1 – A5 only). This thesis offers insight into the carbon emissions associated with DOD airfield paving for both pavement types based on materials, transportation, and construction. In addition to GHG emission observations, recommendations for further research are provided.

1.3 Research Overview

This thesis mirrors the methods and modeling processes outlined in the Washington State Department of Transportation’s (WSDOT) Federal Highway Administration (FHWA) Climate Challenge research, conducted at the University of Washington by Lum (2024), to establish asphalt baseline GHG emissions metrics. Additional information on this research is presented in section 1.3.1. Three DOD installations were selected to collect data on airfield pavement repair projects including material production, transportation, demolition, and paving operations. These results are used to inform the associated GHG emissions from airfield construction based on current military paving practices. Two asphalt paving projects, located in Washington State and Florida, and one concrete paving project, located in Washington State, are studied in this research. Information collected from these projects includes construction data specific to each project (such as construction equipment used, engine sizes, fuel consumption, transportation distance, etc.) and EPDs for the respective asphalt or concrete materials. If any of the requested information was unavailable, these exceptions are noted in section 3.3.2, along with the adjustment approach.

1.3.1 WSDOT’s FHWA Climate Challenge Research

On Earth Day 2022, the FHWA launched the Climate Challenge to promote sustainable pavements in the transportation sector by measuring environmental impacts and lowering emissions produced from pavement infrastructure. WSDOT, in partnership with the UW, was awarded funding for their proposal to explore the use of LCA and EPDs as a standard practice for sustainable pavements through three steps: training, data and metrics, and implementation

(Washington State Department of Transportation 2022). Researchers at the UW and the Carbon Leadership Forum (CLF) completed data acquisition and analysis for WSDOT throughout 2024, reporting results and conclusions in Eryn Lum’s thesis (2024).

Lum (2024) states their research question as: “*What are the GHG emissions associated with materials production, transport to the jobsite, and construction operations for asphalt pavement in Washington State?*” To answer this question, their thesis quantifies carbon emissions from material acquisition, the hot mix asphalt’s (HMA) embodied carbon, material transfer from plant to site, and all on-site construction operations completed for four WSDOT paving project case studies from the 2023 paving season (Lum 2024). It also establishes data collection and analysis methods using LCA to measure environmental impacts from pavement construction, which is reflected in section 3.3.3 of this thesis.

2 Background

This section overviews the LCA process, summarizes EPD reporting, and examines how both tools can be used in pavement construction. An introduction to LCA specific terminology and functional units is also provided. Most information (unless specifically stated) in this Chapter comes directly from the following thesis (unpublished as of 6 December 2024):

Lum, E. 2024. *A Life Cycle Assessment of Asphalt Pavement Construction Projects in Washington State*. M.S. thesis, Seattle, WA: University of Washington.

Tables and figures such as the EPD examples in this section are original to this thesis unless otherwise noted. Any information on concrete pavement is additional to the referenced background from Lum (2024).

2.1 LCA Overview

An LCA is an accounting process used to determine and quantify the environmental impacts of a specified product, system of products, or processes. In this thesis, LCAs are the primary accounting processes used to quantify the Global Warming Potential (GWP) in kg of CO₂ of the three paving projects analyzed. Generally, LCAs are split into three different stages: production (i.e. extraction of upstream production, transport to the factory, manufacturing), construction (i.e. transport to site, installation), use (i.e. use, maintenance, repair, replacement, refurbishment), and end-of-life (i.e. deconstruction/demolition, transport to waste processing or disposal, waste processing, disposal of waste). These stages will be outlined in further detail in section 2.1.3 and Figure 2. This thesis uses the production and construction stages to determine the associated GHG emissions of the asphalt and concrete paving projects. Following is the FHWA's description of LCAs:

“LCA is a technique that can be used for analyzing and quantifying the environmental impact of a product, system, or process. LCA provides a comprehensive approach to evaluating the total environmental burden of a product or process by examining all of the inputs and outputs over the life cycle, from raw material production to end of life. This systematic approach identifies where relevant impacts occur and where the most significant improvements can be made while identifying potential trade-offs. The process and rules for conducting an LCA are generally defined by the International Organization for Standardization (ISO) in its 14040 family of standards (ISO 2006).” (Harvey et al. 2016a).

In the next section, a brief history of LCAs in the United States, from conception to present day will be covered.

2.1.1 LCA Origins

The history of LCAs in the United States outlined in this section is primarily referenced from an LCA report put out by the Scientific Applications International Corporation (SAIC) and the *Life Cycle Assessment: Theory and Practice* textbook published in 2018 (Bjørn et al. 2017; (SAIC) 2006). The origins of LCAs date back to the 1960s, when concerns arose over limited access to raw materials and energy sources. These concerns sparked collaboration between universities and industry to create an accounting tool that quantifies energy use, future resource supplies, and use for a project. The first LCA, then known as Resource and Environmental Profile Analysis (REPA) or Ecobalances, was completed in 1969 by The Coca-Cola Company to compare different types of beverage containers and began the standardization process, which influenced current methods. Early REPA studies were created primarily for a company's internal use and focused on establishing a standard procedure that focused on cataloging the energy and resource use, emissions and generation of solid waste, and environmental impacts of the associated product systems.

2.1.2 LCA Standards

In the 1990s, concerns over the inappropriate use of LCAs to make broad marketing claims were prevalent, leading to industry pressure for standardized LCA methods. The International Organization for Standardization (ISO) is a non-governmental worldwide federation that works to prepare international standards for 170 national standards bodies. Their goal is to bring together experts in their respective fields to share knowledge and collaborate in a way that supports innovation and presents solutions to global challenges. The ISO released one of the leading frameworks used to conduct LCAs worldwide, which includes requirements and guidelines that should be adhered to during the analysis of LCAs. In 2006, the ISO released its latest version of standards for LCAs. From the ISO publication 14044, "LCA addresses the environmental aspects and potential environmental impacts (e.g., use of resources and environmental consequences of releases) throughout a production's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave)."

2.1.3 LCA Framework

The general LCA framework consists of the following four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Figure 1 shows the phases of an LCA framework as outlined in the ISO 14040 standard.

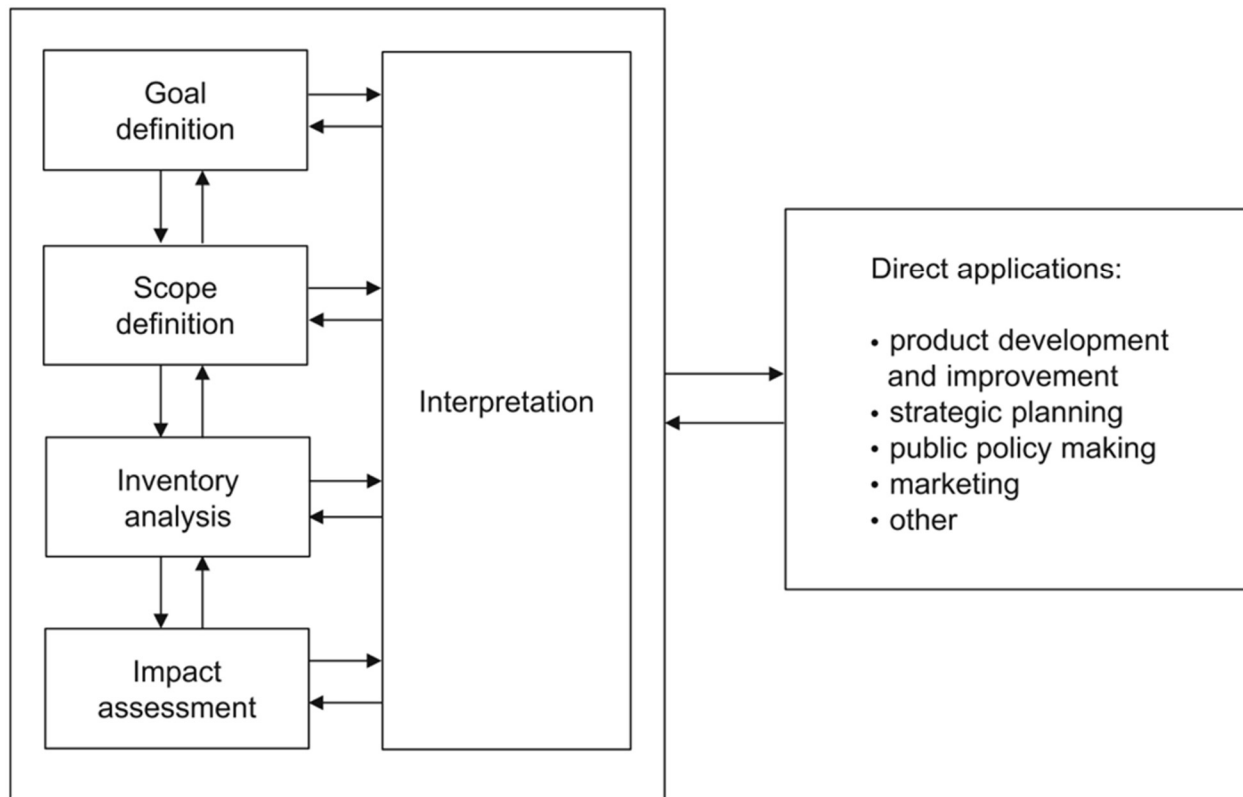


Figure 1 – Framework of an LCA modified from ISO 14040 Standard (Hauschild 2017)

- Goal and Scope Definition should be set by the primary organization performing the LCA.
 - Primary organizations determine the approach to assess impacts, make decisions, and define the system analysis boundary (Harvey et al. 2016b).
 - Functional units are defined as the function and performance of the subject of the product or process being studied (Weiland and Muench 2010).
- Inventory Analysis is where environmental flows for the study are identified and quantified to be used in the model of the process being analyzed.
- Impact Assessment is where tools are used to quantify the environmental and human health impacts of the model process created in the inventory analysis phase (Harvey et al. 2016b).
 - Characterization Factors translate assigned emissions and LCI results into impact indicators. Associated definitions include:
 - TRACI – a tool for the reduction and assessment of chemical and other environmental impacts
 - CML – center for environmental studies at the University of Leiden, the Netherlands
 - Uncertainty of the LCA should also be considered in this phase due to the inherent variability in data, input values, and imprecisions of the model.

- Uncertainty in areas such as a functional unit, the analysis period, system boundary assumptions, the impact assessment, and the sources of data should be considered in the LCA environmental impact calculations.
- Interpretation is connected to every other piece of the framework as results and the data collected are being analyzed in this stage.

The first three phases of the framework typically work in a linear pattern that builds on each other. However, it is important to remember that at each stage, interpretations are made and considered throughout the duration of completing an LCA.

Figure 2 shows a detailed visual representation of standardized life cycle stages defined by ISO 21930 for construction products (Shacat, Richard et al. 2024). When developing the scope of an LCA, identifying which life cycle stages fall within system boundaries is a key step in establishing boundaries for the models. In Figure 2, stages (i.e., production, construction, use, and end-of-life) identify different points in a product’s life cycle and can be used to describe a specific duration of time.

Construction Works Assessment Information														
Construction Works Life Cycle Information Within the System Boundary													Optional supplementary information beyond the system boundary	
A1-A3			A4-A5		B1-B7					C1-C4				D
Production Stage (Cradle-to-Gate)			Construction Stage		Use Stage					End-Of-Life Stage				
A1	A2	A3	A4	A5	B1	B2	B3	B4 ^a	B5	C1	C2	C3	C4	
Extraction upstream production	Transport to factory	Manufacturing	Transport to site	Installation	Use	Maintenance (incl. production, transport, and disposal of necessary materials)	Repair (incl. production, transport, and disposal of necessary materials)	Replacement (incl. production, transport, and disposal of necessary materials)	Refurbishment (incl. production, transport, and disposal of necessary materials)	Deconstruction / Demolition	Transport to waste processing or disposal	Waste processing	Disposal of waste	Potential net benefits from reuse, recycling, and/or energy recovery beyond the system boundary
					B6 Operational Energy Use									
					B7 Operational Water Use									

^a Replacement information module (B4) not applicable at the product level

Figure 2 – Pavement Life Cycle Stages (Shacat Richard et al. 2024)

Additionally, each step within a stage has a corresponding module identifier (i.e., A1, A2, A3, etc.). Module identifiers and labels refer to different parts of a product’s life cycle. For example, if a project considers the entire life cycle of a product, it could be referred to as “cradle to grave”

or “stages A-C.” (Figure 3). This terminology is commonly used when describing which portions of a life cycle an LCA calculates.

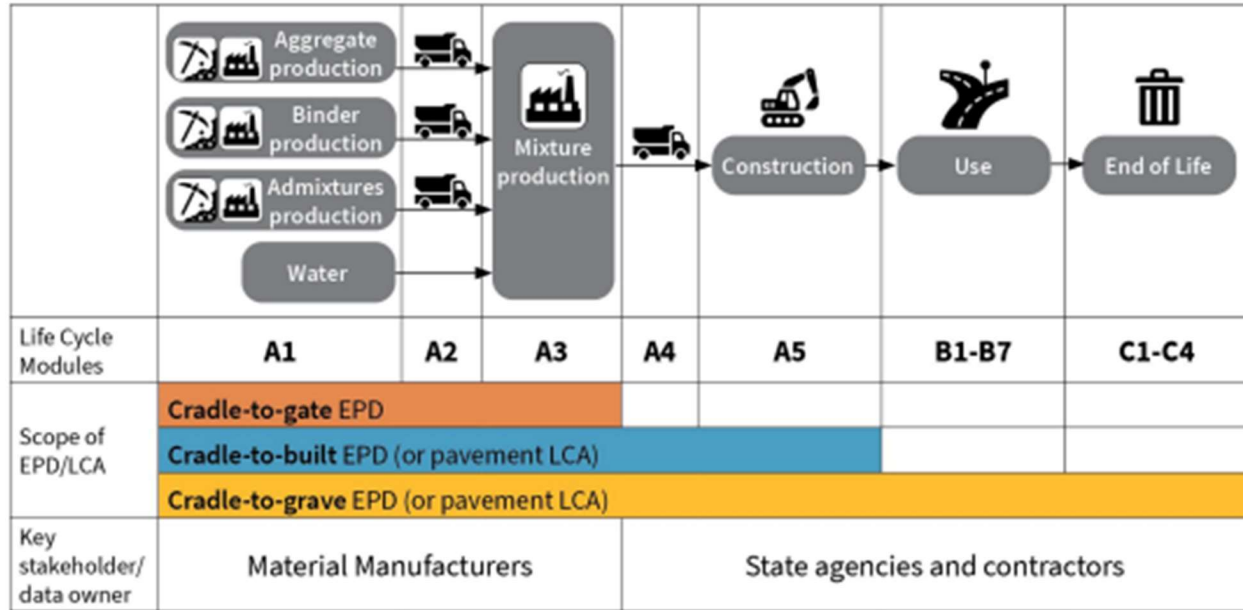


Figure 3 – Life cycle stages included in EPDs or pavement LCA with different scope, based on EN 15804 (Ashtiani et al. 2024)

2.2 EPD Overview

EPDs are reports that quantify and communicate the environmental impacts associated with manufacturing construction materials that manufacturers have verified and developed (Shacat Richard et al. 2024). EPDs can be used to quantify various environmental impacts for a given product (e.g., acidification potential, eutrophication potential, global warming potential, etc.), however, most studies are focused on GWP. The following section will provide a brief overview of EPDs, their origins, and product category rules (PCR) that inform EPDs.

2.2.1 PCR Definition

As defined by the ISO, PCRs are specific rules, requirements, and guidelines for developing an EPD for a product group. PCRs are established by interested parties within the industry group, who then come to a consensus on how their products should be measured. Typically, they specify life cycle stages to include scope, the functional or declared unit, system boundaries, criteria for including or excluding items, data quality requirements, inventory analysis required data, allocation of inputs/outputs, and the impact assessment or parameters used (Frydendal et al. 2017; National Asphalt Pavement Association 2022a). PCRs generally promote consistency between the EPDs generated for similar products to enable transparency and comparability (Frydendal et al. 2017).

2.2.2 EPD Origins

In 1999, EPDs were introduced by ISO 14021 and 14024 as part of environmental labels and declarations. Since then, an updated version, ISO 14025, was released in 2006. The ISO specified three different environmental declarations that can be made. EPDs are a type 3 environmental declaration under ISO 14025. Therefore, EPDs need to be verified by a third party, to report various environmental impacts that reflect a supply chain, and to be calculated using predefined rules known as product category rules (PCR) using LCA methods (Rangelov et al. 2021a).

In recent years, PCRs and EPDs have been developed by various industries (e.g. food, chemical, building industries, etc.) since they are effective ways to communicate product-specific environmental performances from LCAs that are easily comprehensible to audiences, with or without LCA backgrounds (Rangelov et al. 2021a). Two primary EPDs are used: industry-wide and product-specific. Industry-wide EPDs use generalized data for products across many manufacturers and report the average product's environmental impacts. Product-specific EPDs are LCAs done on a singular product from a specific manufacturer and do not consider data that is not explicit to that product. In addition, product-specific EPDs can compare materials used for similar applications. Therefore, as stated in ISO 14025, EPDs can be used to assist purchasers in making an educated decision on the product by considering its environmental performance.

According to the Construction and Engineering Research Lab at the U.S. Army Engineer Research and Development Center (ERDC), EPDs are proposed the most efficient tool to capture environmental impacts of construction materials including GWP. This data is essential to inform decision-making in alignment with the Buy Clean Initiative to prioritize procurement and utilization of lower-embodied carbon infrastructure materials in federally funded construction (Fuhler et al. 2023). Additionally, this research supports initiatives set forth in EO 14057 to transition the U.S. to a net-zero emissions economy and building portfolio by 2050 (White House Council on Environmental Quality, 2022). Continued research and investment into EDPs could aid in developing a standardized approach to compare and select materials. ERDC suggests establishing a primary authority responsible for managing a centralized EPD reporting system which would collect, store, and maintain nation-wide data as well as publishing the necessary standards and guidelines (Fuhler et al. 2023).

2.2.2.1 EPD Examples

In this section, an example of the key pages of an asphalt EPD document, procured from Emerald Eco-Label, are explained with descriptions in Figures 4 – 7, which are original to this thesis (see section 3.2.1). Additionally, an example of the key pages of a concrete EPD document, procured from the Embodied Carbon in Construction Calculator (EC3) tool, are explained with descriptions in Figures 8 – 10, which are also original to this thesis (see section 3.2.2).



An Environmental Product Declaration (EPD) for Asphalt Mixtures

Company Information

Miles Resources is an asphalt mixture producer.

Lakeview, a stationary asphalt plant at
2800 104th St Ct S, Lakewood, WA 98499, USA

Company Information

This EPD was developed for Miles Resources.



Product Description

Product Description

This EPD is for the identified asphalt mixture.

This EPD reports the potential environmental impacts and additional environmental information for an asphalt mixture, which falls under the United Nations Standard Products and Services Code 30111509. Asphalt mixtures are typically incorporated as part of the structure of a roadway, parking lot, driveway, airfield, bike lane, pedestrian path, railroad track bed, or recreational surface.

Mix Name: C19001

Specification Entity: WSDOT

Specification: HMA Class 1/2" - 9-03.8(2) - 2019

Gradation Type: dense

Mix Design Method: superpave

Nominal Maximum Aggregate Size: 0.5 inches

Performance Grade of Asphalt Binder: PG 58-22

Customer [Project/Contract] Number: 19500

This mix producer categorizes this product as a Hot Mix Asphalt (HMA) asphalt mixture. This asphalt mixture was produced within a temperature range of 152 to 157°C (305.0 to 314.0°F). Energy and environmental impacts are based on a plant's average performance over a 12-month period and are not adjusted for mix-specific production temperatures.

PCR Statement of Accordance

This EPD follows ISO 14025:2006 and ISO 21930:2017.



This declaration is an EPD in accordance with ISO 14025:2006¹ and ISO 21930:2017². The PCR is *Product Category Rules for Asphalt Mixtures*^{3,4}. This EPD transparently describes the potential environmental impacts associated with the identified life cycle stages of the described product.

Declaration Number: 98.234.5796 v4

Software Version: 2.2.0

Period of Validity

Date of Issue: Aug. 23, 2024

Period of Validity: March 31, 2027

EPDs are typically valid for 5 years.

This EPD is valid for asphalt mixtures produced at the location indicated on this page. Data used to inform this EPD reflect plant operations from a 12-month period beginning on Jan. 1, 2021.

This EPD can be found at <https://asphaltpd.org/epd/d/qmUY9k/>

LCA performed by: Ben Ciavola, PhD

Figure 4 – Asphalt EPD Interpretation (Project and Mix Design Information, Relevant Dates)

An Environmental Product Declaration for Asphalt Mixtures

Product Ingredients

Product Ingredients

A list of materials included in production of the asphalt with the associated weight percentage contributing to the overall product.

The product ingredients as identified in the mix design are provided in the table below.

TABLE 1. PRODUCT INGREDIENTS

COMPONENT	MATERIAL	WEIGHT %
<i>Aggregate</i>	<i>Natural Stone</i>	28
<i>Aggregate</i>	<i>Natural Stone</i>	59
<i>Aggregate</i>	<i>Natural Stone</i>	8
<i>Binder</i>	<i>Unmodified</i>	6

*Indicates that this material is a data gap. Upstream data associated with extraction and processing is not accounted for in this EPD.

Regulated Hazardous Substances

Regulated hazardous substances, if applicable, are listed on the safety data sheet (SDS) associated with this asphalt mixture. The chemical names and composition of the mix from the SDS are provided here for transparency.

TABLE 2. REGULATED HAZARDOUS SUBSTANCES

CHEMICAL NAME	CAS NO.	WEIGHT %

No SDS declared, mix may include unknown regulated hazardous substances.

Figure 5 – Asphalt EPD Interpretation (Product Ingredients)

An Environmental Product Declaration for Asphalt Mixtures

Environmental Impact

TABLE 3. ENVIRONMENTAL IMPACT SUMMARY TABLE → The asphalt's environmental impact per functional unit.

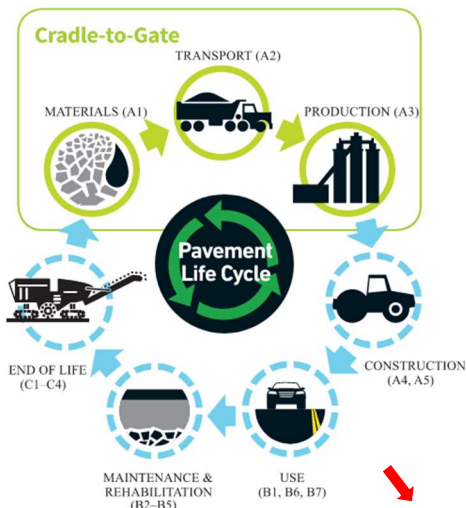
IMPACT CATEGORY	POTENTIAL IMPACT PER METRIC TONNE ASPHALT MIXTURE (PER TON ASPHALT MIXTURE)
Global warming potential (GWP-100)	62.90 (57.06) kg CO ₂ Equiv.
Ozone depletion potential (ODP)	5.01e-08 (4.55e-08) kg CFC-11 Equiv.
Eutrophication potential (EP)	1.33e-02 (1.21e-02) kg N Equiv.
Acidification potential (AP)	1.61e-01 (1.46e-01) kg SO ₂ Equiv.
Photochemical ozone creation potential (POCP)	3.91 (3.55) kg O ₃ Equiv.

Methodological Framework Declared Unit

DECLARED UNIT

This EPD is describing the emissions associated with 1 metric tonne (or 1 short ton) of asphalt mixture. Used for normalization.

The declared unit is 1 metric tonne (1 short ton) of an asphalt mixture (UNSPSC Code 30111509: Asphalt Based Concrete), which is defined as “a plant-produced composite material of aggregates, asphalt binder, and other materials.”³



LIFE CYCLE STAGES AND INFORMATION MODULES

This is a cradle to gate EPD. It covers the raw material supply, transport, and manufacturing life cycle stages (modules A1-A3). It does not include construction (placement and compaction), use, maintenance, rehabilitation, or the end-of-life life cycle stages (modules A4-5, B1-7, and C1-4).³

Materials (A1): This stage includes raw material extraction and manufacturing (e.g., quarry operations for aggregates, petroleum extraction and refinery operations for asphalt binder production, etc.) based on the relative proportion of ingredients in the mix design.

Transport (A2): This stage includes transport of raw materials to the asphalt plant based on actual transportation distances and modes for ingredients in the mix design.

Production (A3): This stage comprises plant operations involved in the production of asphalt mixtures, including generation of electricity and heat used during asphalt mix production (e.g., extraction, refining, and transport of fuels). Data for this stage is plant specific.

LCA Framework

A description of each life cycle stage that is analyzed in this EPD.

LIFE CYCLE INVENTORY

This EPD was created using plant-specific data for asphalt mix production of the production stage (A1-A3). Potential variations due to asphalt mixture design, supplier locations, manufacturing processes, efficiencies, and energy consumption are accounted for in this EPD. All upstream data sources are prescribed in the Product Category Rules (PCR) and are publicly available and freely accessible to enhance transparency and comparability. Use of the prescribed data sources improves comparability among the EPDs developed by limiting variability due to differences in the upstream data within the system boundaries.³

ALLOCATION PROCEDURES

Impacts from upstream production and transportation of raw materials are subdivided based on the relative material quantities (percentages) in the mix design. For conventional asphalt plants that produce both hot-mix asphalt (HMA) and warm-mix asphalt (WMA) mixtures, allocation of energy and other resources for asphalt mix production is on a mass basis. Mix-specific production temperatures are not used to separately allocate energy inputs to HMA and WMA mixtures. For conventional asphalt plants that also produce asphalt mixtures at ambient temperatures using cold central plant recycling (CCPR) technologies, HMA and WMA mixtures are subdivided from CCPR mixtures by segregating burner fuel consumption from CCPR mixtures.

Figure 6 – Asphalt EPD Interpretation (Environmental Impact, Declared Unit, LCA Framework)

An Environmental Product Declaration for Asphalt Mixtures

Project Summary

TABLE 4. LIFE CYCLE IMPACT INDICATORS → Environmental impact based on contribution per life cycle stage.

ACRONYM	INDICATOR	UNIT	QUANTITY PER METRIC TONNE ASPHALT MIXTURE (PER SHORT TON ASPHALT MIXTURE)			
			MATERIALS (A1)	TRANSPORT (A2)	PRODUCTION (A3)	TOTAL (A1-A3)
GWP-100	Global warming potential, incl. biogenic CO ₂	kg CO ₂ Equiv.	37.84 (34.33)	3.66 (3.32)	21.40 (19.41)	62.90 (57.06)
ODP	Ozone depletion potential	kg CFC-11 Equiv.	1.78e-08 (1.62e-08)	2.21e-08 (2.01e-08)	1.02e-08 (9.26e-09)	5.01e-08 (4.55e-08)
EP	Eutrophication potential	kg N Equiv.	1.01e-02 (9.13e-03)	1.09e-03 (9.90e-04)	2.14e-03 (1.94e-03)	1.33e-02 (1.21e-02)
AP	Acidification potential	kg SO ₂ Equiv.	1.08e-01 (9.76e-02)	1.87e-02 (1.69e-02)	3.50e-02 (3.17e-02)	1.61e-01 (1.46e-01)
POCP	Photochemical ozone creation potential	kg O ₃ Equiv.	2.21 (2.00)	0.60 (0.54)	1.10 (1.00)	3.91 (3.55)

Notes:

GWP-100 – Global warming potential. The warming (relative to CO₂) that chemicals contribute to the atmospheric greenhouse effect by trapping the earth's heat. The impact scores for GWP-100 are based on a 100-year time horizon. As prescribed in Section 7.2.7 of the PCR for Asphalt Mixtures, this EPD does not assign a negative flow of CO₂ to GWP-100 when biogenic CO₂ enters the product system through biofuels and bio-based materials unless this information is provided in upstream datasets, in which case the amounts are indicated in Table 7. However, a positive flow of CO₂ is assigned to GWP-100 when biogenic CO₂ is emitted through the combustion of biofuels. This is a conservative approach that may over-estimate GWP-100. Bio-based materials tend to be used in small quantities in asphalt mixtures (<1% by weight of the mix) and biofuels are rarely used for asphalt mixture production, so the impacts are low in most cases. Biogenic carbon uptake for certain biofuels is provided as additional environmental information in Table 9. The location-based accounting method, is used for calculating upstream impacts of purchased electricity. Potential GHG emission reductions associated with the market-based accounting method, if applicable, are provided as Additional Environmental Information in Table 8.

ODP – Ozone depletion potential. The potential damage that chemicals such as chlorofluorocarbons (CFCs) cause to the earth's stratospheric ozone layer, which filters out harmful ultraviolet radiation from the sun. Impact scores for ODP are based on the quantity of ozone-depleting chemicals released to air, normalized to an equivalent mass of CFC-11.

EP – Eutrophication potential. The potential nutrient enrichment to water bodies caused by chemicals that are released to the water or air and subsequently deposited. Impact scores for EP are based on the quantity of nutrients released, normalized to an equivalent mass of N.

AP – Acidification potential. The potential formation of acid rain caused by releases of chemicals to the air. Impact scores for AP are based on the number of hydrogen ions that can be theoretically formed per mass unit of the chemical being releases as compared to SO₂.

POCP – Photochemical ozone creation potential. The release of hydrocarbons and nitrogen oxides that react with sunlight to produce photochemical oxidants, which can cause or aggravate health problems, plant toxicity, and deterioration of certain materials. Impact scores for POCP are based on the quantity of chemicals with POCP equivalency factors released to the air, normalized to an equivalent mass of O₃.

STONEWAY CONCRETE

ENVIRONMENTAL PRODUCT DECLARATION

Mix 456283 • Seattle Plant

Company Information

This EPD was developed for Stoneway Concrete.



This Environmental Product Declaration (EPD) reports the impacts for 1 m³ of ready mixed concrete mix, for use in business-to-business (B2B) communication meeting the following specifications:

- ASTM C94: Ready-Mixed Concrete
- UNSPSC Code 30111505: Ready Mix Concrete
- CSA A23.1/A23.2: Concrete Materials and Methods of Concrete Construction
- CSI Division 03-30-00: Cast-in-Place Concrete

COMPANY

Stoneway Concrete

9216 8th Ave S
Seattle, WA 98108

PLANT

Seattle Plant

3803 E. Marginal Way South
Seattle, WA 98134

EPD PROGRAM OPERATOR

ASTM International

100 Barr Harbor Drive
West Conshohocken, PA 19428



DATE OF ISSUE

01/03/2024 (valid for 5 years until 01/03/2029)

PCR Statement of Accordance

This EPD follows ISO 21930:2017 and PCR for Concrete from NSF International.

Period of Validity

EPDs are typically valid for 5 years.

Product Ingredients

A list of materials included in production of the concrete.

ISO 21930:2017 Sustainability in Building Construction — Environmental Declaration of Building Products: serves as the core PCR
PCR for Concrete, NSF International, December 2022 v2.2 serves as the sub-category PCR

Sub-category PCR review was conducted by Thomas P. Gloria • Industrial Ecology Consultants

Independent verification of the declaration, according to ISO 14025:2006: internal external

Third party verifier Thomas P. Gloria (t.gloria@industrial-ecology.com) • Industrial Ecology Consultants



For additional explanatory material

Manufacture Representative: Greg McKinnon (GMckinnon@stonewayconcrete.com)
Software Tool: CarbonCLARITY Suite, EPD Generator • Verification
LCA & EPD Developer: Climate Earth (support@climateearth.com)

ENVIRONMENTAL IMPACTS

Declared Product: **Product Description**

Mix 456283 • Seattle Plant **This EPD is for the identified concrete mixture.**
Description: FAA P-501 Paving
Compressive strength: 650 PSI at 28 days

Declared Unit: 1 m³ of concrete (1 cyd)

Global Warming Potential (kg CO ₂ -eq)	251 (192)
Ozone Depletion Potential (kg CFC-11-eq)	1.49E-5 (1.14E-5)
Acidification Potential (kg SO ₂ -eq)	0.91 (0.69)
Eutrophication Potential (kg N-eq)	0.23 (0.17)
Photochemical Ozone Creation Potential (kg O ₃ -eq)	22.0 (16.8)
Abiotic Depletion, non-fossil (kg Sb-eq)	4.95 (3.78)
Abiotic Depletion, fossil (MJ)	1,465 (1,120)
Total Waste Disposed (kg)	0.43 (0.33)
Consumption of Freshwater (m ³)	2.86 (2.19)

Product Components: natural aggregate (ASTM C33), Portland cement (ASTM C150), slag cement (ASTM C989), admixture (ASTM C494), fly ash (ASTM C618), batch water (ASTM C1602), admixture (ASTM C260)

Additional detail and impacts are reported on page three of this EPD

Figure 8 – Concrete EPD Interpretation (Project and Mix Design Information, Relevant Dates, Declared Unit)

STONEWAY CONCRETE

ENVIRONMENTAL PRODUCT DECLARATION

Mix 456283 • Seattle Plant



LIFE CYCLE ASSESSMENT → **LCA Framework**
 A description of each life cycle stage that is analyzed in this EPD.

SYSTEM BOUNDARY

This EPD is a cradle-to-gate EPD covering the product stages (A1-A3) only

PRODUCTION Stage (Mandatory)			CONSTRUCTION Stage		USE Stage					END-OF-LIFE Stage			
Extraction and upstream production	Transport to factory	Manufacturing	Transport to site	Installation	Use	Maintenance	Repair	Replacement	Relubrication	De-construction/ Demolition	Transport to waste processing or disposal	Waste processing	Disposal of waste
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4

CUT-OFF

Items excluded from system boundary include: production, manufacture, and construction of manufacturing capital goods and infrastructure; production and manufacture of production equipment, delivery vehicles, and laboratory equipment; personnel-related activities (travel, furniture, and office supplies); and energy and water use related to company management and sales activities that may be located either within the factory site or at another location.

A one percent cut-off is considered for renewable and non-renewable primary energy consumption and the total mass of inputs within a unit process. The sum of the total neglected flows does not exceed 5% of all energy consumption and mass of inputs.

ALLOCATION PROCEDURE

Allocation follows the requirements and guidance of ISO 14044.

The product category rules for this EPD recognize fly ash, silica fume and slag as recovered materials and thus the environmental impacts allocated to these materials are limited to the treatment and transportation required to use as a concrete material input.

LIFE CYCLE INVENTORY (LCI)

This EPD was calculated using manufacturer specific cement data that represents 100% of the total cement used in this mix.

PRIMARY SOURCES OF LCI DATA

- **Admixture:** Supplier specific primary data, 2020
- **Aggregate (crushed):** US-EI (2016): "Gravel, crushed, at mine/US", 2001
- **Aggregate (natural):** US-EI (2016): "Gravel, round, at mine/US", 2001
- **Cleaning Chemicals:** Ecoinvent 3.4: 50% Citric acid and 50% Phosphoric acid, industrial grade, without water, in 70% solution state, market for/GLO, 2017
- **Diesel:** USLCI: "Diesel, combusted in industrial equipment/NREL/US", 2007
- **Electricity (WECC):** Ecoinvent 3.4: "Electricity, medium voltage, market for, cut-off", 2015
- **Fly ash:** byproduct of coal combustion; no upstream manufacturing impacts
- **Municipal Water:** US-EI (2016): "Tap water, at user/US", 2000
- **Municipal Water:** US-EI (2020): "Tap water, at user/US", 2000
- **Natural gas:** USLCI: "Natural gas, combusted in industrial boiler/NREL/US", 2007
- **Non-Hazardous Solid Waste:** US-EI (2016): Disposal, municipal solid waste, 2008
- **Oils, Lubricants and Greases:** Ecoinvent 3.5: Lubricating oil, GLO, market for, cut-off, 2011
- **Portland Cement:** Supplier specific primary data, 2021
- **Rail transport:** USLCI: "Transport, train, diesel powered NREL/US", 2007
- **Ship transport:** USLCI: "Transport, ocean freighter, average fuel mix NREL/US", 2007
- **Slag cement:** Slag Cement Association, industry average EPD, 2014
- **Truck transport:** USLCI: "Transport, combination truck, long-haul, diesel powered/tkm/RNA", 2010
- **Truck transport:** USLCI: "Transport, combination truck, short-haul, diesel powered/tkm/RNA", 2010

Figure 9 – Concrete EPD Interpretation (LCA Framework)

STONEWAY CONCRETE

ENVIRONMENTAL PRODUCT DECLARATION
Mix 456283 • Seattle Plant

Project Summary

Environmental impact based on contribution per life cycle stage.



DECLARATION OF ENVIRONMENTAL INDICATORS DERIVED FROM LCA

Impact Assessment	Unit	A1	A2	A3	Total
Global warming potential	kg CO ₂ -eq	245	2.54	3.04	251
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC-11-eq	1.48E-5	9.70E-11	1.39E-7	1.49E-5
Eutrophication potential	kg N-eq	0.21	2.75E-3	0.01	0.23
Acidification potential of soil and water sources (AP)	kg SO ₂ -eq	0.84	0.05	0.02	0.91
Formation potential of tropospheric ozone (FOCP)	kg O ₃ -eq	20.4	1.47	0.12	22.0
Resource Use					
Abiotic depletion potential for non-fossil mineral resources (ADPelements)*	kg Sb-eq	4.95	-	1.08E-7	4.95
Abiotic depletion potential for fossil resources (ADPfossil)	MJ	1,390	32.7	42.0	1,465
Renewable primary energy resources as energy (fuel), (RPRE)*	MJ	77.3	0.00E+0	5.00	82.3
Renewable primary resources as material, (RPRM)*	MJ	0.00E+0	-	0.00E+0	0.00E+0
Non-renewable primary resources as energy (fuel), (NRPRE)*	MJ	1,709	32.7	46.0	1,787
Non-renewable primary resources as material (NRPRM)*	MJ	0.00E+0	-	0.00E+0	0.00E+0
Consumption of fresh water	m ³	2.82	-	0.04	2.86
Secondary Material, Fuel and Recovered Energy					
Secondary Materials, (SM)*	kg	197	-	0.00E+0	197
Renewable secondary fuels, (RSF)*	MJ	0.00E+0	-	0.00E+0	0.00E+0
Non-renewable secondary fuels (NRSF)*	MJ	0.00E+0	-	0.00E+0	0.00E+0
Recovered energy, (RE)*	MJ	0.00E+0	-	0.00E+0	0.00E+0
Waste & Output Flows					
Hazardous waste disposed*	kg	0.01	-	0.00E+0	0.01
Non-hazardous waste disposed*	kg	0.41	-	3.19E-3	0.42
High-level radioactive waste*	m ³	1.96E-8	-	2.09E-9	2.17E-8
Intermediate and low-level radioactive waste*	m ³	9.45E-8	-	2.13E-8	1.16E-7
Components for reuse*	kg	0.00E+0	-	0.00E+0	0.00E+0
Materials for recycling*	kg	0.00E+0	-	1.24E-3	1.24E-3
Materials for energy recovery*	kg	0.00E+0	-	0.00E+0	0.00E+0
Recovered energy exported from the product system*	MJ	0.00E+0	-	0.00E+0	0.00E+0
Additional Inventory Parameters for Transparency					
Emissions from calcination and uptake from carbonation*	kg CO ₂ -eq	132	-	0.00E+0	132

* Emerging LCA impact categories and inventory items are still under development and can have high levels of uncertainty that preclude international acceptance pending further development. Use caution when interpreting data in these categories.

- Not all LCA datasets for upstream materials include these impact categories and thus results may be incomplete. Use caution when interpreting data in these categories.

This product contains no materials that are considered hazardous as defined by the PCR.

Comparability of EPDs is limited to those applying a functional unit. Comparisons based on A1-A3 data shall be made only if the same secondary data sets and all subsequent life cycle states are equivalent for both EPDs.

REFERENCES

ISO 21930:2017 Sustainability in Building Construction — Environmental Declaration of Building Products

ISO 14044:2006/Amd 1:2017/Amd 2:2020 Environmental Management — Life Cycle Assessment — Requirements and Guidelines

NSF International, December 2022 v2.2 — PCR for Concrete

Figure 10 – Concrete EPD Interpretation (Project Summary)

2.3 LCAs in Pavement Construction

LCAs in pavement construction have varied over the years between studies, covering numerous variations of the life cycle stages. This thesis analyzes the material production through construction and installation stages A1 – A5. LCA usage in the pavement field is still growing, with only a few agencies applying them consistently. Within the pavement agencies that use LCAs, the most common uses are aiding material or pavement structural design selection, evaluation of the potential impact of policy or specification, LCA tool development, scenario evaluation for network-level decisions or strategies for preservation, maintenance, and rehabilitation, and material EPD development for pavement application (Harvey et al. 2016a). Many previous studies have aimed to compare asphalt and concrete pavements which is not appropriate due to the utilization of differing PCRs between the two industries. Although this thesis does evaluate two asphalt projects and one concrete project, it will not attempt to compare these two materials because the measured parameters are not equivalent between asphalt and concrete pavements.

2.3.1 Overview of LCAs in Pavement Construction

One of the first noted LCAs in pavement construction was in 1996 when Häkkinen and Mäkelä completed one of the first studies that evaluated asphalt and concrete pavements in Finland (Häkkinen and Mäkelä 1996). In the years that followed, studies looked at different metrics such as energy (a summation method for life-cycle energy consumption accounting for quality and source of error), exergy (a derivative of energy that describes the distance a product is from thermos equilibrium), impact of industrial by-products (e.g. coal ash, crushed concrete waste, blast furnace slag, etc.), hot and cold production techniques, and material required for urban collector road versus highway routes, to name a few (Santero et al. 2010a). From early LCA analysis between asphalt and concrete pavements, numerous studies in pavement literature had conflicting conclusions and recommendations on which pavement was better with a lower environmental impact (Ashtiani 2022; Barbieri et al. 2021a; Häkkinen and Mäkelä 1996; Horvath and Hendrickson 1998; Stripple 2001; Zapata and Gambatese 2005). However, studies that looked specifically at the use of recycled materials in place of virgin materials found that using these materials had reduced emissions and thus reduced the environmental impact (Santero et al. 2010b).

Inconsistencies and issues such as differing functional units, system boundaries, industry data availability, life cycle inventory (LCI), impact results, and the overall utility of LCAs make it difficult to use LCA results for comparison across industries or geographical areas (Barbieri et al. 2021b; Hoxha et al. 2021; Santero et al. 2010b). Another conclusion drawn from literature on pavement construction was that the acquisition of data and methods used were not always transparent, making these studies hard to replicate (Hoxha et al. 2021) Lastly, it was notable that many LCA studies did not explicitly mention the use of the data collected and analyzed from the

projects to complete an LCA. Since the 1990s, when LCAs were introduced to the pavement construction industries, more funding has been provided in this specific study area, such as the FHWA Climate Challenge grant funding the research this thesis is based on, to quantify the carbon emissions associated with the design, construction, and maintenance of pavements.

2.4 EPD and PCR Development for Pavements

Typically, horizontal construction projects use product-specific EPDs for hot mix asphalt (HMA) and Portland cement concrete (PCC) mix designs. Emerald Eco-Label calculates the asphalt pavement industry product-specific EPDs, which cover stages A1 – A3 or cradle-to-gate (Senseney 2023). “It is common for EPDs for materials to only include the cradle-to-gate stages, since the environmental impacts in subsequent life cycle stages depend on factors outside the control of the manufacturer” (Shacat Richard et al. 2024). The two asphalt EPDs used in this study were created and are available on [Emerald Eco-Label](#). Additionally, the concrete EPD used in development of this thesis is available on [EC3](#).

To address standardization of asphalt products, the National Asphalt Pavement Association (NAPA) established a PCR committee, which comprises stakeholders in industry, academia, and governmental agencies (National Asphalt Pavement Association 2022a). Additionally, NAPA develops and maintains the PCRs for asphalt mixtures produced in North America and is a subcategory under ISO 21930 (National Asphalt Pavement Association 2022b; Shacat Richard et al. 2024). PCRs created by this stakeholder group are used as a standard to inform the EPDs developed by the asphalt industry to keep EPDs consistent.

Similarly, NSF International, supported by the Portland Cement Association (PCA), initiated a PCR committee to collaborate on the development of a PCR, which provides common rules specific to cement for application in building and civil engineer works under ISO 21930 (NSF International 2021). Performance characteristics of cement are typically reported based on ASTM International, American Association of State Highway and Transportation Officials (AASHTO), or Canadian Standards Association (CSA) specifications. Each verified and valid concrete EPD lists which specifications are met within the document such as ASTM C94: Ready-Mixed Concrete to allow for comparison to other concrete EPDs also meeting those standards with uniform declared and functional units.

2.5 EPDs in Pavement Construction

In 2022, NAPA released the second version of the Product Category Rules for Asphalt Mixtures. This report establishes principles, specifications, and requirements as a PCR for asphalt mixtures sold in the U.S. that produce facility-specific and industry-averaged EPDs (National Asphalt Pavement Association 2022c). Asphalt EPDs are strictly cradle-to-gate, meaning they are within Modules A1: Raw Material Supply, A2: Transport, and A3: Manufacturing (Figure 2) (National Asphalt Pavement Association 2022c; Rangelov et al. 2021b). A1 considers the material

acquisition of aggregate, asphalt binder, and other materials within the mixture. A2 considers transporting materials such as RAP from the storage facility to the plant. A3 considers the production of the asphalt mixture at the plant following the material acquisition and transport until the mixture is transferred to a truck that will deliver it to the customer.

Regarding concrete mix designs, NSF International released version 3.2 of the PCR for Portland, Blended, Masonry, Mortar, and Plastic (Stucco) Cements in September 2021. The purpose of this report is identical to that of the PCR for asphalt mixtures, but for cementitious materials. Concrete EPDs are also prepared from cradle-to-gate life cycle results (A1 – A3), which are inclusive of the definitions outlined within the previous paragraph. It should be noted that transport in the production stage of these EPDs include empty backhauls or bulk carriers that return empty (NSF International 2021).

EPDs have been gradually entering the transportation and roadway construction industry. Some regions of the United States have been introducing EPD legislation at the state level. In Oregon and California, EPDs have been required for select building materials and concrete for city construction projects (Rangelov et al. 2021a). These states intend to use the collected EPDs to create an environmental impact benchmark that outlines limitations for specific project materials for buildings. These principles were not initially intended to be applied to roadway construction. However, in 2023, Colorado passed “The Buy Clean Colorado Act,” which requires contractors to submit EPDs for asphalt and asphalt mixtures, cement and concrete mixtures, and steel that is installed on all Colorado Department of Transportation (CDOT) projects (Senseney 2023). Ultimately, the goal of this bill is to encourage construction product manufacturers to reduce their overall emissions and specify greener construction materials. Related to CDOT’s benchmarking goal, NAPA recently published a benchmarking study related to EPD results of asphalt pavements that could be used to inform these decisions (Miller et al. 2024).

2.6 Pavement LCA Calculation Software

In this thesis, openLCA was used as the primary LCA calculation tool. Other software and tools available to calculate LCAs include the FHWA’s LCA Pave tool, Athena, and SimaPro. The LCA Pave tool is a Microsoft® Excel® spreadsheet created by the FHWA to assess the impact of materials, construction processes, and related transportation activities for various pavement design projects (i.e., new construction, reconstruction, rehabilitation, and maintenance and preservation) (Meijer et al. 2021). The Athena Pavement LCA was created with the support of the Cement Association of Canada and Athena Institute members. Users can develop environmental LCAs for their specific roadway design by selecting from the over 150 existing roadway designs in the database or by creating a custom roadway design (Athena Pavement LCA 2002). SimaPro was created in 1990 as an LCA accounting tool that is easy to understand and use when assessing the measurability of sustainability data (PRé Sustainability 1990). Like openLCA, SimaPro can be used for more applications than just roadway pavement.

2.7 OpenLCA Overview

OpenLCA is a tool used for LCA calculations. Within openLCA, input variables such as mass, distance, volume, etc. influence the overall environmental impact of the product or material analyzed. Calculations conducted in openLCA use specified datasets such as the US Life Cycle Inventory (USLCI), ecoinvent, and the FHWA Repository to provide upstream data to inform environmental impact calculations. OpenLCA published accessible [tutorial videos](#) on YouTube, to explain the basics of the program (openLCA 2021). Table 2 outlines common LCA terminology used throughout this thesis.

Table 2 – Common LCA Terminology (Lum 2024)

Term	Description
Background Data	Where all the flow properties (i.e. mass, volume, length, etc.), unit groups (i.e. currency, gram, etc.), actors (provided data & can edit), sources of data (literature data was obtained from), and locations (countries' processes have been made) will be found.
Indicators and Parameters	Where the impact assessment methods, social indicators, global parameters, and data quality systems are located.
Global Parameter	Parameters that stay consistent and can be used throughout calculations.
Data Quality Systems	Used to assess the quality of data; like an uncertainty analysis.
Flow	Basis of processes. Can be used in pre-created or new processes.
Process	Production or modification of products and materials. Based on an initial flow (pre-made or new) that holds background information on the specified product or material.
Input Flow	Quantified product, material, or energy flow that enters a unit process.
Output Flow	Quantified product, material, or energy flow that leaves a unit process.
Provider	This is the correlating process linked to the flow in the input/outputs tab or a process.
Product System	A collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.
Unit Process	The smallest element is considered in the life cycle inventory analysis for which input and output data are quantified.
Project	Allows comparison between product systems and can change specific parameters in the comparison.
Functional Unit	A functional description of the product or system that is being studied. Defines the quantity of the material/system and the key performance aspects that define its function over its lifetime (Ashtiani et al. 2024)
Declared Unit	Can be used in place of a functional unit if the function requirement and application are uncertain or undefined (Ashtiani et al. 2024)

2.8 Functional Units

In pavement construction, functional units are typically a unit of length (lane-miles or lane-kilometers), area (square foot or square meter), or volume (cubic meter or cubic yard) (Zokaei Ashtiani 2022). Ultimately, the functional units are used to normalize the data results. This standardization helps to make relative comparisons between similar projects with the same function unit easier. Asphalt EPD results are reported in per metric ton or per short ton of asphalt for specific mix designs while concrete EPDs are reported in per cubic meter or per cubic yard of concrete. To promote compatibility between projects and discourage comparisons of dissimilar materials, two different functional units were selected for this thesis. All LCA results presented will be reported as per ton of asphalt pavement or per cubic yard of concrete pavement, respective to each project.

3 Methods

This section discusses the decision-making process and methods used in this thesis, which closely follows the research procedures outlined in Lum (2024). Following a project selection narrative, each project is described through metadata in the data collection section. Data gaps, organization, alternatives, and rules of thumb involved in this analysis process will also be identified. Lastly, the modeling process, using openLCA, is summarized and a data quality analysis is performed for each project.

3.1 Project Selection

During the development of this thesis, the objective was to study both concrete and asphalt paving contracts at various DOD installations across the armed services. These projects would establish a broad baseline for federal airfield construction nationwide. Since this was not a sponsored research study, no compensation was provided to government entities or contractors for providing the requested data. As such, it was not possible to require contractors to develop an EPD for each project because there is an associated cost if the contractor hadn't previously generated one. Projects were selected based on opportunity and availability from three different military base locations in Washington State and Florida as shown in Figure 11 and Figure 12.

Since the primary researcher had contacts from prior work experience at the three selected installations, the transportation system managers at each base were contacted to provide a brief overview of the research and to inquire about suitable projects for data collection. This request led to connection with either the individual government project managers or the civilian general contractor. The selected project names and locations are as follows:

- Runway Center Pavement Repair – McChord Airfield
 - Joint Base Lewis-McChord, Tacoma, WA
 - This project was selected to represent a contracted asphalt paving repair project.
- FY22 Pavement Maintenance – Ault Field Airfield
 - Naval Air Station Whidbey Island, Oak Harbor, WA
 - This project was selected to represent a contracted concrete paving repair project.
- Repair Silver Flag Runway – Silver Flag Training Airfield
 - Tyndall Air Force Base, Panama City, FL
 - This project was selected to represent an in-house asphalt paving repair project.

Once the three projects were selected, a virtual research kick-off meeting was held to introduce the UW research team to the stakeholders, to present background on the previous and future FHWA Climate Challenge related efforts, and to provide expectations for data which would be requested on pavement mixes and construction activities in support of this study. Due to time and funding constraints, it was not possible to conduct site visits. However, Quality Control (QC) representatives assigned to each project provided daily construction reports, equipment statistics, and pictures to characterize the entire construction process.

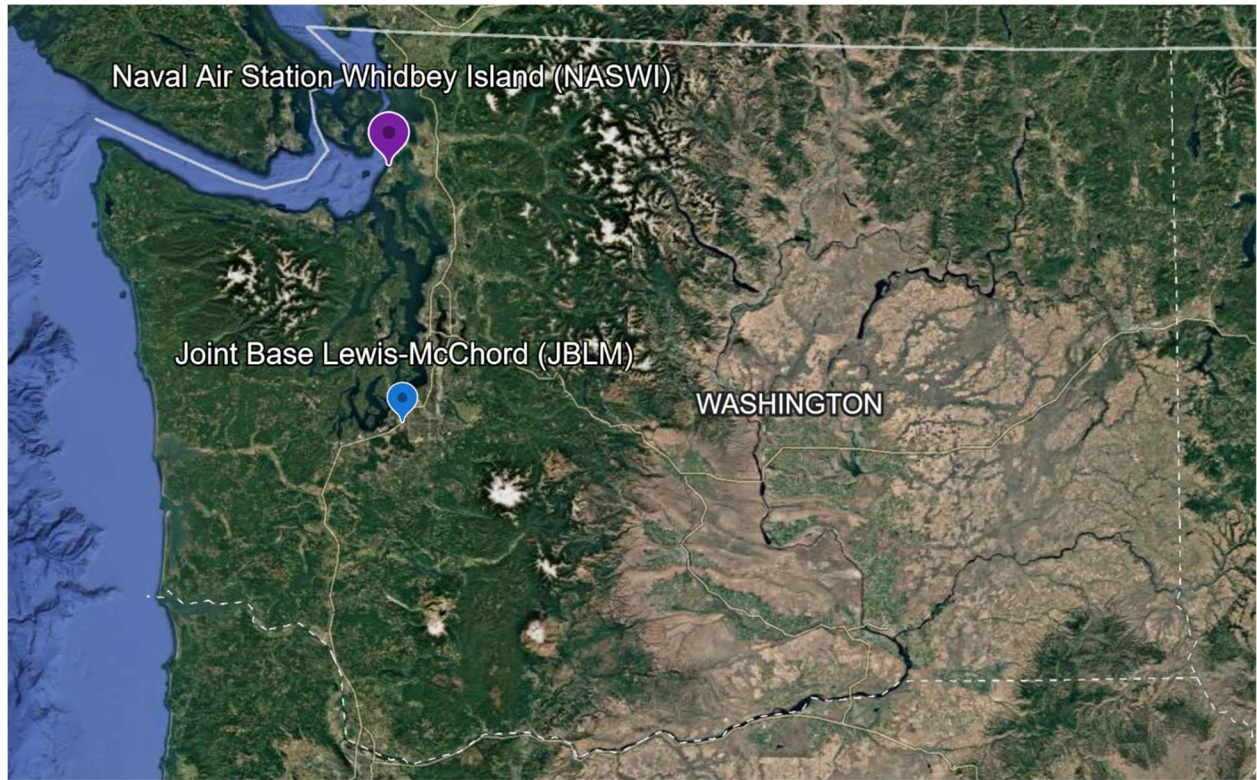


Figure 11 – Washington State Project Locations

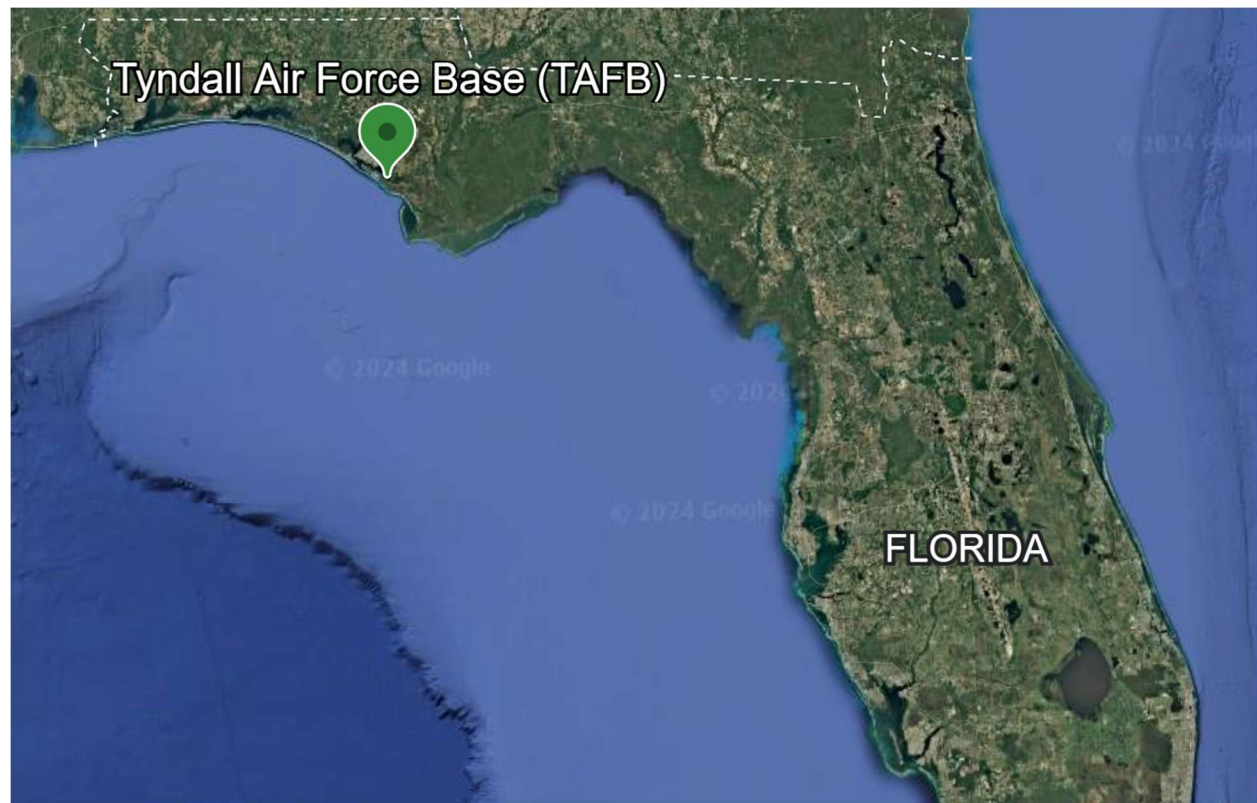


Figure 12 – Florida Project Location

3.2 Data Collection

Following the initial research meeting, the contractors and project managers were contacted to request general project information, all data required for the openLCA model, and any additional information. At a minimum, the pavement mix design, project plans and specifications, transportation trucking distances, types of equipment used, and equipment hours of operation were necessary for model development. If available, the EPDs were obtained from [Emerald Eco-Label](#) or [EC3](#). If the project did not have a generated EPD, the search function was used on these websites to find a similar EPD which would be a fair representation of the project’s provided mix design.

Each contractor and project manager had different methods for collecting the requested data, which was transferred via email through PDFs and Excel spreadsheets. This thesis author compiled and organized the information received to a standardized data set for input into openLCA. Table 3 summarizes the documents requested, the methods by which it was communicated, and how the data was used to produce results. Additional information provided which was not used for this thesis includes construction operations for pavement paint markings, airfield lighting installation, and laying topsoil or hydroseeding. While this data was not integrated into the research presented here, it could be used in future case studies to expand the LCA process for DOD airfields.

Table 3 – Requested Project Data

Document	Method	Desired Data	Utilization
Plans and specifications	PDF	Description of work, project length, pavement section designs, and paving plans	Understand the scope of work, compare projects based on size and purpose, and contribute to the project metadata summary
Mix design	PDF	Pavement material ingredients and quantities, asphalt binder content, concrete strength	Description of materials included in the mix design and quantities of asphalt binder, cement content, admixtures, RAP, and asphalt emulsions
EPD	PDF	Mix design GWP	GWP contribution for LCA model calculation
Construction equipment	PDF and spreadsheet	Equipment types, total fuel consumption, operating hours, engine size, and rate of fuel consumption (gallons per hour)	Total fuel use for LCA calculation
Trucking information	PDF	One-way trucking distance from plant to jobsite	Transportation data for LCA calculation
Final quantities	PDF and spreadsheet	Final material quantities	Calculate final pavement quantities for LCA calculation

3.2.1 Joint Base Lewis-McChord (JBLM) Asphalt Paving Project

JBLM is a United States Army-led installation, which is jointly occupied by the United States Air Force in Tacoma, WA. As the primary service, the Army’s Directorate of Public Works (DPW) is responsible for the repair and sustainment of the joint base’s infrastructure including facilities, pavement, and other designated Real Property. DPW prepared a solicitation package in 2018 for a mill and fill asphalt overlay of the McChord Airfield runway, repairing the area shown in Figure 13. This contract was awarded to Alutiiq General Contractors, LLC as the general contractor who subcontracted materials and paving operations to Miles Resources. Data collection for this project relied entirely on historical records since it was completed in 2019.

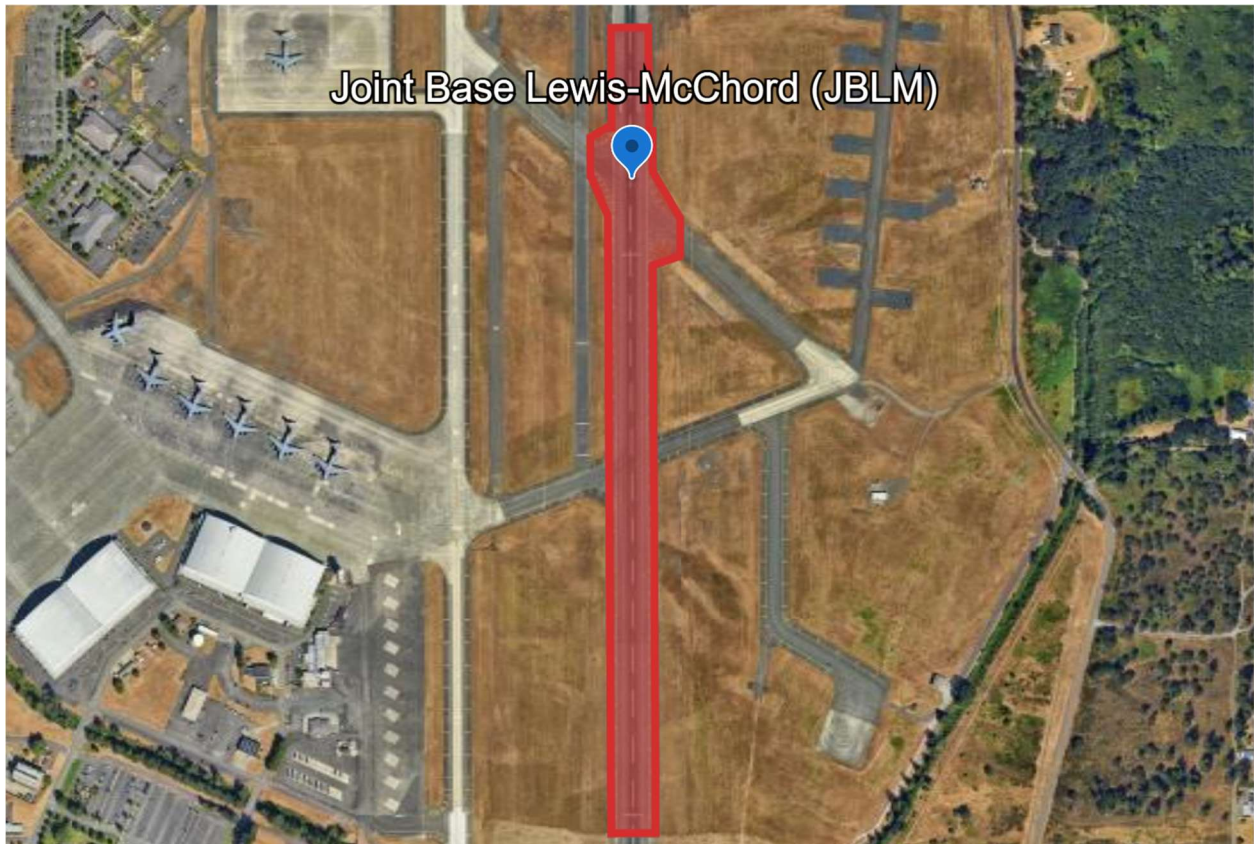


Figure 13 – JBLM Project Area

3.2.1.1 JBLM Project Description

General project information, insights on pavement mix design and construction, and transportation scope can be found in Table 4. This project used one asphalt mix design which did not include any reclaimed asphalt pavement (RAP) in accordance with UFC 3-260-01. Although this DOD governing design standard does encourage the use of recycled materials in airfield pavements, it also suggests the use of mixed-source RAP can be highly problematic in adhering to strict material requirements and states, “... it should not be done at the expense of quality or performance of the final pavement.” Miles Resources provided the EPD for the mix design used on this project.

Table 4 – JBLM Metadata

Joint Base Lewis-McChord (JBLM)	
GENERAL PROJECT DETAILS	
Contractor Names	Alutiiq General Contractors, LLC Miles Resources
Primary Pavement Type	Hot Mix Asphalt
Project Type	Mill and fill with resurfacing
State	Washington
City	Tacoma
County	Pierce
Pavement Activities	Planing bituminous pavement, applying prime / tack coats, paving HMA, joint cutting, overlaying HMA, and grooving resurfaced areas
PAVEMENT CONSTRUCTION DETAILS	
Airfield Features	Runway 34-16, taxiway, and shoulders
Project Area (ft ²)	300,678
Length (ft)	8,387
Number of Paving Days	9
Construction Dates	4/9/19 to 5/1/19
Asphalt Thickness (ft)	0.25 / 0.5
MIX DESIGN DETAILS	
Total HMA Quantity (short tons)	20334
Tack Coat (short tons)	14
HMA GWP A1-A3 (kg CO ₂ e per short ton)	57.06
RAP	0%
HMA Class	1/2"
Performance Grade of Asphalt Binder	PG 58-22
ASPHALT PLANT DETAILS	
Name	Lakeview Plant
Location	Lakewood, WA
TRUCKING DETAILS	
HMA Average One-Way Distance (mi)	6
Tack Coat Estimated Travel Distance (mi)	15
Truck Type Used	Dump Truck – End
Average Number of Trucks Running (daily)	20
Average Truck Capacity (short ton)	21

3.2.1.2 JBLM Typical Paving Operations

For this project, the top 6 inches of the existing asphalt pavement was first demolished using a milling machine. A test section preceded construction, which consisted of overlaying a 4 inch compacted base lift, profile grinding the first lift to 3 inches, sweeping and applying a tack coat, paving a 3 inch compacted wearing course, and completing sampling and volumetric testing. Once test results were completed and accepted, the contractor commenced paving operations on the runway, taxiway, and shoulders.

The paving train included three pavers operating in echelon, two material transfer devices (MTV), three breakdown rollers, three pneumatic rollers, and three finish rollers (one of each aforementioned roller type followed behind all pavers). A tack coat was applied via a distributor truck between the two pavement lifts. Some longitudinal joints were sawcut at the end of a shift while others were matched hot to the adjacent joints (pavement temperatures were above one hundred seventy-five degrees Fahrenheit). Lastly, the runway was grooved in accordance with UFC 3-260-02 to reduce the hydroplaning potential of the pavement surface and to promote safe operation of aircraft. Since this is an active airfield, sweeping operations were conducted periodically to prevent foreign object debris (FOD), which can be harmful to aircraft. Table 5 outlines the types, make and models, and engine sizes of equipment used in paving operations for this project.

3.2.1.3 JBLM Equipment Used

Table 5 – Equipment Record

Equipment Type	Make and Models	Engine Size (kW)
Excavator	John Deere 160	90
Grader	John Deere 672	190
HMA grooving machine	DP Groover	200
Loader	John Deere 744	236
Milling machine	Wirtgen 210i	537
Mini excavator	John Deere 50	26.8
MTV	Roadtec SB-2500B	224
	Weiler e2850	223
Paver	CAT AP1055F	168
Breakdown roller	HAMM HD+ 120VO	100
Pneumatic roller	Sakai GW750	79
Finish roller	IR DD120B	148
Sweeper	Elgin	200*
Tack truck	International	200*
Vacuum truck	Isuzu	200*
Water truck	International 10,000 gal	200*
*Engine sizes not provided but estimated based on proxy data presented in section 3.3.2.		

Data collected from this project included most exact models used for each type of equipment and their associated engine size (exceptions are estimated and are denoted with an asterisk). However, the majority of equipment specifications did not list fuel consumption values. Assumptions were made based on previous research from USEPA (2023) Motor Vehicle Emission Simulator: MOVES4 and Lum (2024). Demolition activities include the following equipment and their estimated percentages:

- Excavator (25%)
- Loader (25%)
- Sweeper (10%)
- Vacuum truck (10%)
- Milling machine (100%)

Currently, the PCR for asphalt specifies demolition should be included in end-of-life (C1), but this thesis chose to include it in construction (A5) because it maintained consistency with Lum (2024). Figures 14 – 17 are photos obtained from the contractor of equipment operating throughout the construction process.



Figure 14 – JBLM Paver



Figure 15 – JBLM Dump Truck, MTV, and Paver



Figure 16 – JBLM Roller



Figure 17 – JBLM Three Pavers in Tandem

3.2.2 Naval Air Station Whidbey Island (NASWI) Concrete Paving Project

NASWI is a United States Navy installation located in Oak Harbor, WA. In October 2021, Naval Facilities Engineering Command (NAVFAC) Northwest's Public Works Department released a solicitation for a design-bid-build contract to perform annual pavement maintenance on Ault Field's airfield. This repair project required concrete slab replacements in the areas highlighted in red on Figure 18. Miles Sand & Gravel was awarded the contract to demolish and reconstruct the failed slabs. Data collection for this project also relied entirely on historical records since it was completed in 2022.



Figure 18 – NASWI Project Area

3.2.2.1 NASWI Project Description

General project information, insights on pavement mix design and construction, and transportation scope can be found in Table 6. This project used two separate cement products: one for controlled density fill (CDF) and one for concrete (PCC). The concrete mix design included type I cement, coarse aggregate, fine aggregate, water, fly ash, and chemical admixtures for water reduction and air entrainment. Since this project did not have an existing EPD, [EC3](#) was used to find a representative EPD from Stoneway Concrete for the PCC and a representative EPD from American Rock Products (ARP) for the CDF. See section 3.3.2.2 for further information on how these EPDs were selected. Steel dowel bars (20 inches long and 1-1/8 inch diameter) were spaced at 15 inches on center to reinforce all construction joints. These dowels

were not included in the material production (A1 – A3) contributions for this project, although steel manufacturing would contribute to the overall GWP.

Table 6 – NASWI Metadata

Naval Air Station Whidbey Island (NASWI)	
GENERAL PROJECT DETAILS	
Contractor Name	Miles Sand & Gravel
Primary Pavement Type	Concrete
Project Type	Slab replacement
State	Washington
City	Oak Harbor
County	Island
Pavement Activities	Saw cutting concrete, demolishing existing panels, placing concrete reinforcement, pouring PCC and CDF, installing doweled construction joints, and sealing joints
PAVEMENT CONSTRUCTION DETAILS	
Airfield Features	Parking apron
Project Area (ft ²)	41,625
Length (ft)	2,775
Number of Paving Days	11
Construction Dates	8/9/22 to 10/5/22
Concrete Thickness (ft)	1.25
MIX DESIGN DETAILS	
Total PCC Quantity (yd ³)	1759
Total CDF Quantity (yd ³)	333
PCC GWP A1-A3 (kg CO ₂ e per yd ³)	166.89
RAP	0%
Design Flexural Strength (psi)	650
Slump (in)	4
W/C ratio	0.38
BATCH PLANT DETAILS	
Name	Hoffman Rd Plant
Location	Oak Harbor, WA
TRUCKING DETAILS	
PCC Average One-Way Distance (mi)	6
Truck Type Used	Dump Truck – End
Average Number of Trucks Running (daily)	14
Average Truck Capacity (yd ³)	10

3.2.2.2 NASWI Typical Paving Operations

For this project, one hundred eighty-five existing 15 foot by 15 foot concrete panels were demolished by saw cutting and removing all material from the failed slabs. The contractor then excavated to a minimum depth of 21 inches and compacted the subgrade. 6 inches of CDF was poured as a base for each slab prior to placing concrete for the slab via a ready mix concrete truck. Doweled construction joints were installed where newly poured concrete met existing or set concrete. Additionally, contraction joints were established in all locations between two concurrently placed concrete slabs. Since this is an active airfield, sweeping operations were conducted periodically to prevent foreign object debris (FOD), which can be harmful to aircraft, especially fighter jets. Table 7 outlines the types, make and models, and engine sizes of equipment used in paving operations for this project.

3.2.2.3 NASWI Equipment Used

Table 7 – Equipment Record

Equipment Type	Make and Model	Engine Size (kW)
Concrete saw	Unknown	55*
Concrete vibrator	Unknown	7.2*
Dowel Drill	Unknown	100*
Excavator	Unknown	90*
Loader	Unknown	236*
Mini excavator	Unknown	26.8*
Roller	Unknown	100*
Screed	Unknown	6.7*
Vacuum truck	Unknown	200*
*Engine sizes not provided but estimated based on proxy data presented in section 3.3.2.		

Data collected from this project did not include all specific types of equipment used and, therefore, was assumed based on the known construction operations which took place. Since the make and models of the equipment were not provided, all engine sizes were estimated based on industry standards and fuel consumption values were referenced from USEPA (2023) Motor Vehicle Emission Simulator: MOVES4. Demolition activities include a portion of the following equipment and their estimated percentages:

- Concrete saw (25%)
- Excavator (25%)
- Loader (25%)
- Vacuum truck (25%)

Currently, the PCR for concrete specifies demolition should be included in end-of-life (C1), but this thesis chose to include it in construction (A5) because it maintained consistency with Lum (2024). There were no photos available from this specific project. However, the government

project manager did provide photos in Figures 19 – 22 of a contract currently in construction as an example for concrete paving.



Figure 19 – NASWI Finishing Concrete



Figure 20 – NASWI Concrete Paving Operations



Figure 21 – NASWI Saw Cutting Expansion Joint



Figure 22 – NASWI Fresh Concrete

3.2.3 Tyndall Air Force Base (TAFB) Asphalt Paving Project

TAFB is a United States Air Force installation located in Panama City, FL, which hosts a training airfield specifically used for civil engineers to rapidly repair concrete or asphalt pavements and is not intended for aircraft landings. This project was constructed by the 823d RED HORSE Squadron (RHS) to serve as a training exercise for deployments with the asphalt material and delivery efforts contracted out to C. W. Roberts Contracting, Inc. Figure 23 identifies the repaired runway section. Out of the three projects studied in this thesis, TAFB was the only one with data collected concurrently with construction, allowing for the most accurate information to be reported by the RHS project manager.

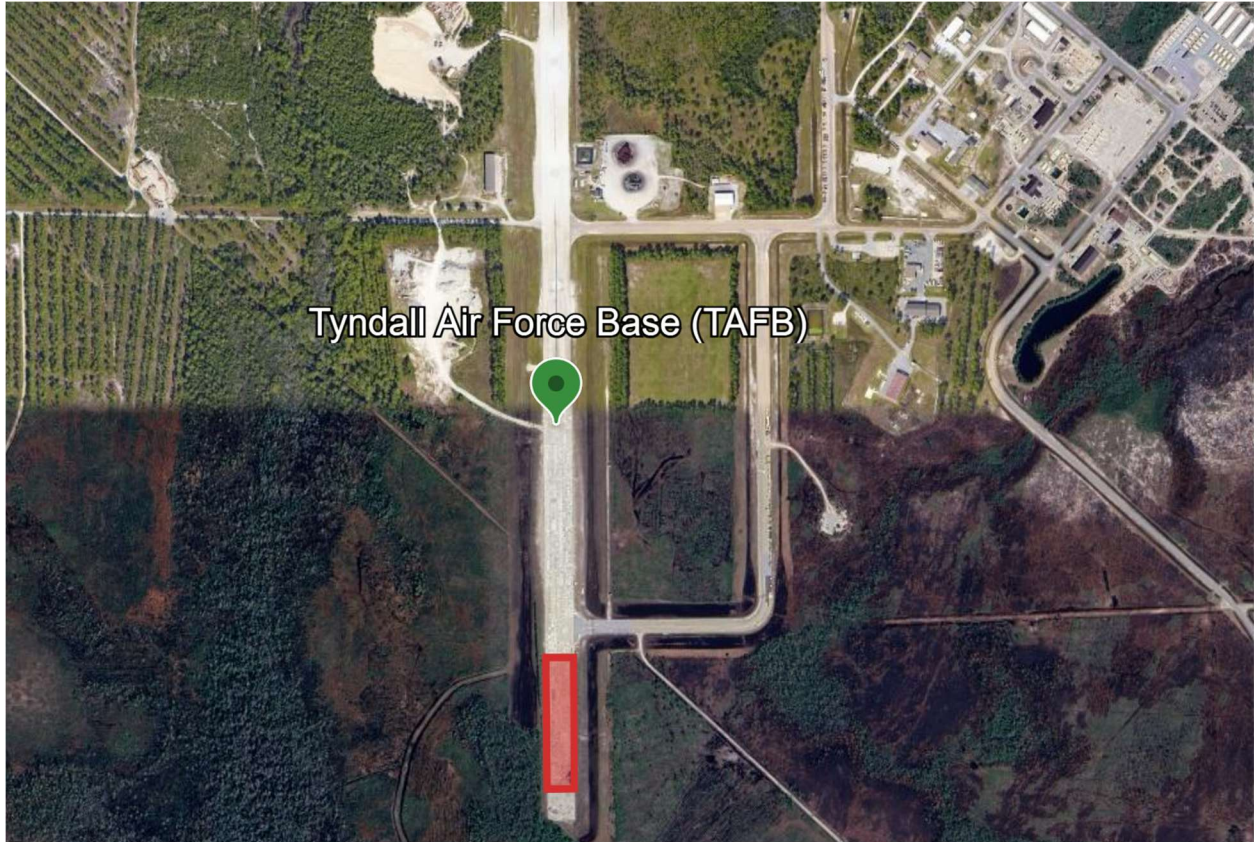


Figure 23 – TAFB Project Area

3.2.3.1 Project Description

General project information, insights on pavement mix design and construction, and transportation scope can be found in Table 8. This project used two asphalt mix designs: one with a 3/8 inch nominal maximum aggregate size (NMAS) and one with a 1/2 inch NMAS. Both mix designs included a 30% RAP content because this is not an active airfield and there is little to no risk of affecting the quality or performance of the final pavement. Since the material contractor for this project did not generate an EPD, [Emerald Eco-Label](#) was used to find two representative EPDs from Preferred Materials, Inc. for both the 3/8 inch NMAS and 1/2 inch NMAS asphalt mixtures. See section 3.3.2.3 for further information on how these EPDs were selected.

Table 8 – TAFB Metadata

Tyndall Air Force Base (TAFB)	
GENERAL PROJECT DETAILS	
Contractor Names	823d RED HORSE Squadron C. W. Roberts Contracting, Inc.
Primary Pavement Type	Hot Mix Asphalt
Project Type	Full depth replacement
State	Florida

City	Panama City
County	Bay
Pavement Activities	Demolishing and removing existing PCC, compacting base course, applying prime / tack coats, and paving HMA
PAVEMENT CONSTRUCTION DETAILS	
Airfield Features	Runway
Project Area (ft ²)	105,000
Length (ft)	700
Number of Paving Days	7
Construction Dates	7/15/24 to 8/1/24
Asphalt Thickness (ft)	0.42
MIX DESIGN DETAILS	
Total HMA Quantity (short tons)	3505
Tack Coat (short tons)	10
HMA GWP A1-A3 (kg CO ₂ e per short ton)	69.39
RAP	30%
HMA Class	3/8" & 1/2"
Performance Grade of Asphalt Binder	PG 58-22
ASPHALT PLANT DETAILS	
Name	CW Roberts Plant #5
Location	Panama City, FL
TRUCKING DETAILS	
HMA Average One-Way Distance (mi)	18
Tack Coat Estimated Travel Distance (mi)	18
Truck Type Used	Dump Truck - End
Average Number of Trucks Running (daily)	24
Average Truck Capacity (short ton)	21

3.2.3.2 TAFB Typical Paving Operations

For this project, approximately 3,900 cubic yards of existing concrete pavement was demolished by saw cutting and removing all material from the repair area. 823d RHS used excavators, loaders, and dump trucks to excavate approximately 18 inches below the surface to reach the subgrade or up to 26 inches in areas which had been previously repaired. Additional aggregate material was delivered to allow craftsmen to place 8 inches of aggregate base course at 95% of laboratory compaction (maximum density from ASTM D1557). Before paving began, an asphalt emulsion prime coat was evenly applied. The first lift of asphalt was 2.5 inches thick, paved with the 1/2 inch NMAAS mix design, and compacted to 95% of laboratory compaction. A tack coat

was applied between the two lifts of asphalt, which was the same asphalt emulsion as was applied for the prime coat. For the second lift, 2.5 inches of the 3/8 inch NMAS mix design was paved and compacted to 100% laboratory compaction.

The paving train included one paver, end dump trucks to transfer asphalt to the paver, and three rollers (vibratory, pneumatic, and finish). This runway was not grooved as the JBLM runway project was because it is not intended for aircraft use and the risk of hydroplaning is non-existent. Sweeping or vacuum truck operations were not required since this is not an active airfield and FOD is not as much of a concern. Table 9 outlines the types, make and models, and engine sizes of equipment used in paving operations for this project.

3.2.3.3 TAFB Equipment Used

Table 9 – Equipment Record

Equipment Type	Make and Model	Engine Size (kW)
Excavator	Volvo D6H	128
	Kobelco SK350LC	198
Grader	Volvo G930	152
	CAT 120M	103
Loader	John Deere 544	123
	CAT 963D	141
Paver	CAT AP600	129
Roller	CAT CB13	106
	Volvo DD90	97
	Volvo PT125	63
Skid steer	CAT 289D	54
	Bobcat S650	54
Tack truck	International	200*
Water truck	West-Mark 500T	200*
*Engine sizes not provided but estimated based on proxy data presented in section 3.3.2.		

As previously mentioned, data was collected from this project as it was constructed, which allowed specific types of equipment and their engine sizes to be reported. The two exceptions are denoted with an asterisk because the tack and water trucks were owned and operated by the material contractor. Similar to the other projects researched, fuel consumption values were assumed based on the USEPA (2023) Motor Vehicle Emission Simulator: MOVES4. Demolition activities include the following equipment and their estimated percentages:

- Excavator (100%)
- Loader (45%)

Currently, the PCR for asphalt specifies demolition should be included in end-of-life (C1), but this thesis chose to include it in construction (A5) because it maintained consistency with Lum

(2024). Figures 24 – 27 are photos obtained from the 823d RHS project manager of their craftsman operating equipment during construction.



Figure 24 – TAFB Paver, Dump Truck, and Roller



Figure 25 – TAFB Paver and Dump Truck



Figure 26 – TAFB Paver



Figure 27 – TAFB Asphalt Transfer to Paver

3.3 Data Analysis

This section discusses the data organization and cleaning process including organization, gaps, rules of thumb or assumptions, and modeling. Following data collection, the three projects selected for this thesis were evaluated based on stages A1 – A5 (otherwise known as cradle-to-built as defined in Figure 3). Concrete and asphalt EPDs, transportation distances, and construction equipment fuel consumption values are used to analyze the GWP of the specific pavement material and to present LCA calculations for each project. Any materials or construction activities outside of this scope, such as painting, lighting, and sodding, were not considered in the LCA calculations presented here. The format and sequence of this section is based on that presented in the following thesis:

Lum, E. 2024. *A Life Cycle Assessment of Asphalt Pavement Construction Projects in Washington State*. M.S. thesis, Seattle, WA: University of Washington.

However, all project data, tables, and figures are original to this thesis. Methods for the concrete LCA are built upon the foundation of asphalt methods provided in Lum (2024), but altered to account for concrete pavement construction practices.

3.3.1 Data Organization

All documents procured from each project manager were identified, organized, and compiled into a comprehensive spreadsheet, which includes the information presented in Table 3. Copies of each document were created for filing purposes and to ensure integrity of the original information prior to performing any calculations. Data was categorized as either material, transportation, or construction to prepare for input in openLCA modeling. For the equipment data, the primary information collected was the engine size, operation time, and fuel consumption while equipment make, model, year, and fuel type were also noted.

3.3.2 Data Gaps

Since the units of the received data was not uniform, it was necessary to convert the acquired data to a common unit and fill any data gaps prior to inputting data into openLCA. For example, the majority of equipment engine sizes were provided in units of horsepower (hp) while the FHWA repository uses units of kilowatts (kW). A unit conversion of 1.341 hp/kW was used to obtain the appropriate units and compared with equipment engine specifications for accuracy. Table 10 displays the required units for openLCA input while remaining data gaps were settled based on the established rules of thumb listed in section 3.3.2.4.

Table 10 – Unit Conversions for openLCA Input

Data Type	Received Data Units	openLCA Units
Fuel consumption	Hours (hrs) Gallons per hour (gph)	Total gallons (gal)
Engine size	Horsepower (hp) Kilowatts (kW)	Megajoule (MJ)
Asphalt emulsion (tack coat)	Gallons (gal)	Short tons (sh tn)
Emulsion travel distance	Miles (mi)	Miles (mi)
One-way truck travel	Miles (mi)	Miles (mi)
Total asphalt tonnage	Short tons (sh tn)	Short tons (sh tn)
Total concrete volume	Cubic yards (yd ³)	Cubic yards (yd ³)

3.3.2.1 JBLM Data Gaps

Data received from the JBLM project includes each type of equipment used as well as the associated make and models with exception of the dump truck, water truck, and tack truck, which were identified as “international.” An approximation of the total operating hours for each piece of equipment over the lifetime of the project was also provided. The contractor reported equipment operating hours were compared to WSDOT’s Plans Preparation Manual (2023) to

reveal these values are significantly larger than expected for the scope and time-frame of the project. However, the models developed for this research use the operation hours from the contractor rather than the WSDOT production rates, despite being almost doubled from what likely occurred, because there is no evidence to suggest the data was faulty.

Since total fuel consumption data was unavailable, these values were calculated based on engine sizes, reported time of operation, and rules of thumb as outlined in section 3.3.2.4 and Table 13 for the majority of construction equipment used on the project. However, the contractor supplied actual fuel consumption rates for the milling machine and the paver. Additionally, the total volume of asphalt emulsion (tack coat) used in gallons was not reported for the project. Instead, the contractor provided the area in square yards and an application rate of 0.1 gallons per square yard was assumed based on UFC 3-260-02 to receive an overall value for gallons of emulsion. Lastly, this project was the only one in this research which provided the actual EPD for the asphalt mix design.

3.3.2.2 NASWI Data Gaps

Data received from the NASWI project was the least comprehensive in regard to equipment used, operating hours, and construction timelines. Outside of design documentation, the government project manager provided daily QC reports to narrate contractor on-site operations from which types of equipment used, dates of use, hours of operation, and daily material quantities were pulled. Research on widely used equipment types for this method was performed to determine fuel consumption rates and to develop the rules of thumb listed in Table 14. Concrete construction daily production rates were referenced from the WSDOT Plans Preparation Manual. Final volumes of CDF and concrete constructed were supplied in cubic yards via trucking material delivery weigh tickets.

Since there wasn't an available EPD, two representative EPDs were found from similar mix designs in Washington State on EC3 for both the CDF and concrete mixes (compared in Table 11). The most notable difference between the concrete mixes include the EPD mixes used recycled materials and slag cement while the actual mixes did not. This could cause a significant difference in the openLCA model but was unavoidable since there were no other EPDs available which would be more realistic.

Table 11 – NASWI Actual vs Proxy Data EPD Comparison

Mix Design Factor	Actual PCC	EPD PCC	Actual CDF	EPD CDF
Recycled Materials (kg/m ³)	0	197	0	263
Flexural Strength (psi)	650	650	50	50
Cements	Type II Fly ash	Type I – II Fly ash Slag cement	Type I	Type I Fly ash

Additives	Air entrainer Water reducer	Air entrainer Water reducer	Air entrainer	Air entrainer
-----------	--------------------------------	--------------------------------	---------------	---------------

3.3.2.3 TAFB Data Gaps

Data received from the TAFB project was the most comprehensive in regard to equipment used, operating hours, and construction timelines. The 823d RHS project manager provided material delivery tickets, construction equipment make and models, equipment operation hours for the entire project life, and daily contractor reports. Similar to the other asphalt project in this research, the equipment hours of operation were significantly higher than the production rates published in the WSDOT Plans Preparation Manual, but the values obtained from the project manager were used because there is no evidence to suggest the data is faulty. Since this project did not provide fuel consumption data, these values were also calculated based on engine sizes, reported time of operation, and rules of thumb as outlined in section 3.3.2.4 and Table 13. However, unlike JBLM, this project provided the total volume of asphalt emulsion used for prime and tack coats in gallons as well as the associated application rate.

No EPD was produced for either asphalt mix design used in this project. As an alternative, two representative EPDs were found from similar mix designs in Florida on Emerald Eco-Label for both the 3/8 inch NMAS and the 1/2 inch NMAS mixes (compared in Table 12). The main concern in this comparison is the difference in virgin percent binder (Pb). Since the EPDs round this value to the nearest whole number, the EPD mixes could have more Pb than the actual mixes, which would increase the GWP.

Table 12 – TAFB Actual vs Proxy Data EPD Comparison

Mix Design Factor	Actual Mix 1	EPD Mix 1	Actual Mix 2	EPD Mix 2
RAP Content (%)	30	29	30	29
Asphalt Binder Specification	PG 58-22	PG 58-22	PG 58-22	PG 58-22
Virgin Percent Binder (Pb, %)	3.53	4.00	3.83	4.00
NMAS (inches)	1/2	1/2	3/8	3/8
Additives	Anti-strip	Anti-strip	Anti-strip	Anti-strip

3.3.2.4 Rules of Thumb and Proxy Data

The fuel consumption data from this thesis was compiled to produce a set of standard fuel consumption values that are used to fill in for missing data. Rule of thumb values for asphalt and concrete construction equipment are shown in Table 13 and Table 14, respectively. In the columns below the project identifier, average gallons per hour is reported for the specific piece of equipment in the corresponding rows. The second column shows the average value of gph per specified equipment across the two projects that were used to obtain total fuel consumption.

Since there is only one concrete project included in this research, its equipment fuel consumption values serve as the rule of thumb. Rollers for the asphalt construction are separated into two different engine size ranges because those are the ranges given for construction equipment engine sizes in the FHWA repository and is being used for analysis in openLCA. However, the concrete project is assumed to have used one larger roller for the base course compaction.

Table 13 – Asphalt Construction Fuel Consumption Averages

Equipment Type	Fuel Consumption (gph)		
	Average	JBLM	TAFB
Dump Truck	5.52	5.52	5.52
Excavator	3.86	3.86	3.86
Grader	6.48	6.48	6.48
HMA Grooving Machine	2.51	2.51	
Loader	6.88	6.44	7.32
Milling Machine	14.3	14.3	
Mini Excavator	1.03	1.03	
MTV	5.87	5.87	
Paver	3.76	3.65	3.87
Roller (19 – 55 kW)	1.78	1.89	1.67
Roller (56 – 560 kW)	3.52	3.35	3.70
Skid Steer	2.00		2.00
Sweeper	4.17	4.17	
Tack Truck	3.71	3.94	3.47
Vacuum Truck	4.38	4.38	
Water Truck	3.20	2.95	3.44

Table 14 – Concrete Construction Fuel Consumption Average

Equipment Type	Fuel Consumption (gph)
Concrete Saw	1.34
Concrete Vibrator	0.37
Dowel Drill	1.91
Dump Truck	5.52
Excavator	3.86
Loader	6.44
Mini Excavator	1.03
Roller	3.70
Screed	0.66
Vacuum Truck	4.38

Additional proxy data was referenced from the USEPA (2023) Motor Vehicle Emission Simulator: MOVES4. Proxy data was not based on any data received from contractors or project managers specifically for these projects being analyzed. The EPA MOVES4 tool includes fuel consumption and emission information for various engine sizes of construction diesel and gasoline equipment, industrial diesel and gasoline equipment, and gardening equipment. Proxy data was solely used for the equipment with no reported fuel consumption data to allow GWP analysis of the subject project.

3.3.3 LCA Modeling

LCA modeling uses characterization factors to convert life cycle inventory (LCI) results to the common unit used by impact categories. This thesis focuses exclusively on GWP, with units of kg CO₂ eq, as the main impact category of the paving projects. Life cycle stages encompassed in this thesis are A1 – A5 to include material production (A1 – A3), transportation (A4), and construction (A5), identified in Figure 3 as cradle-to-build. The material production (A1 – A3) calculation for each project was completed by the contractor through an EPD or estimated by the primary researcher through a proxy EPD. The transportation (A4) and construction (A5) data was collected at the end of each project for work done on-site, with the exception of the TAFB project where data was collected throughout the construction process. Within each stage, the following was considered:

1. Material production (A1 – A3)
 - a. Pavement (HMA, CDF, or PCC) mix design EPD
 - b. Asphalt emulsion or prime / tack coat (including estimated transportation)
2. Transportation (A4)
 - a. Material haul distances
3. Construction (A5)
 - a. Construction equipment fuel consumption
 - i. Asphalt paving construction and demolition equipment: excavator, grader, HMA grooving machine, loader, milling machine, mini excavator, MTV, paver, roller, skid steer, sweeper, tack truck, vacuum truck, and water truck
 - ii. Concrete paving construction and demolition equipment: concrete saw, concrete vibrator, dowel drill, excavator, loader, mini excavator, roller, screed, and vacuum truck

In today's industry, there is a lack of consensus on which stage asphalt milling and concrete demolition should be included (Dr. Amlan Mukherjee personal communication with Eryn Lum, 2024). Since these operations were performed by the contractor in conjunction with the paving, Lum (2024) included existing pavement demolition in stage A5. Demolition is considered within the construction (A5) system boundary for this thesis to maintain consistency with Lum (2024) and to appropriately describe construction as it occurred.

3.3.4 openLCA Modeling

This thesis used openLCA version 2.0.2 and the FHWA Pavement Life Cycle Assessment Background Data Repository as the software and data set of choice to maintain consistency with Lum (2024). On the Climate Challenge Community of Scholars website, there are learning modules, data collection protocols, and resources available to help researchers get started with openLCA modeling as well as the link to download the FHWA dataset. Although the asphalt models were produced based on a template developed by Lum (2024), the concrete LCA model was created from the FHWA dataset concrete material parameters and construction equipment. The openLCA software calculates the GWP of a project, in kg of CO₂ eq, from the upstream data provided by the FHWA repository dataset (i.e., equipment based on engine size and hauling trucks) and the input data (i.e., truck mileage, fuel consumption, etc.). Other environmental impact categories such as acidification, eutrophication, freshwater ecotoxicity, human health (cancer, non-cancer, and particulate matter), ozone depletion, and smog formation can also be calculated in openLCA. However, this thesis focuses solely on each project’s GWP results.

3.3.4.1 Global Parameters

Global parameters are properties and conversions that remain constant for all analyses. They were used when setting up dependent parameter calculations and inputs within the openLCA model (see 10 Appendix D: openLCA Variables). Benefits of using global parameters in openLCA include convenience of use and automatic updating where they are referenced. Global parameters used in this model are listed in Table 15 with their associated value and description. Once input into the database, global parameters can be found in the parameters tab of a process, which is shown in

Figure 28 – openLCA Global Parameters.

Table 15 – Global Parameters

Material and Fuel Properties		
Parameter	Value	Description/UOM
Asphalt Density	113	This is the target density of asphalt paving in units lb/sq yd/in of paving mat
CDF Density	115.4	This is the reported density from the CDF mix design in lb/ft ³
Concrete Density	146.1	This is the reported density from the concrete mix design in lb/ft ³
Diesel Density	867.30	Density of diesel in kg/m ³
Diesel LHV	42.91	Lower heating value of diesel in MJ/kg
MJ per gal diesel	140.88	LHV (MJ/kg) * Density (kg/m ³) / conversion factor gal/m ³
CSS-1 gal per ton	237.98	Gallons per ton of CSS-1 emulsion

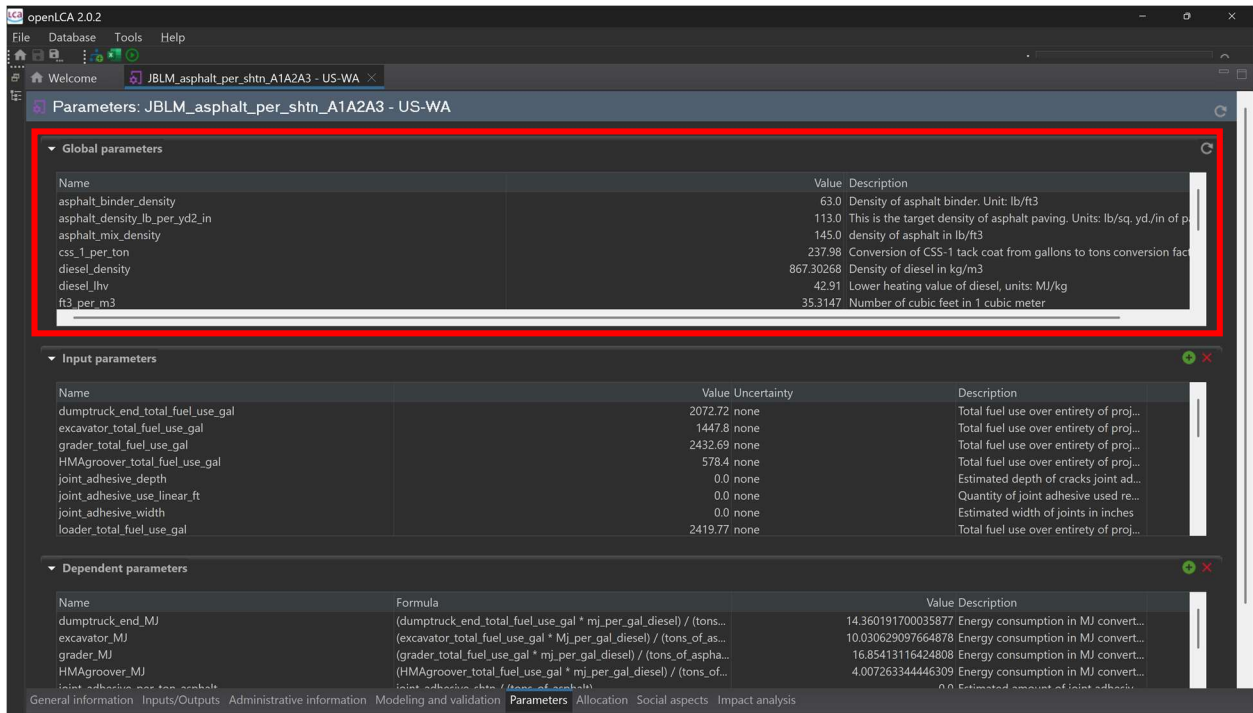


Figure 28 – openLCA Global Parameters

3.3.5 Manual Addition of EPDs

The EPD data used in this study was added manually to each model as a separate flow and process to replicate the efforts in Lum (2024). A new reference flow was made to represent the EPD for the asphalt or concrete mixture in the project's LCA. This one flow was used as the reference for each project's EPD process. The unit of choice for this flow representing EPDs is mass because the environmental impact results were reported per short ton of asphalt or per cubic yard of concrete. Once this flow was made, a new process could be used in the project's LCA. Resource use indicator quantities in Table 16 were entered in the input section of each process as seen in Figure 29. The corresponding process added life cycle impact indicators in Table 17 as output flows, which is also shown in Figure 29. Flows added were a combination of existing flows from the FHWA repository and new flows created to represent indicators not already present.

Table 16 – Resource Use Indicators from EPDs

Acronym	Indicator	Unit	openLCA Associated Flow
ADP_E	Abiotic depletion potential for non-fossil mineral resources	kg Sb Equiv.	New flow: ADP Elements
ADP_F	Abiotic depletion potential for fossil resources	MJ	New flow: ADP Fossil
RPR_E	Renewable primary resources used as an energy carrier (fuel)	MJ	Electricity, from renewable source, unspecified
NRPR_E	Non-renewable primary resources used as an energy carrier (fuel)	MJ	Energy, fossil, unspecified
NRPR_M	Non-renewable primary resources used as a material (fuel)	MJ	New flow: NRPR Materials
NRSF	Non-renewable secondary fuels	MJ	New flow: NRSF
SM	Secondary (recycled) materials	Kg	RAP
RE	Recovered Energy	MJ	New flow: RE
RPR_M	Renewable primary resources with energy content used as material	MJ	New flow: RPR Materials
RSF	Renewable secondary fuels	MJ	New flow: RSF
FW	Consumption of fresh water	m ³	Water, fresh

Table 17 – Life Cycle Impact Indicators from EPDs

Acronym	Indicator	Unit	FHWA Repository Flow
GWP	Global warming potential, including biogenic CO ₂	kg CO ₂ Equiv.	Carbon dioxide
ODP	Ozone depletion potential	kg CFC-11 Equiv.	CFC-11
EP	Eutrophication potential	kg N Equiv.	Nitrogen
AP	Acidification potential	kg SO ₂ Equiv.	Ozone
POCP	Photochemical ozone creation potential	kg O ₃ Equiv.	Sulfur dioxide

Inputs										
Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality entr	Location	Description
ADP_F	FHWA_WSDOT_Climate_Challe...	3110.00000	MJ		none					
Electricity, from renewable ...	Technosphere Flows/CUTOFF F...	10.45000	MJ		none					RPR_E
Energy, fossil, unspecified	22: Utilities/2213: Water, Sewa...	1035.00000	MJ		none					NRPR_E
NRPR Materials	FHWA_WSDOT_Climate_Challe...	2120.00000	MJ		none					
NRSF	FHWA_WSDOT_Climate_Challe...	0.00000	MJ		none					
RAP - US	FHWA Flows/Asphalt Mixture	0.00000	kg		none					SM
RE	FHWA_WSDOT_Climate_Challe...	0.00000	MJ		none					
RPR Materials	FHWA_WSDOT_Climate_Challe...	0.00000	MJ		none					
RSF	FHWA_WSDOT_Climate_Challe...	0.00000	MJ		none					
Water, fresh	resource/air	7.10000	m3		none					

Outputs										
Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided product	Provider	Data quality entr	Location	Description
Carbon dioxide	emission/air	57.06000	kg		none					
CFC-11	emission/air	4.55000E-8	kg		none					
Nitrogen	emission/air	0.01210	kg		none					
Ozone	emission/air	3.55000	kg		none					
Sulfur dioxide	emission/air	0.09760	kg		none					
WSDOT EPDs - US-WA	FHWA_WSDOT_Climate_Challe...	1.00000	sh tn		none					

Figure 29 – openLCA EPD Inputs and Outputs

3.3.6 Project Specific LCA Model

For each paving project, a new flow and process was created in openLCA. Unlike the research performed in Lum (2024), the three projects studied in this thesis were not significantly similar, which meant it was not possible to duplicate a process outlining the life cycle from stages A1 to A5. Instead, each process was created from the beginning including adjustment to the parameter values input to the project. In each new process and flow created, appropriate metadata was specified to describe what was represented in the model. Metadata included information regarding general project information and links to data where applicable, as well as input, output, and global parameters used. Additionally, specific time and geographic data was defined where possible. Since time is documented in dates, paving timelines were entered for each project with their respective locations specified as either United States – Washington, or United States – Florida.

3.3.6.1 Processes Parameters

The parameters section of the process is where all the project data was input from the data analysis stage. This acted as the only area where numerical data organized in the data analysis was used. Input parameters included any value that did not require any conversions or calculations. Dependent parameters possess a formula section where numbers, as well as global and input parameters, were used to calculate a value. Input parameters included total fuel consumption for construction equipment, one-way travel distance (from plant to site) for pavement material delivery trucks, total travel distance of emulsion, total amount of emulsion

used, and total short tons of asphalt or cubic yards of concrete used on the project, which is shown in Figure 30. Dependent parameters included the energy consumption for each piece of construction equipment, tons of emulsion, and the ton*miles of emulsion, all per short ton or cubic yards (Figure 30).

Global parameters			
Input parameters			
Name	Value	Uncertainty	Description
dumptruck_end_total_fuel_use_gal	2072.72	none	Total fuel use over entirety of proje...
excavator_total_fuel_use_gal	1447.8	none	Total fuel use over entirety of proje...
grader_total_fuel_use_gal	2432.69	none	Total fuel use over entirety of proje...
HMAgroover_total_fuel_use_gal	578.4	none	Total fuel use over entirety of proje...
joint_adhesive_depth	0.0	none	Estimated depth of cracks joint adh...
joint_adhesive_use_linear_ft	0.0	none	Quantity of joint adhesive used rep...
joint_adhesive_width	0.0	none	Estimated width of joints in inches...
loader_total_fuel_use_gal	2419.77	none	Total fuel use over entirety of proje...
millingmachine_total_fuel_use_gal	2002.27	none	Total fuel use over entirety of proje...
miniexc_total_fuel_use_gal	385.91	none	Total fuel use over entirety of proje...
mtv_total_fuel_use_gal	1056.06	none	Total fuel use over entirety of proje...
Dependent parameters			
Name	Formula	Value	Description
dumptruck_end_MJ	(dumptruck_end_total_fuel_use_gal * mj_per_gal_diesel) / (tons...	14.360191700035877	Energy consumption in MJ convert...
excavator_MJ	(excavator_total_fuel_use_gal * mj_per_gal_diesel) / (tons_of_asph...	10.030629097664878	Energy consumption in MJ convert...
grader_MJ	(grader_total_fuel_use_gal * mj_per_gal_diesel) / (tons_of_asphal...	16.85413116424808	Energy consumption in MJ convert...
HMAgroover_MJ	(HMAgroover_total_fuel_use_gal * mj_per_gal_diesel) / (tons_of_...	4.007263344446309	Energy consumption in MJ convert...
joint_adhesive_per_ton_asphalt	joint_adhesive_shtn / (tons_of_asphalt)	0.0	Estimated amount of joint adhesive...
joint_adhesive_shtn	(asphalt_binder_density * joint_adhesive_use_linear_ft * joint_ad...	0.0	Estimated amount of joint adhesive...
loader_MJ	(loader_total_fuel_use_gal * mj_per_gal_diesel) / (tons_of_asphalt)	16.764618988573382	Energy consumption in MJ convert...
millingmachine_MJ	(millingmachine_total_fuel_use_gal * mj_per_gal_diesel) / (tons...	13.872100927877785	Energy consumption in MJ convert...
miniexc_MJ	(miniexc_total_fuel_use_gal * mj_per_gal_diesel) / (tons_of_asph...	2.6736566342587746	Energy consumption in MJ convert...
mtv_MJ	(mtv_total_fuel_use_gal * mj_per_gal_diesel) / (tons_of_asphalt)	7.316581133360941	Energy consumption in MJ convert...
naver_MJ	(naver_total_fuel_use_gal * mj_per_gal_diesel) / (tons_of_asphalt)	2.2759094202119856	Energy consumption in MJ convert...

Figure 30 – openLCA Process Parameters

3.3.6.2 Input and Output Data

Flows from the FHWA repository, aside from the flow created for EPD data, were the primary sources of input. Diesel construction equipment flows, asphalt emulsion (used as prime and tack coats), truck transport (for pavements and emulsion), and the previously created EPD flows for concrete and asphalt materials were the primary input sources for the projects. Each piece of construction equipment required a separate flow. For example, if the data entered was for five various pieces of equipment, five separate diesel construction flows were added. Similarly, trucking for asphalt mixes, asphalt emulsion, and concrete mixes also had separate input flows. By separating each piece of equipment and providing a separate flow, their individual fuel consumption contribution was identified in the final results. Each flow had an associated product system that became the “provider” for the input flow.

To allow the final LCA impact results to be separated by input (emulsion, pavement mix, construction equipment, or trucking), each input was assigned to a specific provider. Asphalt emulsion and the pavements were separated since there are no similar flows. However, the construction equipment and trucking initially used the same FHWA repository flow as their

provider. For each input flow to have its own provider, copies of the original FHWA flows were made and renamed to the appropriate piece of corresponding equipment and set as the corresponding provider. By copying the pre-made FHWA flow, the model retained all of the background data input into the associated process from the repository but calculated their impact separately. This thesis followed this procedure by replicating the template processes established from Lum (2024) and adding individual types of construction equipment as dictated by the data collected from each project. Additional equipment flows evaluated included the following: concrete saw, concrete vibrator, dowel drill, grader, HMA grooving machine, mini excavator, screed, skid steer, and vacuum truck. The flows for backhoe, belly dump truck, and super dump truck were also removed since none of the three projects analyzed in this thesis used those pieces of equipment.

Once all the flows and providers were appropriately identified, descriptions were added for each flow. Units were also appropriately identified in the input variable's naming convention. The units for the construction equipment are in megajoules (MJ), asphalt emulsion is in short tons, trucking for asphalt pavements and emulsion are in ton*miles, trucking for concrete pavements are also in ton*miles (requiring a conversion from the cubic yards functional unit), asphalt EPD data is in short tons, and concrete EPD data is in cubic yards. The "amount" section of the input table was where the calculations done in the parameters stage were input as shown in Figure 31. After referencing the parameter name, openLCA linked the associated value with the input. This allowed the parameter to be linked and to automatically change if any numbers or calculations are changed in the input and dependent parameters.

Flow	Category	Amount	Unit	Costs/Revenues	Uncertainty	Avoided waste	Provider	Data quality	entr	Location	Description
Asphalt binder - GLO	42: Wholesale Trade/4247: Pet...	joint_adhesive...	sh tn		none		JOINT ADH...				Estimated join...
Diesel equipment operation...	23: Construction/2389: Other S...	roller_19to56k...	MJ		none		ROLLER Op...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	miniexc_MJ	MJ		none		MINI EXC ...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	tacktruck_MJ	MJ		none		TACK TRUC...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	loader_MJ	MJ		none		LOADER O...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	roller_56to560...	MJ		none		ROLLER Op...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	grader_MJ	MJ		none		GRADER O...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	watertruck_MJ	MJ		none		WATER TR...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	sweeper_56to...	MJ		none		SWEEPER ...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	paver_MJ	MJ		none		PAVER Ope...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	millingmachin...	MJ		none		MILLING M...				Energy consu...
Diesel equipment operation...	23: Construction/2389: Other S...	mtv_MJ	MJ		none		MTV Opera...				Energy consu...
Outputs											
Asphalt Pavement Constr...	FHWA_WSDOT_Climate_Cha...	1.00000	sh tn		none						

Figure 31 – openLCA Process Inputs and Outputs

3.3.6.3 Final LCA Calculation

Next, a product system was created directly from the completed process with all of the project-specific data added. Within the product system, a model graph was automatically generated. This model graph identified all of the flows, their providers, and the associated upstream flows that contributed to the overall output flow. The final environmental impact results were calculated through the product system. OpenLCA will calculate the environmental impacts of the processes linked to the product system based on the selected impact assessment method. This study used the TRACI 2.1 impact assessment method to evaluate each project's GWP. Following calculation completion, environmental impacts were presented in multiple different formats including the graph listed in Figure 32. To view individual impacts that each flow contributed to the overall impact, the contribution tree separated each provider by percentage of the total impact as exhibited in Figure 33.

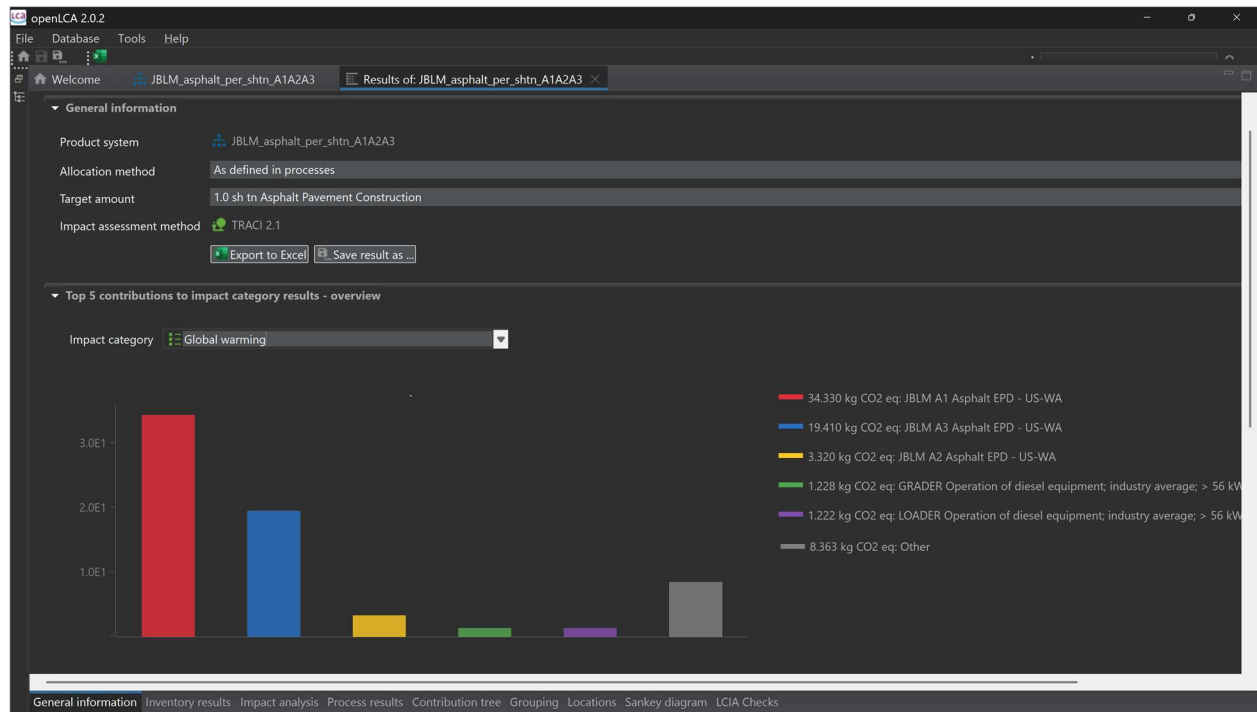


Figure 32 – openLCA Calculation Result Graph

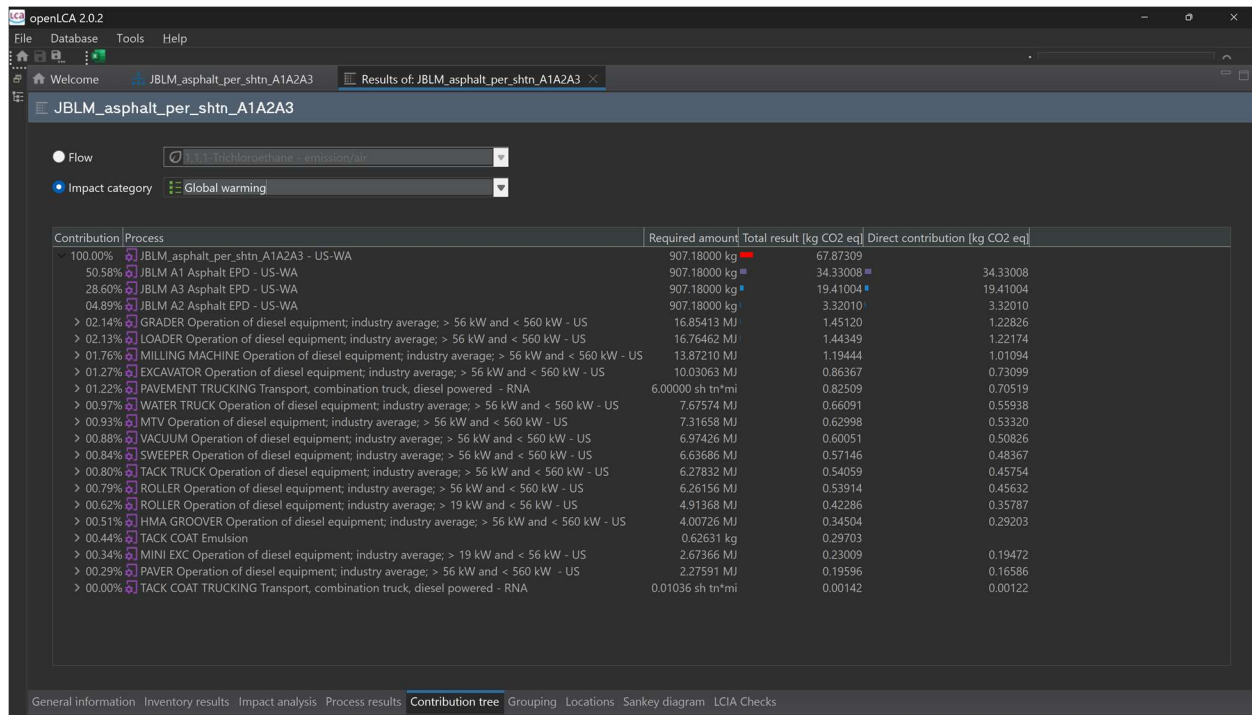


Figure 33 – openLCA Calculation Result Contribution Tree

3.4 Data Quality Analysis

Following the LCA calculation process, a data quality analysis was completed for each project’s input variables. These parameters were assessed based on the openLCA pedigree matrix from the International Reference Life Cycle Data System (ILCD) data quality system. Each input variable was given a rating for the categories in Table 18. An example of how the pedigree matrix from Table 18 was used in openLCA is illustrated in Figure 34. Tables 47 – 49 in Appendix F categorize the data quality analysis for each project studied throughout this thesis, accounting for the respective data gaps addressed in section 3.3.2.

Table 18 – openLCA ILCD Pedigree Matrix

	Very Good (5)	Good (4)	Fair (3)	Poor (2)	Very Poor (1)
Technological Representativeness	Technology aspects have been modelled exactly as described in the title and metadata, without any significant need for improvement.	Technology aspects are very similar to what is described in the title and metadata with need for limited improvements. For example: use of generic	Technology aspects are similar to what is described in the title and metadata but merits improvements. Some of the relevant processes are	Technology aspects are different from what described in the title and metadata. Requires major improvements.	Technology aspects are completely different from what is described in the title and metadata. Substantial improvement is necessary.

		technologies' data instead of modelling all the single plants.	not modelled with specific data but using proxies.		
Time Representativeness	The data (collection date) can be maximum 2 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the dataset.	The data (collection date) is older than 8 years with respect to the "reference year" of the dataset.
Geographical Representativeness	The processes included in the dataset are fully representative for the geography stated in the "location" indicated in the metadata.	The processes included in the dataset are well representative for the geography stated in the "location" indicated in the metadata.	The processes included in the dataset are sufficiently representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.	The processes included in the dataset are only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different electricity grid mix profile.	The processes included in the dataset are not representative for the geography stated in the "location" indicated in the metadata.
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations.	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations.	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods.	Representative data from only one site relevant for the market considered or some sites but from shorter periods.	Representativeness unknown or data from a small number of sites and from shorter period.
Precision	Measured / calculated and verified. Very low uncertainty (< 7%).	Measured / calculated / literature and plausibility checked by reviewer.	Measured / calculated / literature and plausibility not checked by reviewer	Qualified estimate based on calculations, plausibility	Rough estimate with known deficits.

			OR Qualified estimate based on calculations plausibility checked by reviewer.	not checked by reviewer.	
Methodological Appropriateness and Consistency	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact an in comparison to an ideal situation.
Overall Quality	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.

	Very good	Good	Fair	Poor	Very poor
Technological representativeness	Technology aspects have been modelled exactly as described in the title and metadata without any significant need for improvement	Technology aspects are very similar to what described in the title and metadata with need for limited improvements. For example: use of generic technologies' data instead of modelling all the single plants.	Technology aspects are similar to what described in the title and metadata but merits improvements. Some of the relevant processes are not modelled with specific data but using proxies.	Technology aspects are different from what described in the title and metadata. Requires major improvements.	Technology aspects are completely different from what described in the title and metadata. Substantial improvement is necessary
Time representativeness	The data (collection date) can be maximum 2 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the dataset.	The data (collection date) is older than 8 years with respect to the "reference year" of the dataset.
Geographical representativeness	The processes included in the dataset are fully representative for the geography stated in the "location" indicated in the metadata	The processes included in the dataset are well representative for the geography stated in the "location" indicated in the metadata	The processes included in the dataset are sufficiently representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.	The processes included in the dataset are only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different electricity grid mix	The processes included in the dataset are not representative for the geography stated in the "location" indicated in the metadata.
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Precision	Measured/calculated and verified. Very low uncertainty (< 7%)	Measured/calculated/ literature and plausibility checked by reviewer	Measured/calculated/ literature and plausibility not checked by reviewer	Qualified estimate based on calculations, plausibility not checked by reviewer	Rough estimate with known deficits

Figure 34 – Data Quality Pedigree Matrix in openLCA

Table 19 shows a comparison of the data quality analysis for the three projects studied in this thesis. TAFB had the highest data quality analysis project score because it was currently in construction at the time of data collection and the requested information was readily available, excluding the EPD. JBLM had the second highest score because it provided each equipment type and model as well as the actual EPD for the pavement material, despite being the oldest project. NASWI had the lowest score because the openLCA model was largely based on proxy data for the construction equipment and EPD. This data quality analysis could be considered slightly subjective as each researcher may assign the categories differently.

Table 19 – Data Quality Analysis Comparison

Category	Project Score		
	JBLM	NASWI	TAFB
Technological Representativeness	4	3	3
Time Representativeness	3	4	5
Geographical Representativeness	5	5	5
Completeness	4	3	4
Precision	3	2	4
Methodological Appropriateness and Consistency	3	3	4
Overall Quality	3.7	3.3	4.2

4 Results

This section presents a summary of each project’s calculated LCA impacts and categorized GWP results. A comparison of the two asphalt projects will be made as well as a presentation of the concrete LCA analysis. The asphalt and concrete projects are not compared to each other, which is explained further in section 5.

4.1 JBLM Results

In Table 20, the openLCA calculated environmental impacts of the pavement construction activities are displayed per short ton of asphalt. Figure 47, Figure 48, and Figure 49 exhibit calculated results for the GWP impact of this project normalized per short ton of asphalt, the total GWP for the whole project, and the specific percent contribution for all materials and equipment modeled, respectively. Additionally, Table 21 categorizes each material and type of equipment used in the environmental impact calculation into the following life cycle stages: material (A1 – A3), transportation (A4), and construction (A5), including both demolition and paving activities. These outcomes are shown graphically in Figure 50. Lastly, a Sankey diagram for this project is presented in Figure 35 to visually depict the flows and corresponding processes through the LCA stages for the global warming impact category.

Table 20 – JBLM TRACI 2.1 Impact Category Results per Short Ton

TRACI 2.1 Impact Category	Impact	Unit
Acidification	0.47	kg SO ₂ eq
Eutrophication	0.017	kg N eq
Freshwater ecotoxicity	9.64	CTUeco
Global warming	90.52	kg CO ₂ eq
Human health – cancer	7.76E-09	CTUcancer
Human health – non-cancer	7.18E-07	CTUoncancer
Human health – particulate matter	0.021	PM 2.5 eq
Ozone depletion	1.16E-07	kg CFC-11 eq
Smog formation	8.05	kg O ₃ eq

Table 21 – JBLM Categorized GWP Results

LCA Stage – Associated Equipment / Material	GWP (kg CO₂ eq) per Short Ton	Total GWP (kg CO₂ eq)	Percent Contribution
Material (A1) – HMA	34.33	698068	37.92%
Material (A2) – HMA	3.32	67511	3.67%
Material (A3) – HMA	19.41	394684	21.44%
Material (A1-A3) – Asphalt Emulsion	0.88	17947	0.98%
Transportation (A4) – HMA Trucking	2.47	50223	2.73%
Transportation (A4) – Asphalt Emulsion Trucking	0.0014	29	0.0016%
Construction (A5) – Grader	4.51	91690	4.98%
Construction (A5) – Loader	4.49	91203	4.95%
Construction (A5) – Milling Machine	3.71	75467	4.10%
Construction (A5) – Roller	2.99	60791	3.30%
Construction (A5) – Excavator	2.68	54569	2.96%
Construction (A5) – Water Truck	2.05	41757	2.27%
Construction (A5) – MTV	1.96	39804	2.16%
Construction (A5) – Vacuum Truck	1.87	37941	2.06%
Construction (A5) – Sweeper	1.78	36106	1.96%
Construction (A5) – Tack Truck	1.68	34155	1.86%
Construction (A5) – HMA Grooving Machine	1.07	21800	1.18%
Construction (A5) – Mini Excavator	0.72	14543	0.79%
Construction (A5) – Paver	0.61	12381	0.67%
<i>Grand Total</i>	<i>90.52</i>	<i>1840668</i>	<i>100.00%</i>

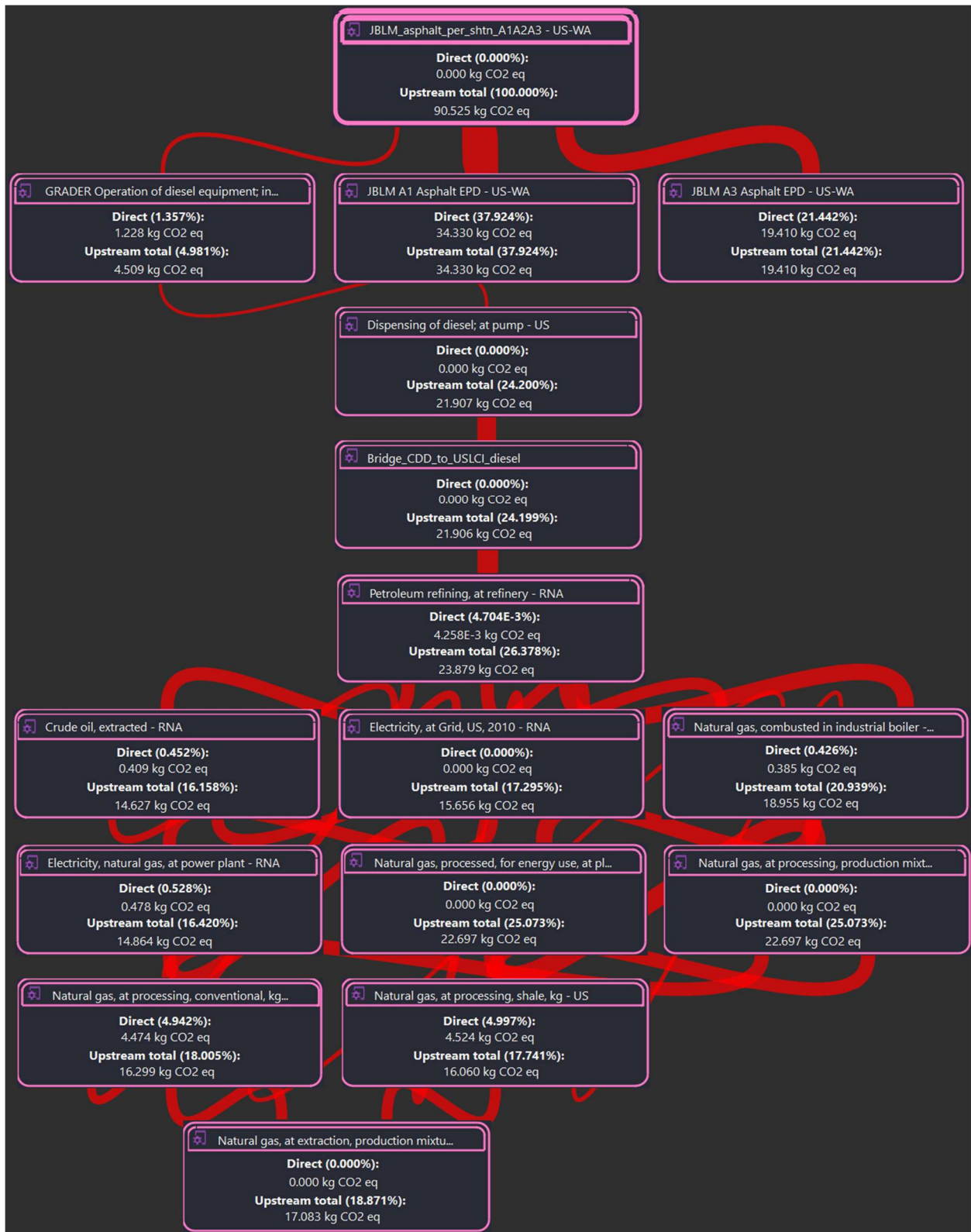


Figure 35 – JBLM GWP Sankey Diagram

4.2 NASWI Results

In Table 22, the openLCA calculated environmental impacts of the pavement construction activities are displayed per cubic yard of concrete. Figure 51, Figure 52, and Figure 53 exhibit calculated results for the GWP impact of this project normalized per cubic yard of concrete, the total GWP for the whole project, and the specific percent contribution for all materials and equipment modeled, respectively. Additionally, Table 23 categorizes each material and type of equipment used in the environmental impact calculation into the following life cycle stages: material (A1 – A3), transportation (A4), and construction (A5), including both demolition and paving activities. These outcomes are shown graphically in Figure 54. Lastly, a Sankey diagram for this project is presented in Figure 36 to visually depict the flows and corresponding processes through the LCA stages for the global warming impact category.

Table 22 – NASWI TRACI 2.1 Impact Category Results per Short Ton

TRACI 2.1 Impact Category	Impact	Unit
Acidification	0.92	kg SO ₂ eq
Eutrophication	0.039	kg N eq
Freshwater ecotoxicity	10.28	CTUeco
Global warming	202.85	kg CO ₂ eq
Human health – cancer	8.53E-09	CTUcancer
Human health – non-cancer	7.29E-07	CTUnoncancer
Human health – particulate matter	0.048	PM 2.5 eq
Ozone depletion	9.82E-06	kg CFC-11 eq
Smog formation	8.73	kg O ₃ eq

Table 23 – NASWI Categorized GWP Results

LCA Stage – Associated Equipment / Material	GWP (kg CO₂ eq) per Cubic Yard	Total GWP (kg CO₂ eq)	Percent Contribution
Material (A1) – PCC	157.53	277099	77.66%
Material (A1) – CDF	3.96	1318	1.95%
Material (A2) – PCC	1.60	2810	0.79%
Material (A2) – CDF	1.15	382	0.56%
Material (A3) – PCC	1.93	3402	0.95%
Material (A3) – CDF	0.72	241	0.36%
Transportation (A4) – Pavement Trucking	2.47	5167	1.22%
Construction (A5) – Loader	8.64	18083	4.26%
Construction (A5) – Vacuum Truck	6.55	13702	3.23%
Construction (A5) – Excavator	6.50	13603	3.21%
Construction (A5) – Roller	4.07	8507	2.00%
Construction (A5) – Concrete Saw	2.72	5692	1.34%
Construction (A5) – Dowel Drill	2.54	5320	1.25%
Construction (A5) – Screed	1.04	2176	0.51%
Construction (A5) – Mini Excavator	0.78	1630	0.38%
Construction (A5) – Concrete Vibrator	0.64	1345	0.32%
<i>Grand Total</i>	<i>202.85</i>	<i>360477</i>	<i>100.00%</i>

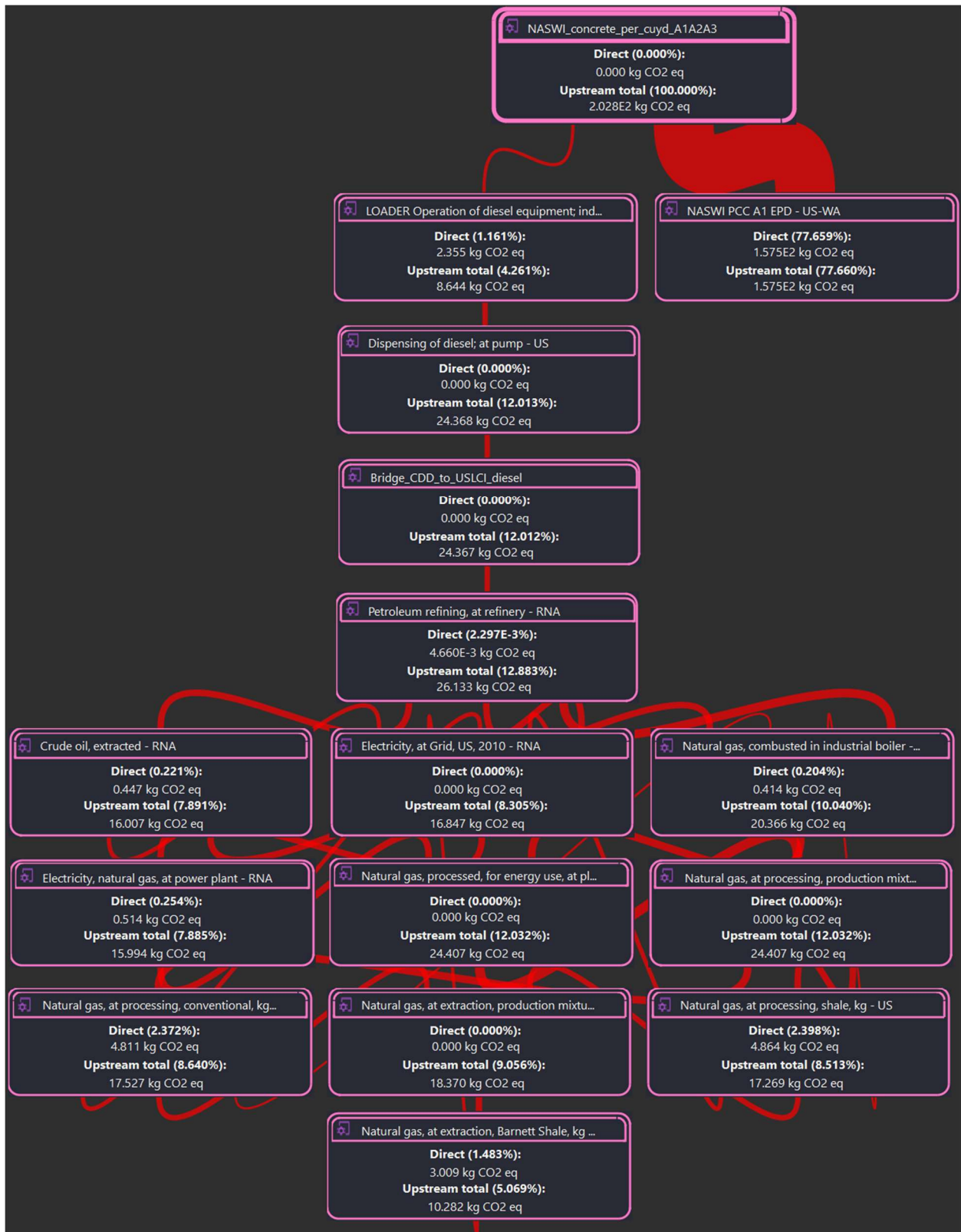


Figure 36 – NASWI GWP Sankey Diagram

4.3 TAFB Results

In Table 24, the openLCA calculated environmental impacts of the pavement construction activities are displayed per short ton of asphalt. Figure 55, Figure 56, and Figure 57 exhibit calculated results for the GWP impact of this project normalized per short ton of asphalt, the total GWP for the whole project, and the specific percent contribution for all materials and equipment modeled, respectively. Additionally, Table 25 categorizes each material and type of equipment used in the environmental impact calculation into the following life cycle stages: material (A1 – A3), transportation (A4), and construction (A5), including both demolition and paving activities. These outcomes are shown graphically in Figure 58. Lastly, a Sankey diagram for this project is presented in Figure 37 to visually depict the flows and corresponding processes through the LCA stages for the global warming impact category.

Table 24 – TAFB TRACI 2.1 Impact Category Results per Short Ton

TRACI 2.1 Impact Category	Impact	Unit
Acidification	1.06	kg SO ₂ eq
Eutrophication	0.042	kg N eq
Freshwater ecotoxicity	24.53	CTUeco
Global warming	154.21	kg CO ₂ eq
Human health – cancer	2.02E-08	CTUcancer
Human health – non-cancer	1.87E-06	CTUnoncancer
Human health – particulate matter	0.045	PM 2.5 eq
Ozone depletion	3.59E-07	kg CFC-11 eq
Smog formation	20.45	kg O ₃ eq

Table 25 – TAFB Categorized GWP Results

LCA Stage – Associated Equipment / Material	GWP (kg CO₂ eq) per Short Ton	Total GWP (kg CO₂ eq)	Percent Contribution
Material (A1) – HMA 9.5 NMAS	12.21	21434	7.92%
Material (A1) – HMA 12.5 NMAS	11.60	20284	7.52%
Material (A2) – HMA 9.5 NMAS	8.53	14968	5.53%
Material (A2) – HMA 12.5 NMAS	8.45	14782	5.48%
Material (A3) – HMA 9.5 NMAS	14.33	25160	9.29%
Material (A3) – HMA 12.5 NMAS	14.28	24979	9.26%
Material (A1-A3) – Asphalt Emulsion	3.25	6901	2.11%
Transportation (A4) – HMA Trucking	7.41	25971	4.81%
Transportation (A4) – Asphalt Emulsion Trucking	0.019	40	0.0122%
Construction (A5) – Loader	32.60	114252	21.14%
Construction (A5) – Excavator	13.91	48752	9.02%
Construction (A5) – Roller	9.17	32138	5.95%
Construction (A5) – Grader	7.73	27110	5.02%
Construction (A5) – Paver	5.81	20347	3.76%
Construction (A5) – Skid Steer	2.91	10205	1.89%
Construction (A5) – Water Truck	1.59	5559	1.03%
Construction (A5) – Tack Truck	0.42	1485	0.27%
<i>Grand Total</i>	<i>154.21</i>	<i>414368</i>	<i>100.00%</i>

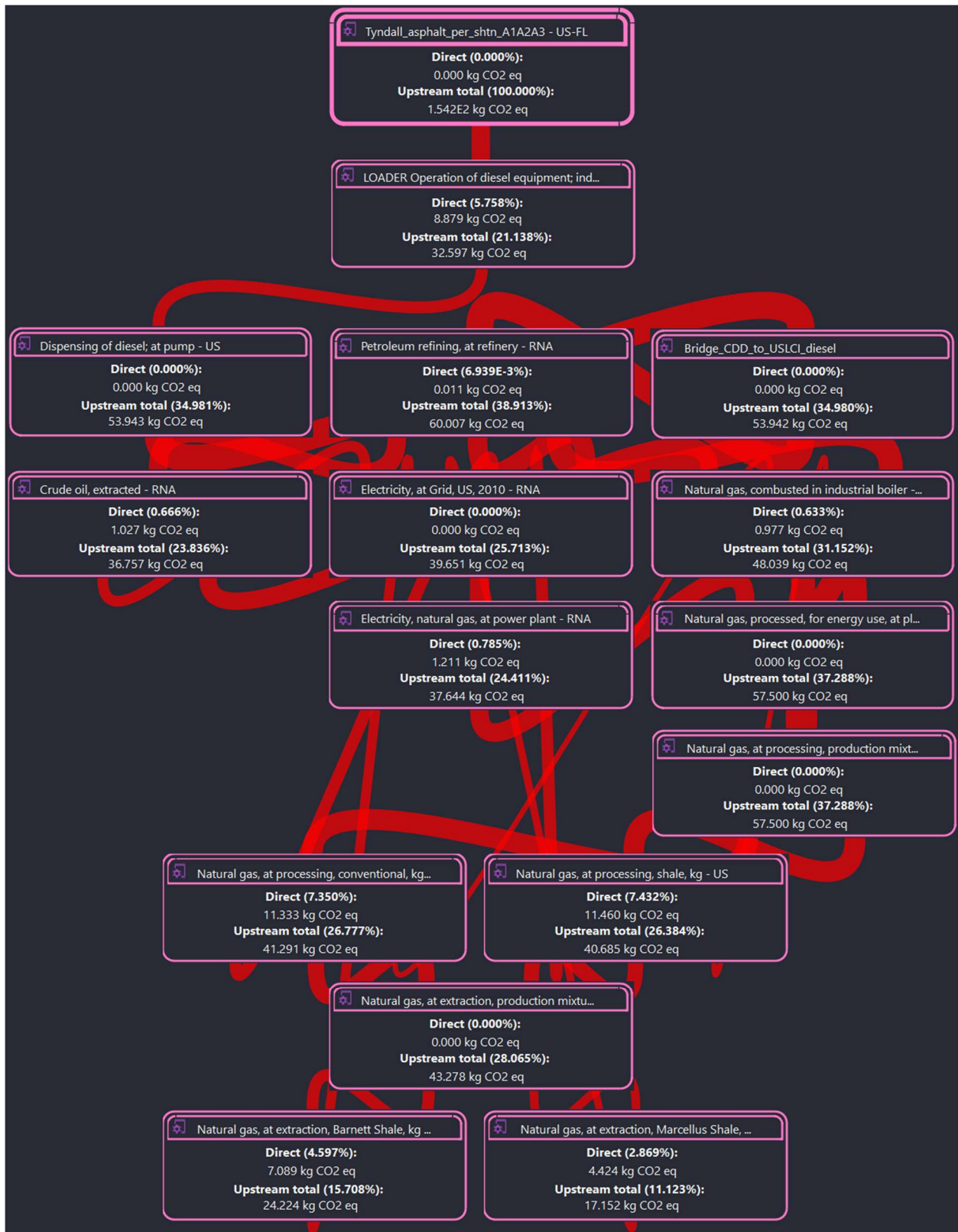


Figure 37 – TAFB GWP Sankey Diagram

4.4 Summary Results

This section outlines the correlations between asphalt projects and establishes a baseline for the concrete results. It should be noted, average values are not included because there is no value added in calculating a mean for two projects with dissimilar objectives. Tables 26 – 29 and Figures 38 – 41 summarize the asphalt comparisons for the calculated GWP impact for each project normalized per short ton of pavement, the total GWP for the entire project, the specific percent contribution for each material and equipment type modeled, and the overall evaluation by life cycle stage. Meanwhile, Tables 30 – 33 and Figures 42 – 45 present the concrete project totals for the calculated GWP impact normalized per cubic yard of pavement, the GWP for the entire project, the specific percent contribution for each material and equipment type modeled, and the overall evaluation by life cycle stage.

4.4.1 Asphalt Evaluation

Table 26 – GWP (kg CO₂ eq) per Short Ton of Asphalt Comparison

LCA stage – Associated Equipment / Material	GWP (kg CO ₂ eq) per Short Ton	
	JBLM	TAFB
Material (A1) – Pavement	34.33	23.80
Material (A2) – Pavement	3.32	16.98
Material (A3) – Pavement	19.41	28.61
Material (A1-A3) – Asphalt Emulsion	0.88	3.25
Transportation (A4) – Pavement Trucking	2.47	7.41
Transportation (A4) – Asphalt Emulsion Trucking	0.0014	0.0189
Construction (A5) – Excavator	2.68	13.91
Construction (A5) – Grader	4.51	7.73
Construction (A5) – HMA Grooving Machine	1.07	0.00
Construction (A5) – Loader	4.49	32.60
Construction (A5) – Milling Machine	3.71	0.00
Construction (A5) – Mini Excavator	0.72	0.00
Construction (A5) – MTV	1.96	0.00
Construction (A5) – Paver	0.61	5.81
Construction (A5) – Roller	2.99	9.17
Construction (A5) – Skid Steer	0.00	2.91
Construction (A5) – Sweeper	1.78	0.00
Construction (A5) – Tack Truck	1.68	0.42
Construction (A5) – Vacuum Truck	1.87	0.00
Construction (A5) – Water Truck	2.05	1.59
<i>Grand Total</i>	<i>90.52</i>	<i>154.21</i>

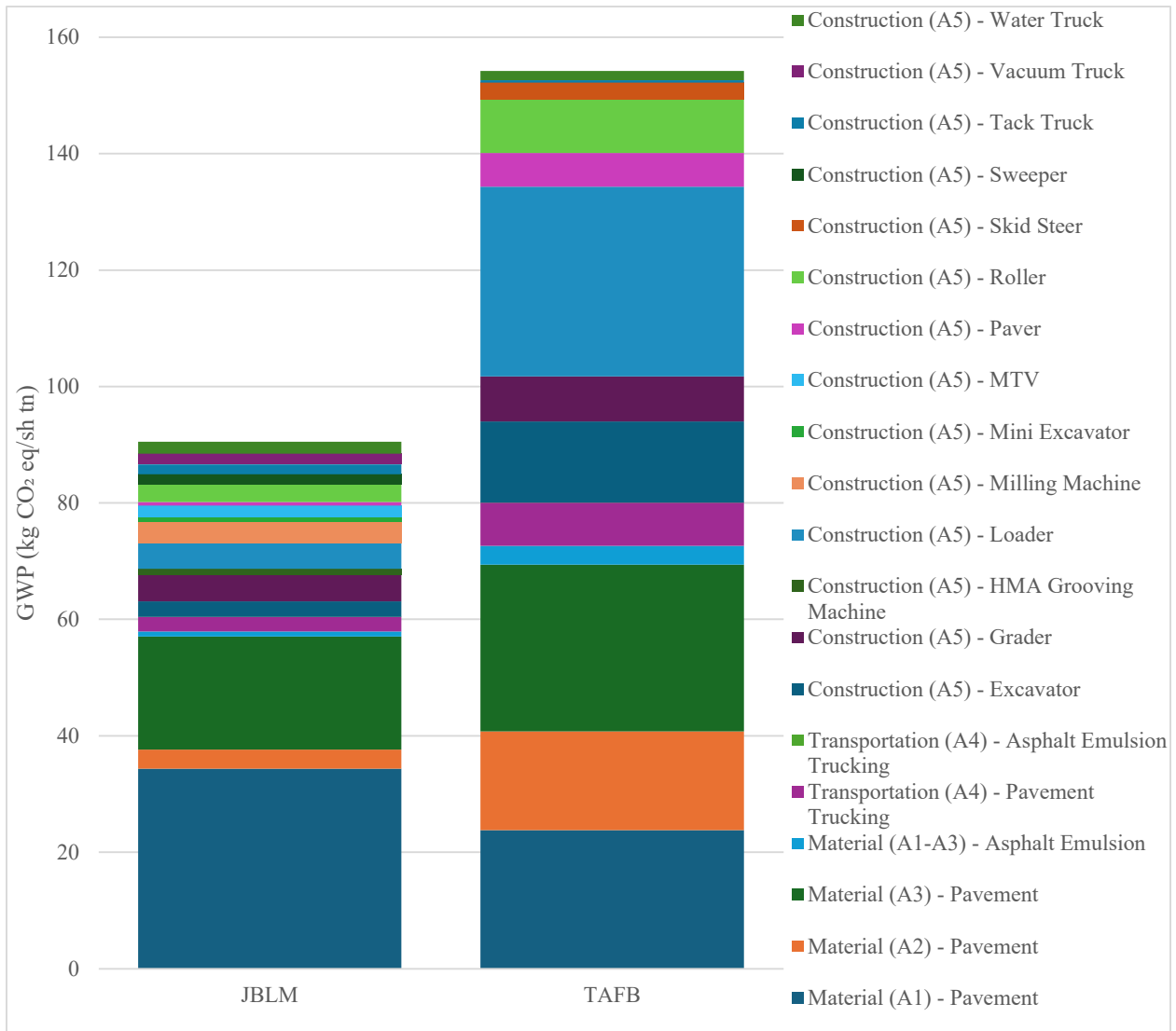


Figure 38 – GWP (kg CO₂ eq) per Short Ton of Asphalt Comparison

Table 27 – Asphalt Projects Total GWP (kg CO₂ eq) Comparison

LCA stage – Associated Equipment / Material	Total GWP (kg CO ₂ eq) per Project	
	JBLM	TAFB
Material (A1) – Pavement	698067.85	41717.73
Material (A2) – Pavement	67510.91	29749.99
Material (A3) – Pavement	394683.75	50139.87
Material (A1-A3) – Asphalt Emulsion	17946.99	6901.34
Transportation (A4) – Pavement Trucking	50223.15	25971.14
Transportation (A4) – Asphalt Emulsion Trucking	28.87	40.000
Construction (A5) – Excavator	54568.53	48752.34
Construction (A5) – Grader	91689.67	27110.05
Construction (A5) – HMA Grooving Machine	21800.28	0.00

Construction (A5) – Loader	91202.67	114251.68
Construction (A5) – Milling Machine	75466.79	0.00
Construction (A5) – Mini Excavator	14542.67	0.00
Construction (A5) – MTV	39803.60	0.00
Construction (A5) – Paver	12381.37	20346.88
Construction (A5) – Roller	60790.93	32137.80
Construction (A5) – Skid Steer	0.00	10204.88
Construction (A5) – Sweeper	36105.66	0.00
Construction (A5) – Tack Truck	34155.22	1485.00
Construction (A5) – Vacuum Truck	37941.21	0.00
Construction (A5) – Water Truck	41757.50	5559.35
<i>Grand Total</i>	<i>1840667.64</i>	<i>414368.05</i>

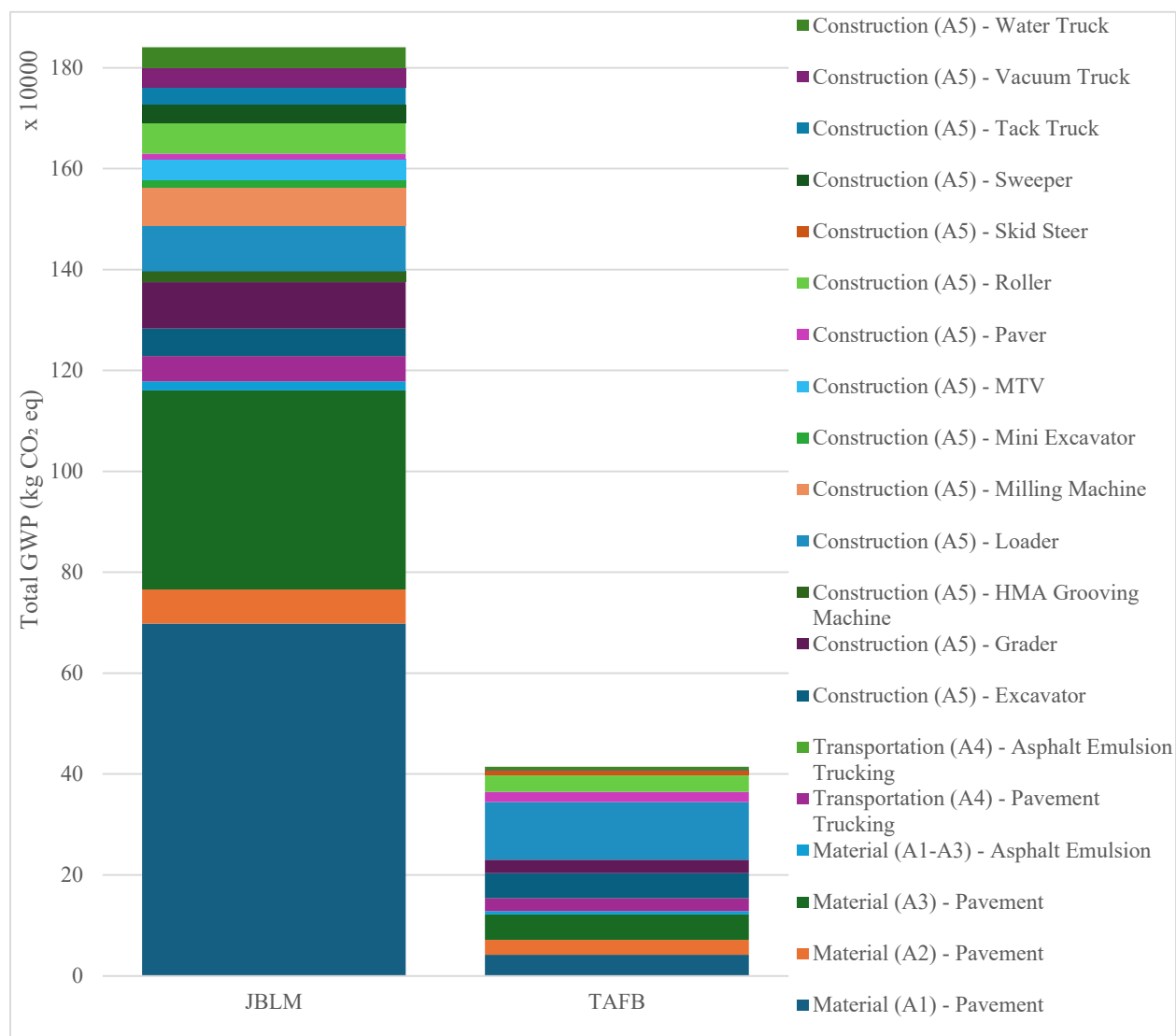


Figure 39 – Asphalt Projects Total GWP (kg CO₂ eq) Comparison

Table 28 – Asphalt GWP (kg CO₂ eq) Percent Contribution Comparison

LCA stage – Associated Equipment / Material	Percent Contribution per Project	
	JBLM	TAFB
Material (A1) – Pavement	37.92%	15.44%
Material (A2) – Pavement	3.67%	11.01%
Material (A3) – Pavement	21.44%	18.55%
Material (A1-A3) – Asphalt Emulsion	0.98%	2.11%
Transportation (A4) – Pavement Trucking	2.73%	4.81%
Transportation (A4) – Asphalt Emulsion Trucking	0.0016%	0.0122%
Construction (A5) – Excavator	2.96%	9.02%
Construction (A5) – Grader	4.98%	5.02%
Construction (A5) – HMA Grooving Machine	1.18%	0.00%
Construction (A5) – Loader	4.95%	21.14%
Construction (A5) – Milling Machine	4.10%	0.00%
Construction (A5) – Mini Excavator	0.79%	0.00%
Construction (A5) – MTV	2.16%	0.00%
Construction (A5) – Paver	0.67%	3.76%
Construction (A5) – Roller	3.30%	5.95%
Construction (A5) – Skid Steer	0.00%	1.89%
Construction (A5) – Sweeper	1.96%	0.00%
Construction (A5) – Tack Truck	1.86%	0.27%
Construction (A5) – Vacuum Truck	2.06%	0.00%
Construction (A5) – Water Truck	2.27%	1.03%
<i>Grand Total</i>	<i>100.00%</i>	<i>100.00%</i>

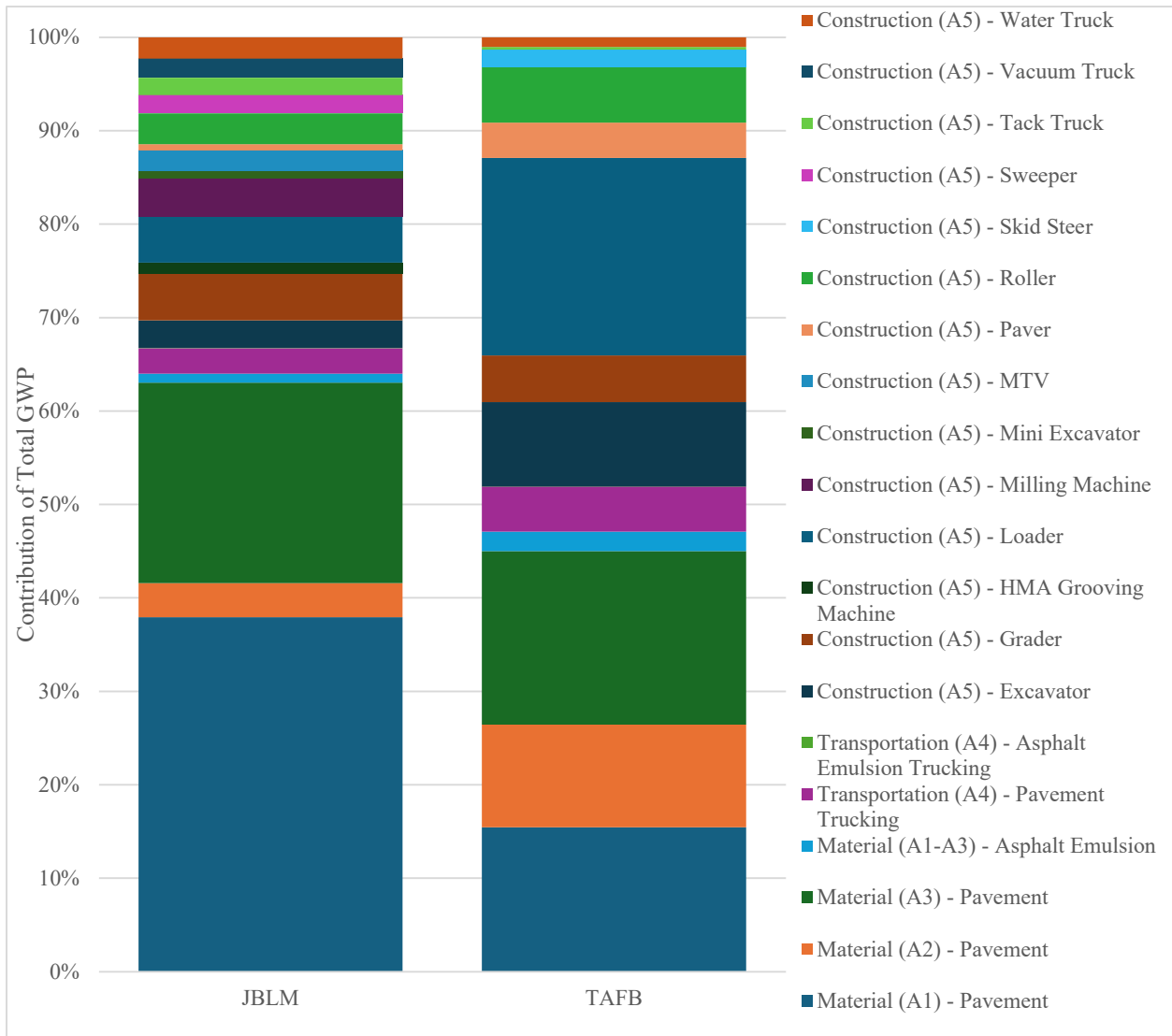


Figure 40 – Asphalt GWP (kg CO₂ eq) Percent Contribution Comparison

Table 29 – Asphalt GWP (kg CO₂ eq) by Life Cycle Stage Percent Contribution Comparison

Life Cycle Stage	JBLM	TAFB
Material (A1-A3)	64.01%	47.11%
Transportation (A4)	2.73%	4.82%
Construction (A5) – Demolition	6.48%	18.57%
Construction (A5) – Paving	26.78%	29.50%

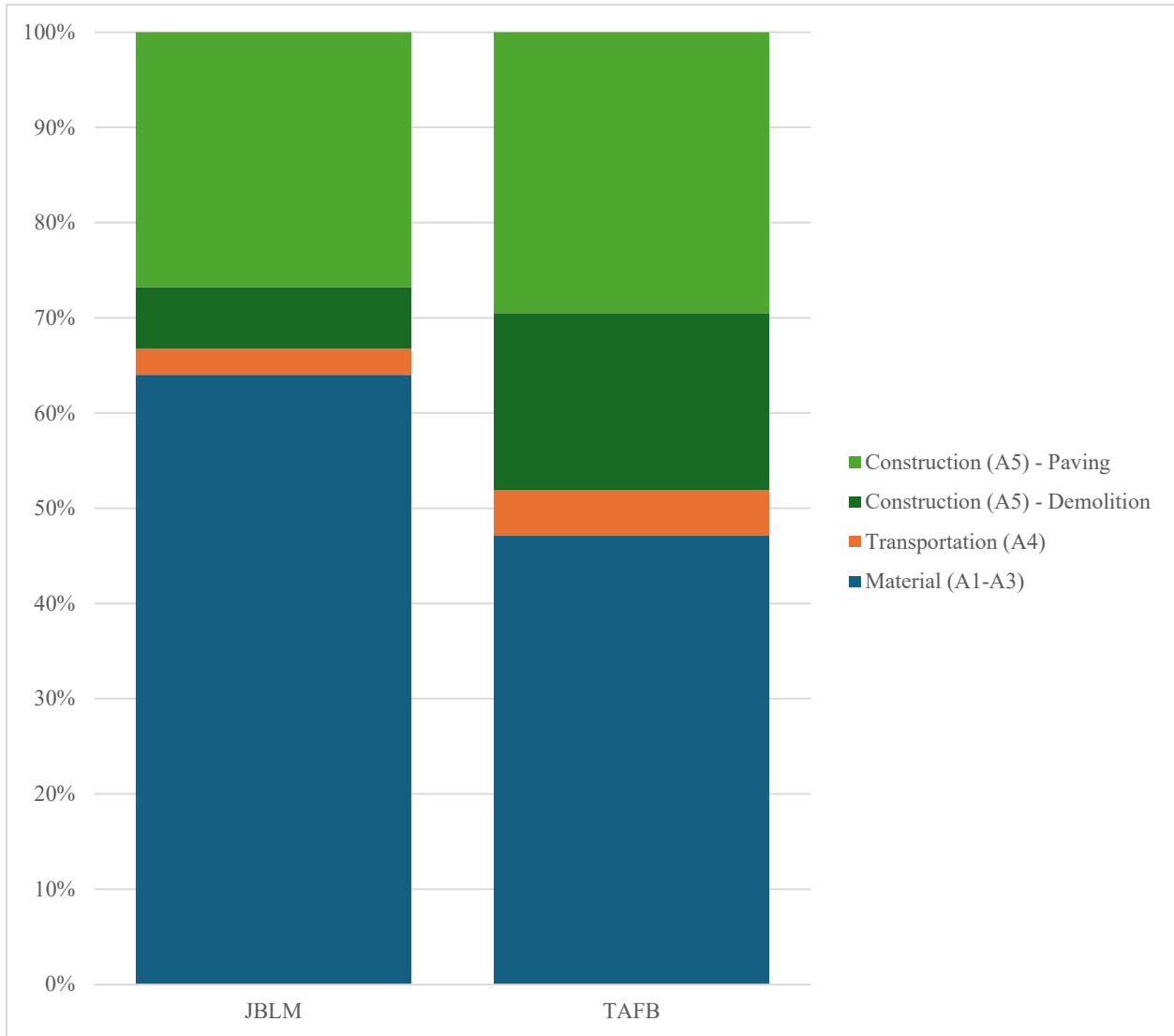


Figure 41 – Asphalt GWP (kg CO₂ eq) by Life Cycle Stage Percent Contribution Comparison

4.4.2 Concrete Evaluation

Table 30 – GWP (kg CO₂ eq) per Cubic Yard of Concrete Results

LCA stage – Associated Equipment / Material	GWP (kg CO ₂ eq) per Cubic Yard
	NASWI
Material (A1) – Pavement	161.49
Material (A2) – Pavement	2.74
Material (A3) – Pavement	2.66
Transportation (A4) – Pavement Trucking	2.47
Construction (A5) – Concrete Saw	2.72
Construction (A5) – Concrete Vibrator	0.64
Construction (A5) – Dowel Drill	2.54
Construction (A5) – Excavator	6.50

Construction (A5) – Loader	8.64
Construction (A5) – Mini Excavator	0.78
Construction (A5) – Roller	4.07
Construction (A5) – Screed	1.04
Construction (A5) – Vacuum Truck	6.55
<i>Grand Total</i>	<i>202.85</i>

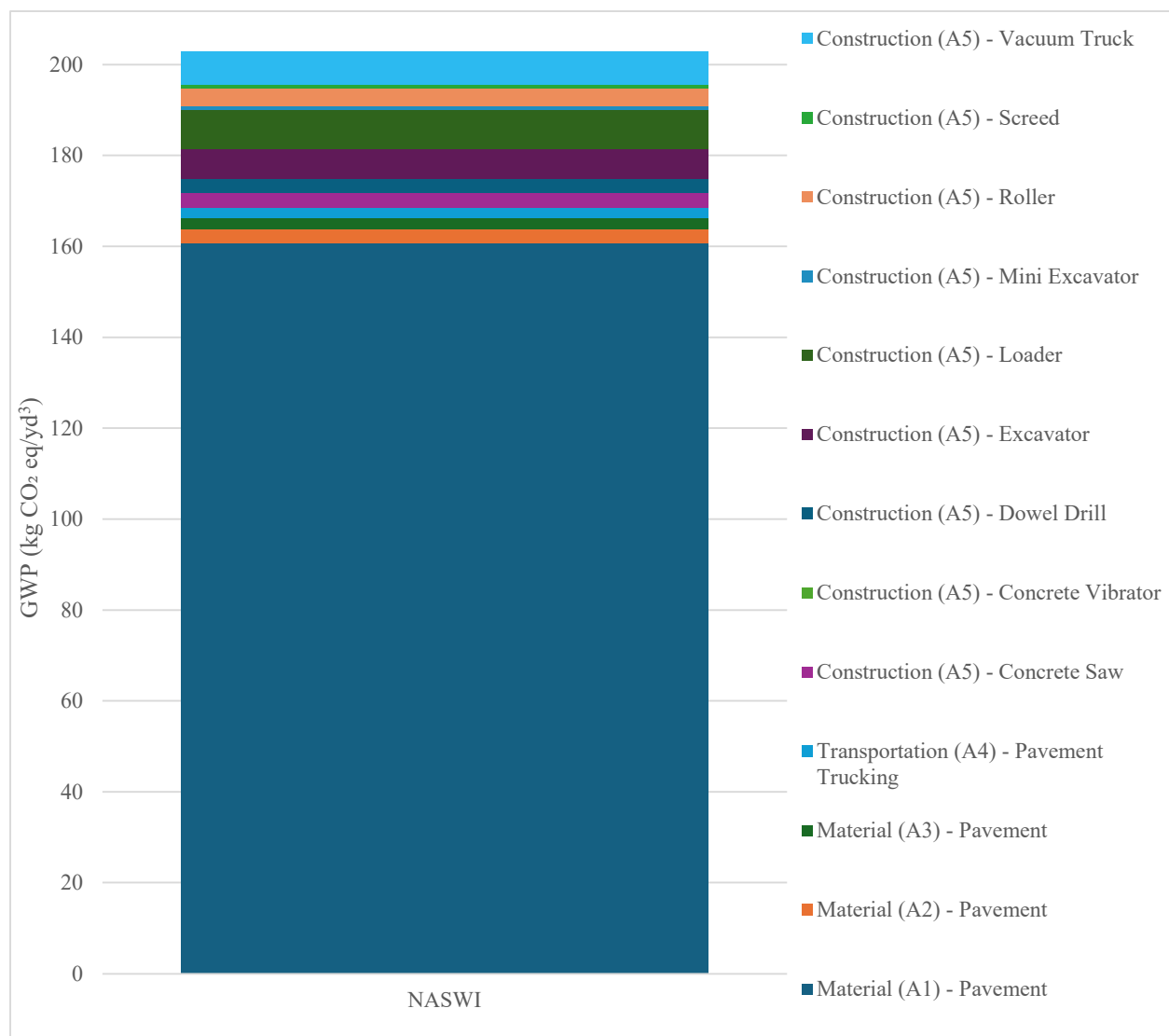


Figure 42 – GWP (kg CO₂ eq) per Cubic Yard of Concrete Results

Table 31 – Concrete Project Total GWP (kg CO₂ eq) Results

LCA stage – Associated Equipment / Material	Total GWP (kg CO ₂ eq)
	NASWI
Material (A1) – Pavement	278416.85
Material (A2) – Pavement	3191.75

Material (A3) – Pavement	3643.66
Transportation (A4) – Pavement Trucking	5167.05
Construction (A5) – Concrete Saw	5692.21
Construction (A5) – Concrete Vibrator	1345.37
Construction (A5) – Dowel Drill	5319.66
Construction (A5) – Excavator	13602.94
Construction (A5) – Loader	18083.21
Construction (A5) – Mini Excavator	1630.21
Construction (A5) – Roller	8506.78
Construction (A5) – Screed	2175.72
Construction (A5) – Vacuum Truck	13702.06
<i>Grand Total</i>	<i>360477.47</i>

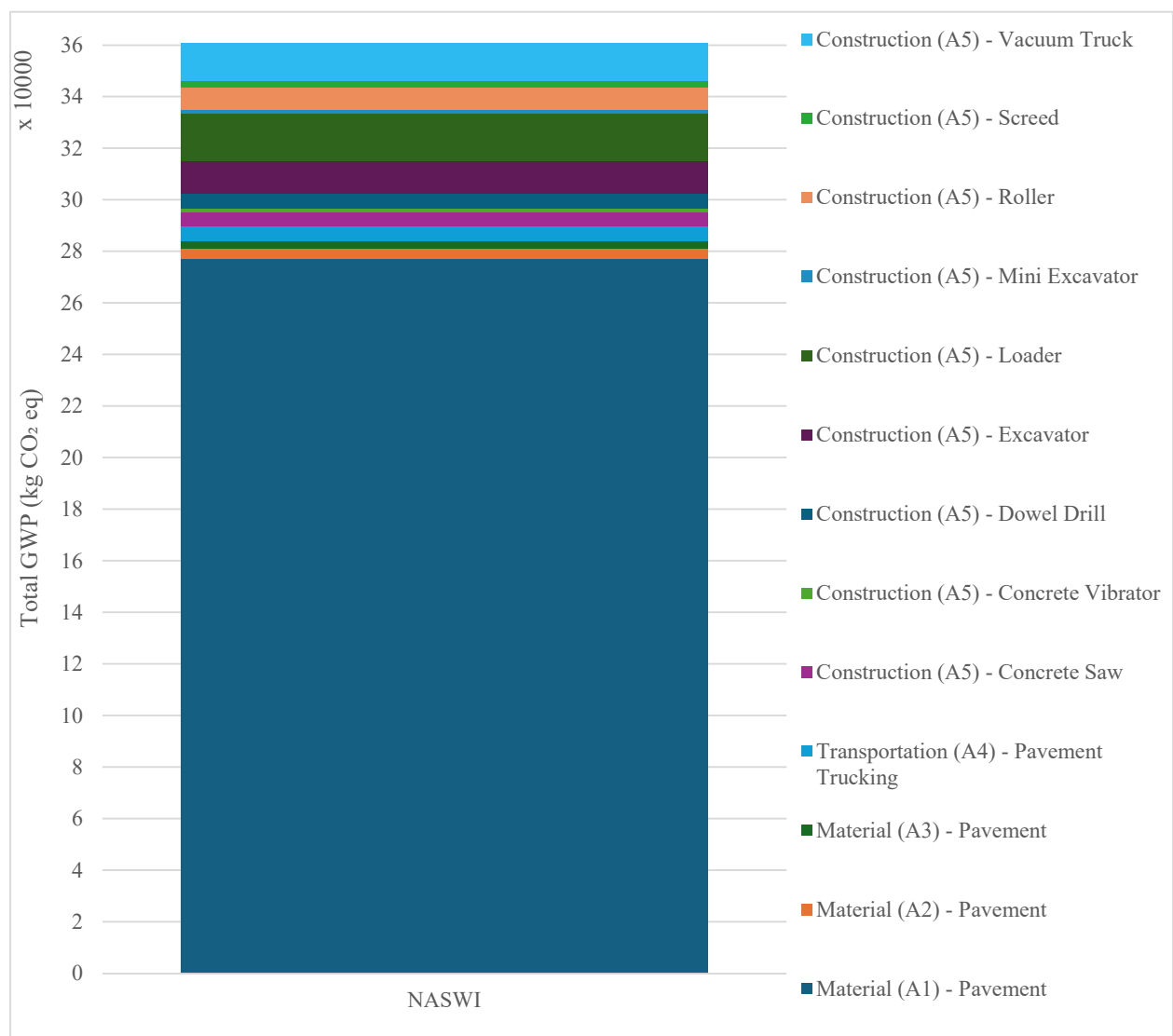


Figure 43 – Concrete Project Total GWP (kg CO₂ eq) Results

Table 32 – Concrete GWP (kg CO₂ eq) Percent Contribution Results

LCA stage – Associated Equipment / Material	Percent contribution
	NASWI
Material (A1) – Pavement	79.61%
Material (A2) – Pavement	1.35%
Material (A3) – Pavement	1.31%
Transportation (A4) – Pavement Trucking	1.22%
Construction (A5) – Concrete Saw	1.34%
Construction (A5) – Concrete Vibrator	0.32%
Construction (A5) – Dowel Drill	1.25%
Construction (A5) – Excavator	3.21%
Construction (A5) – Loader	4.26%
Construction (A5) – Mini Excavator	0.38%
Construction (A5) – Roller	2.00%
Construction (A5) – Screed	0.51%
Construction (A5) – Vacuum Truck	3.23%
<i>Grand Total</i>	<i>100.00%</i>

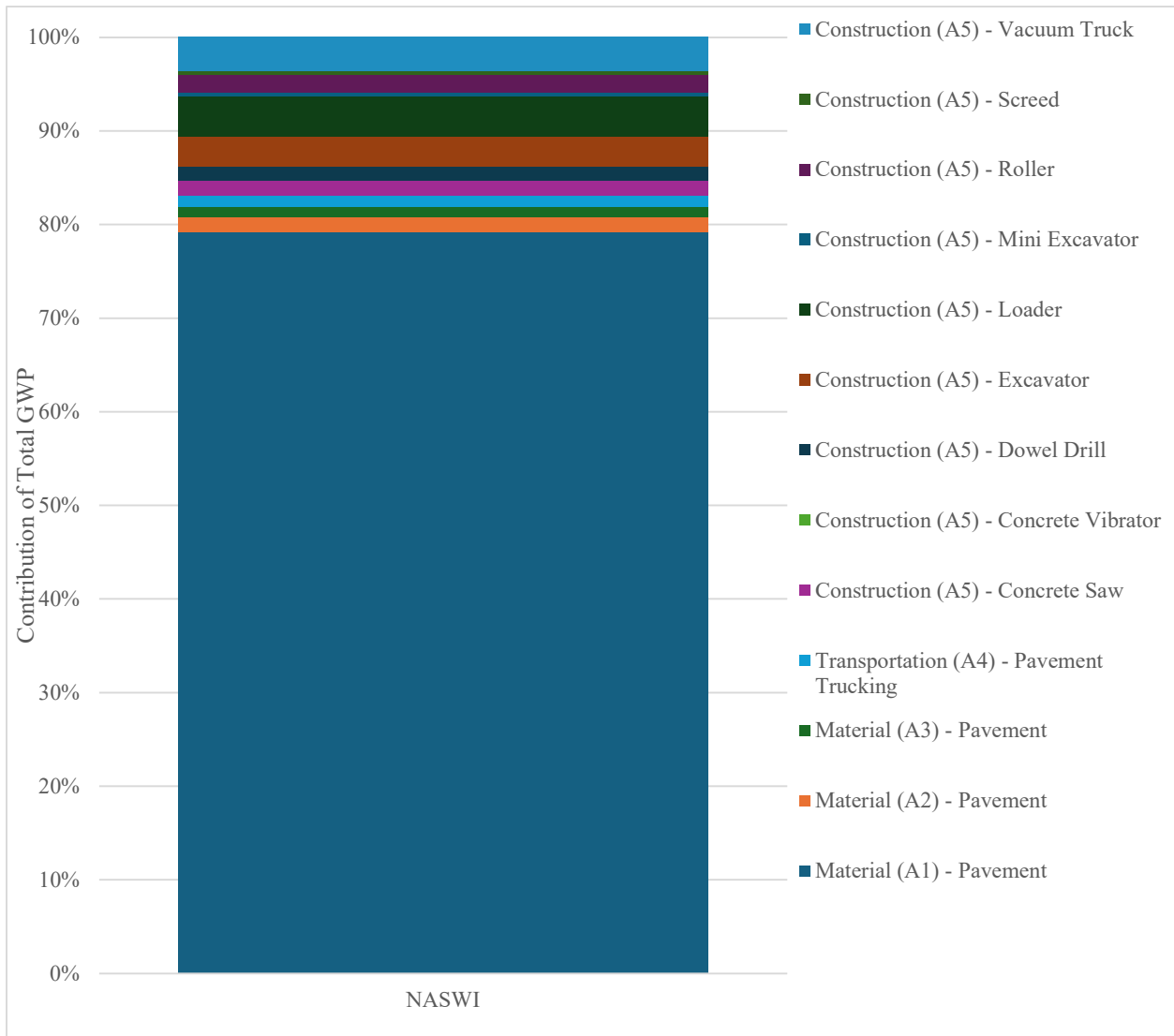


Figure 44 – Concrete GWP (kg CO₂ eq) Percent Contribution Results

Table 33 – Concrete GWP (kg CO₂ eq) by Life Cycle Stage Percent Contribution Results

Life Cycle Stage	NASWI
Material (A1-A3)	82.27%
Transportation (A4)	1.22%
Construction (A5) – Demolition	3.01%
Construction (A5) – Paving	13.50%

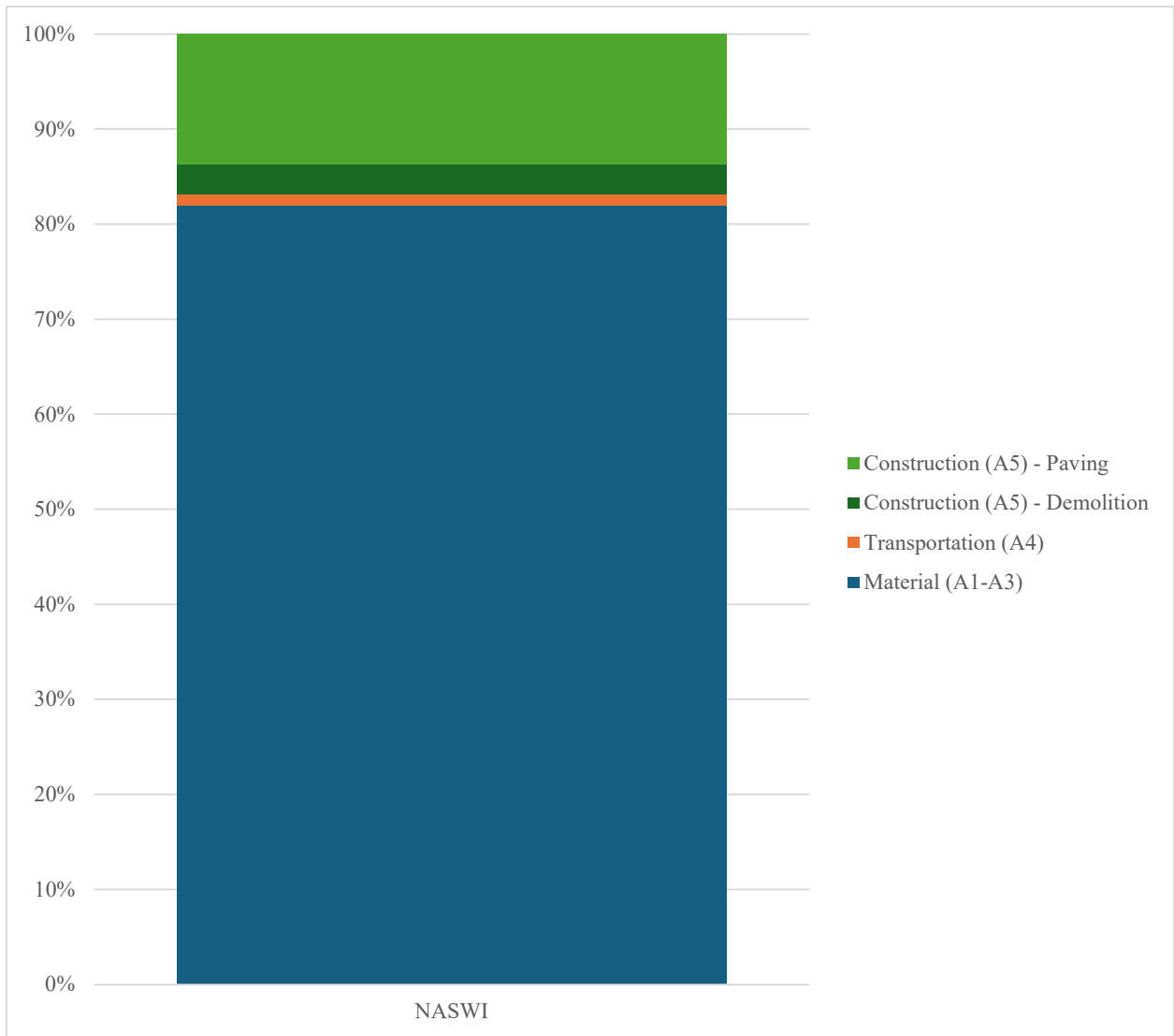


Figure 45 – Concrete GWP (kg CO₂ eq) by Life Cycle Stage Percent Contribution Results

5 Discussion

This section discusses contribution observations from each LCA stage for asphalt and concrete, separately. Comparisons to the WSDOT FHWA Climate Challenge Lum (2024) research conducted at the UW are made throughout the asphalt dialogue to demonstrate differences in environmental impacts based on various factors such as transportation distances and construction equipment decisions. Additionally, research limitations, data collection challenges, and model limitations are considered.

Asphalt and concrete observations are discussed independently due to the inappropriate nature of comparing LCAs with differing data sets, specifically EPDs in this thesis. From (Harvey and Butt 2023), a definition of what qualifications must be met to allow comparisons of EPDs in a procurement process are provided: "...ISO 14025:2006 requires the following be the same: product category definition, goal scope of the LCA that produced the EPD, inventory analysis, impact categories, reporting categories, provision of additional information, materials and substances, data collection, format for declaration, equivalency of stages and period of validity." Therefore, an EPD comparison is only valid if the underlying methods and information are the same, which excludes comparison of asphalt and concrete materials on the basis of an EPD. Additionally, the three selected projects are diverse in size and purpose, which presents a risk of drawing unfounded conclusions from comparison. These observations should not be used as rules of thumb in construction decision-making processes as further research is needed on similar projects to substantiate the results.

5.1 Asphalt Project Observations

Material production (A1 – A3) contributes the most to the GWP for both projects. As shown in Table 34, the HMA upstream material production impacts are 64% (JBLM) and 47% (TAFB). Stages A1 – A3 includes the HMA EPD data as well as the asphalt emulsions used for prime and tack coats. Notably, these results are consistent with previous research, which is discussed in section 5.1.2.1.

Construction (A5) is the second highest contributor to the GWP, including both demolition and paving activities. As shown in Table 34, the demolition impacts are 6.5% (JBLM) and 18.6% (TAFB) while paving impacts are 26.8% (JBLM) and 29.5% (TAFB). Stage A5 includes all known construction equipment emissions to complete the project scope, outside exceptions identified in section 3.3.2.

Transportation (A4) contributes the least to the GWP due to the minimal distance between the batch plant and the project site. As shown in Table 34, trucking impacts are 2.7% (JBLM) and 4.8% (TAFB). Stage A4 includes transportation of HMA and asphalt emulsion materials. Each stage is broken down further in the subsequent sections.

Table 34 – Asphalt LCA Stage Contribution

LCA Stage	JBLM	TAFB
Material (A1-A3)	64.01%	47.11%
Transportation (A4)	2.73%	4.82%
Construction (A5) – Demolition	6.48%	18.57%
Construction (A5) – Paving	26.78%	29.50%

5.1.1 WSDOT FHWA Climate Challenge Research Comparison

Since this thesis is based on the methods and LCA modeling process established in Lum (2024) for the WSDOT FHWA Climate Challenge research, a comparison of results broken down by life cycle stage is presented in Table 35. This analysis is also displayed graphically in Figure 46.

This thesis ranks GWP contributions from DOD airfield paving in the following order (from largest to smallest):

1. **Materials (A1 – A3)**
2. **Construction (A5)**
 - a. **Paving**
 - b. **Demolition**
3. **Transportation (A4)**

Comparatively, Lum (2024) ranks GWP contributions from WSDOT highway paving in the following order (from largest to smallest):

1. **Materials (A1 – A3)**
2. **Transportation (A4)**
3. **Construction (A5)**
 - a. **Paving**
 - b. **Demolition**

Each of the next three discussion sections on material (A1 – A3), transportation (A4) , and construction (A5) contributions are followed by a comparison to the results from Lum (2024).

Table 35 – Asphalt LCA Stage Comparison to WSDOT FHWA Climate Challenge Research

Life Cycle Stage	JBLM	TAFB	WSDOT 9914	WSDOT 9954	WSDOT XE3404	WSDOT XE3419
Material (A1-A3)	64.01%	47.11%	74.10%	65.08%	65.96%	81.00%
Transportation (A4)	2.73%	4.82%	15.95%	21.88%	21.15%	10.39%
Construction (A5) – Demolition	6.48%	18.57%	2.45%	4.40%	4.09%	2.81%
Construction (A5) – Paving	26.78%	29.50%	7.50%	8.64%	8.80%	5.80%

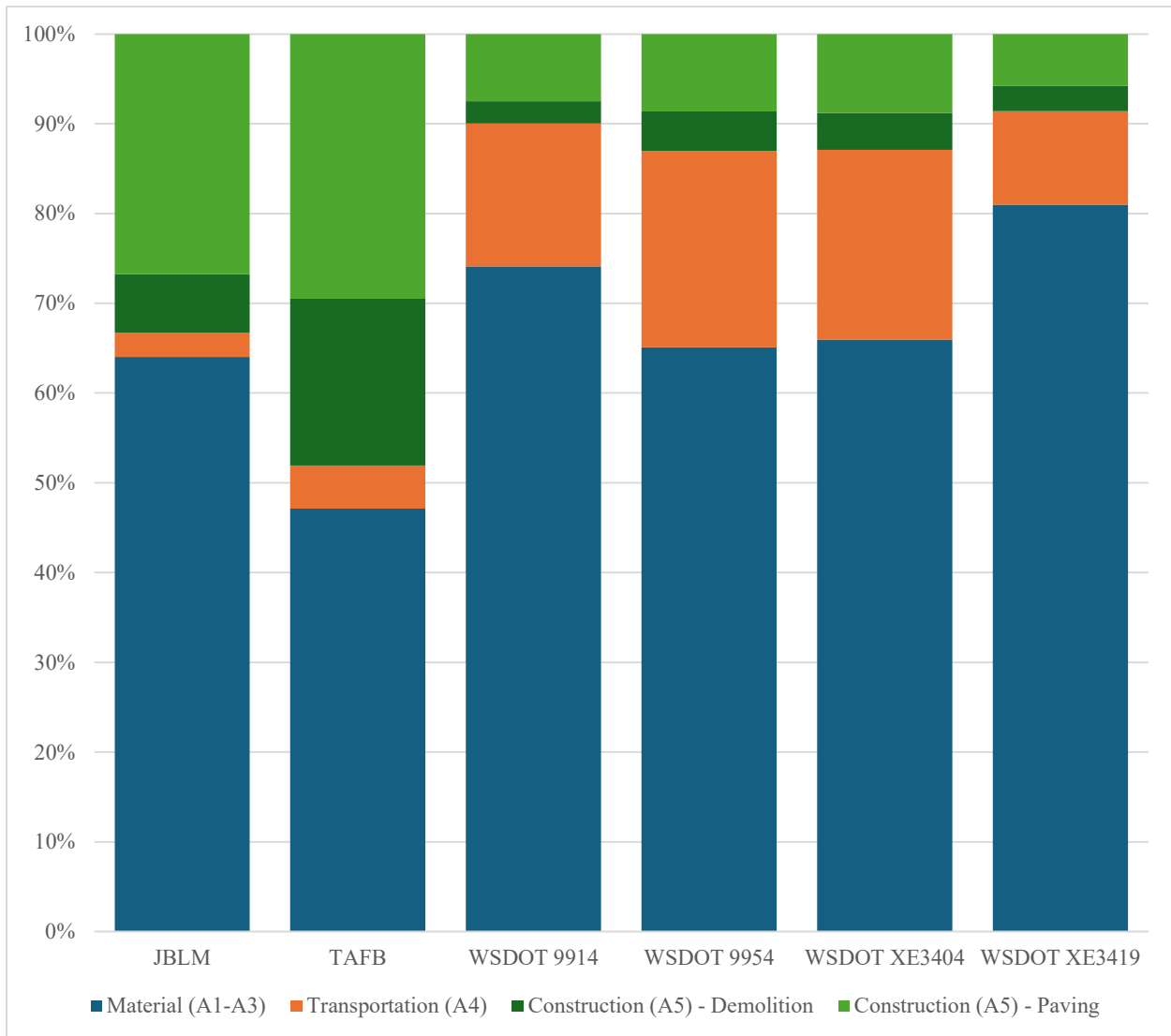


Figure 46 – Asphalt LCA Stage Comparison to WSDOT FHWA Climate Challenge Research

5.1.2 Material Contributions

JBLM’s highest contributor to material production is raw material extraction and manufacturing (A1) while TAFB’s highest contributor is HMA production and plant operations, extraction, refining, and transport of fuels (A3), as shown in Table 36.

Meanwhile, the inverse is true for the second highest contributor, meaning JBLM’s second is A3 and TAFB’s second is A1. These contributions are followed by transport of raw material to the asphalt plant (A2), and asphalt emulsion materials (A1 – A3).

Notably, TAFB’s A2 contributions are approximately five times higher than JBLM’s due to a lack of locally available airfield-quality aggregate in Florida compared to Washington State. This significant A2 result is consistent with the NAPA EPD Benchmark study, which identifies Florida as a state with far greater transport impacts than the national average (Miller et al. 2024).

Table 36 – Asphalt Material (A1-A3) GWP (kg CO₂ eq) per Short Ton of Asphalt Pavement and Percent Contribution Comparison by Product

LCA Stage – Product	GWP (kg CO ₂ eq) per Short Ton		Percent Contribution	
	JBLM	TAFB	JBLM	TAFB
Material (A1) – Pavement	34.33	23.80	37.92%	15.44%
Material (A2) – Pavement	3.32	16.98	3.67%	11.01%
Material (A3) – Pavement	19.41	28.61	21.44%	18.55%
Material (A1-A3) – Asphalt Emulsion	0.88	3.25	0.98%	2.11%

Table 37 compares the GWP per short ton of asphalt for each mix design used, one for the entire JBLM project and one for each lift of the TAFB project, based on three factors: RAP content, virgin percent asphalt binder, and NMAS. From this limited comparison, **the asphalt binder content (by weight of the total mix) has a large influence on HMA overall emissions.** The JBLM HMA mix has the highest percent binder at 5.7%, the lowest RAP content at 0%, and the highest GWP per short ton of mix at 57.06 kg CO₂ eq. Alternatively, the TAFB HMA Mix 1 (used for the first lift of asphalt pavement) has the lowest virgin percent binder at 3.5%, a higher RAP content at 30%, and the lowest GWP per short ton of mix at 34.32 kg CO₂ eq. Both of these mixes used the same NMAS. This difference in GWP could be attributed to the higher RAP content because there is already an asphalt binder on the RAP that contributes to the total asphalt binder content, requiring less virgin asphalt binder (approximately 2% less in this case). When comparing the two TAFB asphalt mixes, which have the same RAP content, Mix 2 has a slightly higher GWP because the smaller NMAS requires more asphalt binder to cover the aggregate in the mix design. However, TAFB experiences the higher overall GWP per short ton of asphalt at 69.39 kg CO₂ eq because both Mix 1 and 2 were used on the project and must be summed.

Table 37 – HMA Mix Design Comparison

Mix Design Factor	Average	JBLM Mix	TAFB Mix 1	TAFB Mix 2
RAP Content (%)	20	0	30	30
Virgin Percent Binder (Pb, %)	4.3	5.7	3.5	3.8
NMAS (inches)	1/2	1/2	1/2	3/8
GWP (kg CO ₂ eq) per short ton	42.15	57.06	34.32	35.06

5.1.2.1 Material Comparison to WSDOT FHWA Climate Challenge Research

Material production (A1 – A3) GWP percent contributions are lower on average for the DOD projects in comparison to the WSDOT projects. Since the construction contributions are significantly higher on these airfield projects than the highway projects, it is expected that the DOD materials would contribute less on a percentage basis for the total life cycle than the WSDOT materials (as shown in Figure 46).

However, **these asphalt mixtures produced similar GWP contributions when compared based on mix design factors**, as shown in Table 38. JBLM’s GWP per short ton of asphalt is slightly higher than the WSDOT average at approximately 57 kg CO₂ eq, which could be attributed to the lack of RAP in the mix design and the higher percentage of binder. Alternatively, TAFB’s GWP per short ton of asphalt, which is a sum of the two mixes used in the project, is the highest of all mix designs included. This is due to the use of more than one mix design as separately the GWP contributions per short ton are the lowest values at 34.3 and 35.1 kg CO₂ eq relative to Mix 1 and 2 (as shown in Table 37).

Table 38 – HMA Mix Design Comparison with WSDOT Projects

Mix Design Factor	JBLM	TAFB	WSDOT 9914	WSDOT 9954	WSDOT XE3404	WSDOT XE3419
RAP Content (%)	0	30	20	39	18	19
Virgin Percent Binder (Pb, %)	5.7	3.5 & 3.8	5.4	3.4	5.5	5.3
NMAS (inches)	1/2	1/2 & 3/8	3/8	1/2	1/2	3/8
GWP (kg CO ₂ eq) per short ton	57.06	69.39	58.43	41.44	49.53	56.71

5.1.3 Transportation Contributions

HMA trucking (A4) contributes 4.94 kg CO₂ eq per short ton of asphalt on average and approximately 0.412 kg of CO₂ eq per short ton of asphalt for every mile the material was hauled. Transportation of materials is the lowest contributor to the project’s overall GWP impact, which includes calculations for the distance from the asphalt plant to the project’s site and the total amount of HMA used on the project. From Table 39, the contribution from material transportation accounts for 2.7% – 4.8% of the project’s total emissions. Since transport of emulsion is nearly negligible towards GWP, it could be excluded from future LCA calculations.

Table 39 – Transportation (A4) GWP (kg CO₂ eq) per Short Ton of Asphalt Pavement and Percent Contribution Comparison by Activity

LCA Stage – Activity	GWP (kg CO ₂ eq) per Short Ton		Percent Contribution	
	JBLM	TAFB	JBLM	TAFB
Transportation (A4) – Pavement Trucking	2.47	7.41	2.73%	4.81%
Transportation (A4) – Asphalt Emulsion Trucking	0.0014	0.0189	0.0016%	0.0122%

5.1.3.1 Transportation Comparison to WSDOT FHWA Climate Challenge Research

When comparing transportation (A4) contributions, this thesis calculates significantly lower carbon emissions than the WSDOT research because of the shorter haul distances.

However, the measured GWP per mile trucked values are equivalent at 0.412 kg of CO₂ eq per short ton of asphalt. JBLM’s pavement trucking distance is 6 miles while TAFB’s transportation distance is 18 miles. Comparatively, the WSDOT trucking distances for pavement are 32 miles, 35 miles, 40 miles, and 18 miles respective to projects 9914, 9954, XE3404, and XE3419. Since the distance traveled in the DOD projects is less than half of the distance traveled for the WSDOT projects on average, it is logical that HMA trucking contributes 4.94 kg CO₂ eq versus 12.8 kg CO₂ eq per short ton of asphalt, respectively. WSDOT asphalt emulsion trucking also has an insignificant impact to the GWP at an average of 0.083 kg CO₂ eq per short ton of asphalt, which is consistent with the results from this thesis.

5.1.4 Construction Contributions

Construction operations (A5) are the second highest contributor at approximately 33% and 48% of the project’s GWP impact for JBLM and TAFB, respectively. These calculated results are displayed in Table 40, organized by equipment type. Table 29 and Figure 41 provide the established boundary for demolition versus paving.

Table 40 – Construction (A5) GWP (kg CO₂ eq) per Short Ton of Asphalt Pavement and Percent Contribution Comparison by Equipment Type

LCA Stage – Equipment	GWP (kg CO ₂ eq) per Short Ton		Percent Contribution	
	JBLM	TAFB	JBLM	TAFB
Construction (A5) – Excavator	2.68	13.91	2.96%	9.02%
Construction (A5) – Grader	4.51	7.73	4.98%	5.02%
Construction (A5) – HMA Grooving Machine	1.07	0.00	1.18%	0.00%
Construction (A5) – Loader	4.49	32.60	4.95%	21.14%
Construction (A5) – Milling Machine	3.71	0.00	4.10%	0.00%
Construction (A5) – Mini Excavator	0.72	0.00	0.79%	0.00%
Construction (A5) – MTV	1.96	0.00	2.16%	0.00%
Construction (A5) – Paver	0.61	5.81	0.67%	3.76%
Construction (A5) – Roller	2.99	9.17	3.30%	5.95%
Construction (A5) – Skid Steer	0.00	2.91	0.00%	1.89%
Construction (A5) – Sweeper	1.78	0.00	1.96%	0.00%
Construction (A5) – Tack Truck	1.68	0.42	1.86%	0.27%
Construction (A5) – Vacuum Truck	1.87	0.00	2.06%	0.00%
Construction (A5) – Water Truck	2.05	1.59	2.27%	1.03%

5.1.4.1 Construction Comparison to WSDOT FHWA Climate Challenge Research

Construction (A5) contributions are 3 – 4 times higher for the DOD projects than the WSDOT average. This could be attributed to the equipment used for the demolition phase, the extra activities required for airfield construction, and the differing purposes of each project.

WSDOT’s demolition activities consists of only the milling machine’s contributions (100%) while this research’s demolition varies by project (see section 3.2.1.3 and section 3.2.3.3). Paving contributions are also higher for both DOD projects in comparison to the WSDOT projects. TAFB was intended to be a training project for 823 RHS craftsmen, which inherently led to increased equipment operations hours as well as time to complete the project because the focus was on building competency rather than expediting the construction timeline. Meanwhile, the WSDOT and JBLM projects were constructed by general contractors who were selected to perform the work based on paving expertise. Notably, the JBLM data is of lower data quality as discussed in section 3.4. Construction operations on an active airfield would also increase emissions for JBLM due to added requirements for sweeping and vacuuming to eliminate the risk of FOD.

5.2 Concrete Project Observations

Material production (A1 – A3), specifically the concrete mixture, contributes the most to the GWP for this project. As shown in Table 33, the concrete upstream material production impacts are 82.3% of the total project emissions. Stages A1 – A3 include the EPD data for both the PCC and the CDF.

Construction (A5) is the second highest contributor to the GWP, including both demolition and paving activities. As shown in Table 33, the demolition impacts are 3.0% while the paving impacts are 13.5%. Stage A5 includes all known construction equipment emissions to complete the project scope, outside exceptions identified in section 3.3.2.

Transportation (A4) contributes the least to the GWP due to the minimal distance between the batch plant and project site. As shown in Table 33, trucking impacts are 1.2%. Stage A4 includes transportation of PCC and CDF materials. Each stage is broken down further in the subsequent sections.

5.2.1 Material Contributions

NASWI’s highest contributor to material production is raw material extraction and upstream production (A1), as shown in Table 41. The significant 80% A1 contribution is followed by transport to the factory (A2) and manufacturing (A3), which are nearly equivalent at 1.35% and 1.31%, respectively. Since cement production is included in A1, these results are consistent with typical industry expectations.

Table 41 – Material (A1-A3) Baseline by Product

LCA Stage – Product	GWP (kg CO ₂ eq) per Cubic Yard	Percent Contribution
Material (A1) – Pavement	161.49	79.61%
Material (A2) – Pavement	2.74	1.35%
Material (A3) – Pavement	2.66	1.31%

5.2.2 Transportation Contributions

Concrete trucking (A4) contributes 2.47 kg CO₂ eq per cubic yard of pavement and approximately 0.412 kg of CO₂ eq per cubic yard of pavement for every mile the material was hauled. Transportation of materials is the lowest contributor to the project’s overall GWP impact, which includes calculations for the distance from the concrete batch plant to the project’s site and the total amount of PCC and CDF used on the project. From Table 42, the material transportation contribution accounts for 1.2% of the project’s total emissions.

Table 42 – Transportation (A4) Baseline by Activity

LCA Stage – Activity	GWP (kg CO ₂ eq) per Cubic Yard	Percent Contribution
Transportation (A4) – Pavement Trucking	2.47	1.22%

5.2.3 Construction Contributions

Construction operations (A5) are the second highest contributor at approximately 16.5% of the project’s GWP impact. These calculated results are displayed in Table 43, organized by equipment type. Table 33 and Figure 45 provide the established boundary for demolition versus paving, which attribute 3.0% and 13.5%, respectively, to the overall GWP.

Table 43 – Construction (A5) Baseline by Equipment Type

LCA Stage – Equipment	GWP (kg CO ₂ eq) per Cubic Yard	Percent Contribution
Construction (A5) – Concrete Saw	2.72	1.34%
Construction (A5) – Concrete Vibrator	0.64	0.32%
Construction (A5) – Dowel Drill	2.54	1.25%
Construction (A5) – Excavator	6.50	3.21%
Construction (A5) – Loader	8.64	4.26%
Construction (A5) – Mini Excavator	0.78	0.38%
Construction (A5) – Roller	4.07	2.00%
Construction (A5) – Screed	1.04	0.51%
Construction (A5) – Vacuum Truck	6.55	3.23%

5.4 Research Limitations

DOD airfield paving decision-making processes should not be based solely on this research due to the limited data collected. If additional funding and time was available, it would be important to seek buy-in from a variety of military installations to receive more data points on both concrete and asphalt pavement construction projects. Recommendations for this practice will be discussed further in section 6.2. Outside data availability constraints to fuel this research, limitations were encountered in the data collection and modeling stages.

5.4.1 Data Collection Challenges

The main obstacle for the data collection process is from the five principle materials analyzed in the three projects, only one provided an EPD. It was difficult to find a matching proxy EPD for the four other materials (e.g., one with similar asphalt binder percentage, RAP, and cement content). The proxy EPDs likely do not match the actual mix production data, meaning conclusions drawn involving those projects are tentative at best. EPDs are highly influential on the GWP for each project since material production contributes the most to the project's overall emissions. Comparisons of the actual project material to the proxy EPD used are listed in sections 3.3.2.2 and 3.3.2.3, respective to NASWI and TAFB.

Differences in granularity of information provided by the project managers or general contractor was another difficulty faced. Each project had a different method for communicating operation hours, fuel consumption, total material volumes, etc., which absorbed a significant portion of time to organize and analyze into a uniform research portfolio. It was also not possible to verify the authenticity of reported equipment use hours and fuel consumption. This may have increased construction (A5) contributions due to inflated idle time. Methods adopted to overcome this hurdle are described in section 3.3.2.

Typical operational airfield repair and maintenance requirements outside of paving such as installing airfield lighting, paint markings, and sodding are outside the scope of this thesis. Since this research focuses on embodied carbon in pavements, other activities, which were in the scope of each project not related to paving are not prioritized. EPDs for materials included in these activities largely do not exist, which would hinder the modeling process. Although contract line items additional to paving are not approached in this thesis, it is not out of the realm of possibilities for future research, which is discussed in section 6.3.

5.4.2 Model Limitations

The FHWA Pavement Life Cycle Assessment Background Data Repository limits the precision of the model for equipment engine sizes and trucking contribution calculations. Most diesel engine sizes fell within the 56 – 560 kW range in the repository, which is quite large. All equipment in the same category is considered to have the same emissions, only varying by fuel consumption. For example, the milling machine with a 537 kW engine is treated the same as the roller with a 63 kW engine. Additionally, transportation (A4) contributions are calculated based on the volume of material by travel distance (units of ton-miles), not by direct fuel consumption as the construction (A5) contributions are calculated. The three projects studied in this research did not use truck double-cycling (the act of hauling material to the jobsite and transferring material back to the plant in one trip) as experienced in Lum (2024). Therefore, it was not a modeling limitation that openLCA cannot consider double-cycling in calculations.

5.4.3 Uncertainty Analysis

Uncertainty analysis was not considered in this study to maintain consistency with Lum (2024). An inherent uncertainty is associated with all data due to the nature of accepting project data from various sources with differing collection methods. However, that is not justification to manufacture uncertainty. Due to this reasoning, underlying uncertainty was not explicitly expressed, and all final results are presented as exact numbers despite ambiguity associated with the data quality and processing. As noted in Lum (2024), if decisions in the LCA process follow an agreed upon manner, the uncertainty of each separate study should be similar and, therefore, are already accounted for by the process itself.

6 Conclusion and Recommendations

In this thesis, the research question addressed is: “*What are the GHG emissions associated with material production, transportation to the jobsite, and construction operations for airfield paving on DOD installations?*” Three DOD airfield paving projects, two asphalt and one concrete, were selected to provide information on material acquisition, pavement production, material transportation from the plant to the jobsite, and construction operations over a 6-year period. LCA calculations were performed using openLCA to quantify GWP environmental impact results, in terms of kg CO₂ equivalent. This section provides general conclusions about measurement of carbon emissions from airfield paving and recommendations for continued research in this area.

6.1 General Conclusions

Based on the outcomes of this research, the following generalizations were constructed:

- **GWP can be reasonably quantified with the use of appropriate proxy data to fill input data gaps.** The projects analyzed in this thesis did not provide EPDs for most materials and reported unverifiable high equipment operation hours, leading to low data quality. It is possible to perform an LCA based on a suitable proxy EPD for material production (A1 – A3) and an approximate trucking distance for transportation (A4), while equipment operation hours and fuel consumption can greatly vary the results for construction (A5).
- **Dissimilar materials, in this case asphalt and concrete, cannot be compared due to the use of differing PCRs and functional units.** EPDs are not intended to be used as a contrasting mechanism for the two main pavement types (Reduced Carbon Concrete Consortium (RC3) 2024). However, two of the same materials (such as the two asphalt projects researched here), which were developed under the same PCR and meet similar performance requirements can be compared on a material EPD basis.
- **Comparisons between the three projects studied in this thesis are of limited use because they are different types of projects, with different materials, and in different parts of the country.** Reported GWP contributions are better used for process improvement and less useful for direct comparison between markedly different projects, materials, and regions.
- **Demolition operations can generate a significant fraction of project GHG emissions.** Demolition for the three projects contributed 6.5% (JBLM), 18.6% (TAFB), and 3.0% (NASWI). This compares to an average of 2.5% from Lum (2024), where demolition was limited to milling machine operations. Notably, the training purpose of the TAFB project results in significant demolition equipment hours of operation. while other sources (e.g., Lum 2024 and Muench 2010) have noted small fractional contributions for construction activities, this may not be true if extensive demolition is required.

- **Batch plants in close proximity to military installations allow for significantly lower transportation (A4) carbon emissions.** The asphalt projects in thesis calculated material hauling contributions at less than half of those presented in Lum (2024) at 4.94 kg CO₂ eq versus 12.8 kg CO₂ eq per short ton of asphalt, respectively.
- **General GWP ranges per LCA stage for concrete and asphalt, respectively, are as follows:**
 - Material production (A1 – A3): 80% and 45 – 65%
 - Transportation (A4): 2% and 3 – 5%
 - Construction (A5): 18% and 30 – 50%
- **Pavement material EPDs, accounted for in material production (A1 – A3), are the most important data to collect** because of their high influence on environmental impacts, specifically owing to cement (A1), virgin asphalt (A1), and plant heating (A3).
- **Trucking distances, accounted for in transportation (A4), are least impactful for DOD airfield pavement LCA.** This is contradictory to research conclusions for DOT highway pavement construction because of the decreased transport mileage. However, the ability to use 0.412 kg CO₂ eq per functional unit of pavement for every mile traveled as a proxy value is consistent.
- **Construction equipment fuel consumption, accounted for construction (A5), is the second highest contributor for DOD airfield paving carbon emissions.** Accurate and transparent construction equipment data is essential because the GWP contribution results rely heavily on these inputs and can lead to significant variability.

6.2 Recommendations for Study Replicability

When developing models in openLCA, each project was based on standard templates and assumptions with the input variables being for materials, fuel, and energy. To use the methods outlined in this research on additional airfield construction projects, the following data is necessary from each life cycle stage to calculate a reasonably accurate A1 – A5 LCA:

- **Pavement material EPD (A1 – A3): The EPD will provide all required information from these stages including cement type, admixtures, aggregates, RAP, virgin asphalt binder content, plant information, and environmental impacts in declared units.** This description, in combination with knowledge of the substantial carbon emissions from material production, defines why the actual EPD for the project’s mix design is essential to the GWP calculation process.
- **Transportation distance (A4): Since pavement transport distance for airfield paving is generally minimal, the distance from the concrete or asphalt plant to the project site in miles will be sufficient for LCA modeling.** Emulsion trucking data is insignificant and, therefore, not essential to this process.
- **Construction equipment fuel consumption (A5): The highest contributors to demolition and paving in this project are milling machines, excavators, loaders,**

graders, and rollers. Therefore, it is important to collect fuel data from at least those pieces of equipment if not all information is available.

It is necessary to ensure general contractor involvement in this process because the owner typically does not collect enough information in their standard documents and reports to provide this data. Methods for the federal government to secure general contractor support are discussed in section 6.3. The general contractor is best equipped to provide the following:

1. Pavement material EPD
2. Plant location and one-way transportation distance
3. Equipment operation hour logs

6.3 Future Work Suggestions

The first step in combating global warming is understanding embodied carbons to fuel reduction goals. By continuing pavement LCA at a variety of installations, the DOD can quantify existing carbon emissions associated with airfield paving and establish realistic strategies for reducing them. This section includes recommendations to pavement engineers at a base-level for progressing this necessary research.

- **Selected projects should be currently in construction or programmed for upcoming fiscal years to support ease of accurate reporting.** It was challenging collecting data from projects which were substantially complete prior to research development because not all of the necessary data was available, and data quality decreases with time.
- **The DOD should establish a standardized format to require EPDs from general contractors.** One method could be to include a contract line item number (CLIN) requiring the general contractor to produce pavement material EPDs when preparing solicitation packages. Contracting officers (CO) would determine the associated federal government obligations and reasonable compensation to the general contractor.
- **A DOD centralized EPD reporting system would be beneficial to regulate uniformity and documentation of collected material EPDs.** This repository could aid in comparing and selecting materials across all federally-funded construction.
 - **An airfield carbon emission research database could also be created to transparently share results between installations across the DOD.** Measurement efforts would be more efficient if all military services could understand the implications and synchronize on the way forward, beginning with appropriate knowledge-sharing.
- **General contractors should be provided with a standardized construction equipment data collection form prior to construction.** This could be done at the pre-construction meeting to ensure the contractor's contractual responsibilities are understood and give them the opportunity to ask questions.

- **Researching one airfield from cradle-to-grave (A1 – C4) could provide insight on holistic embodied carbon for the selected period (e.g., 10 years).** This would require data from maintenance and repair activities in use stages (B1 – B5) such as spall repairs, crack sealing, rubber removal, paint striping, etc.

7 Appendix A: JBLM Results Figures

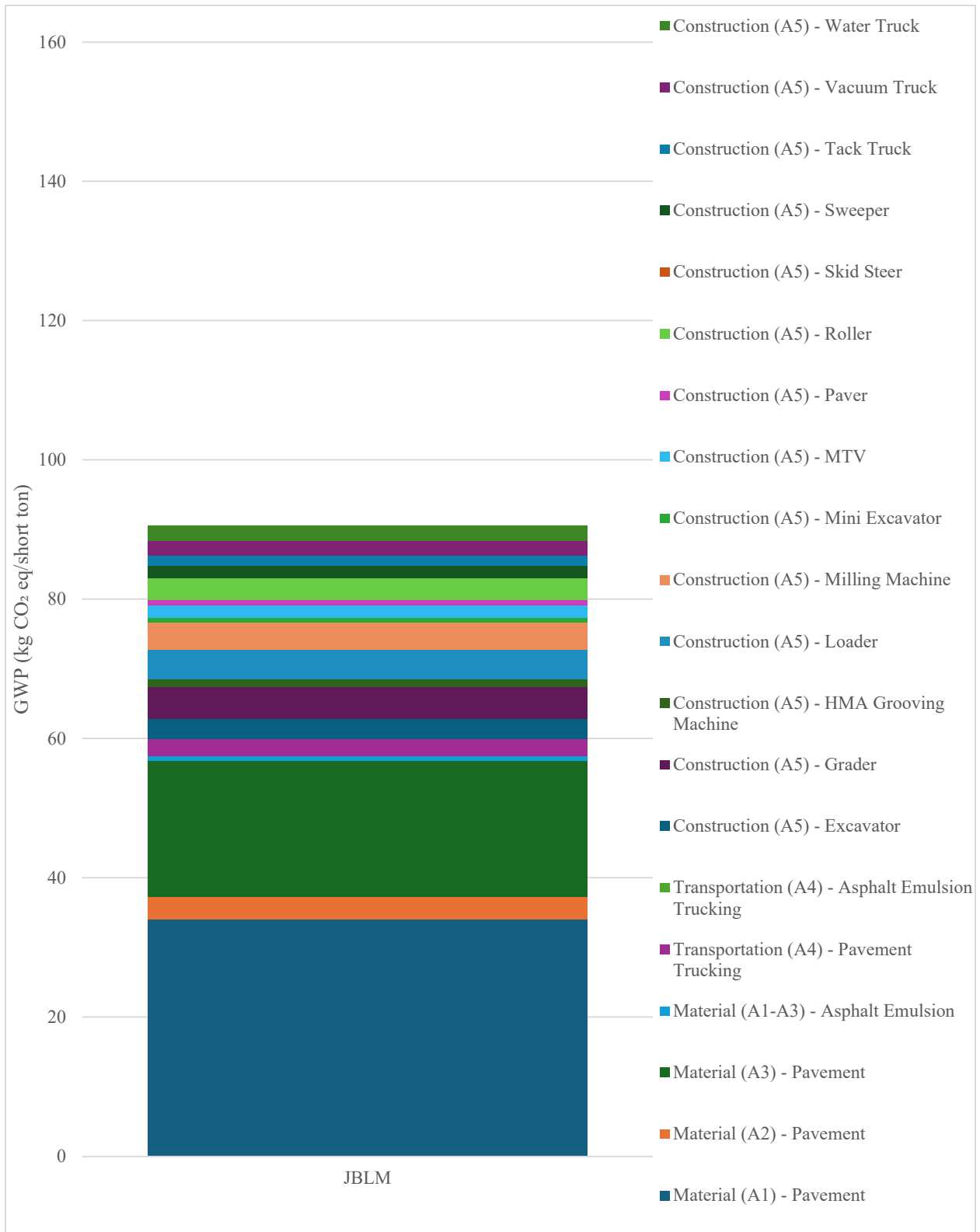


Figure 47 – JBLM GWP (kg CO₂ eq) per Short Ton of Asphalt

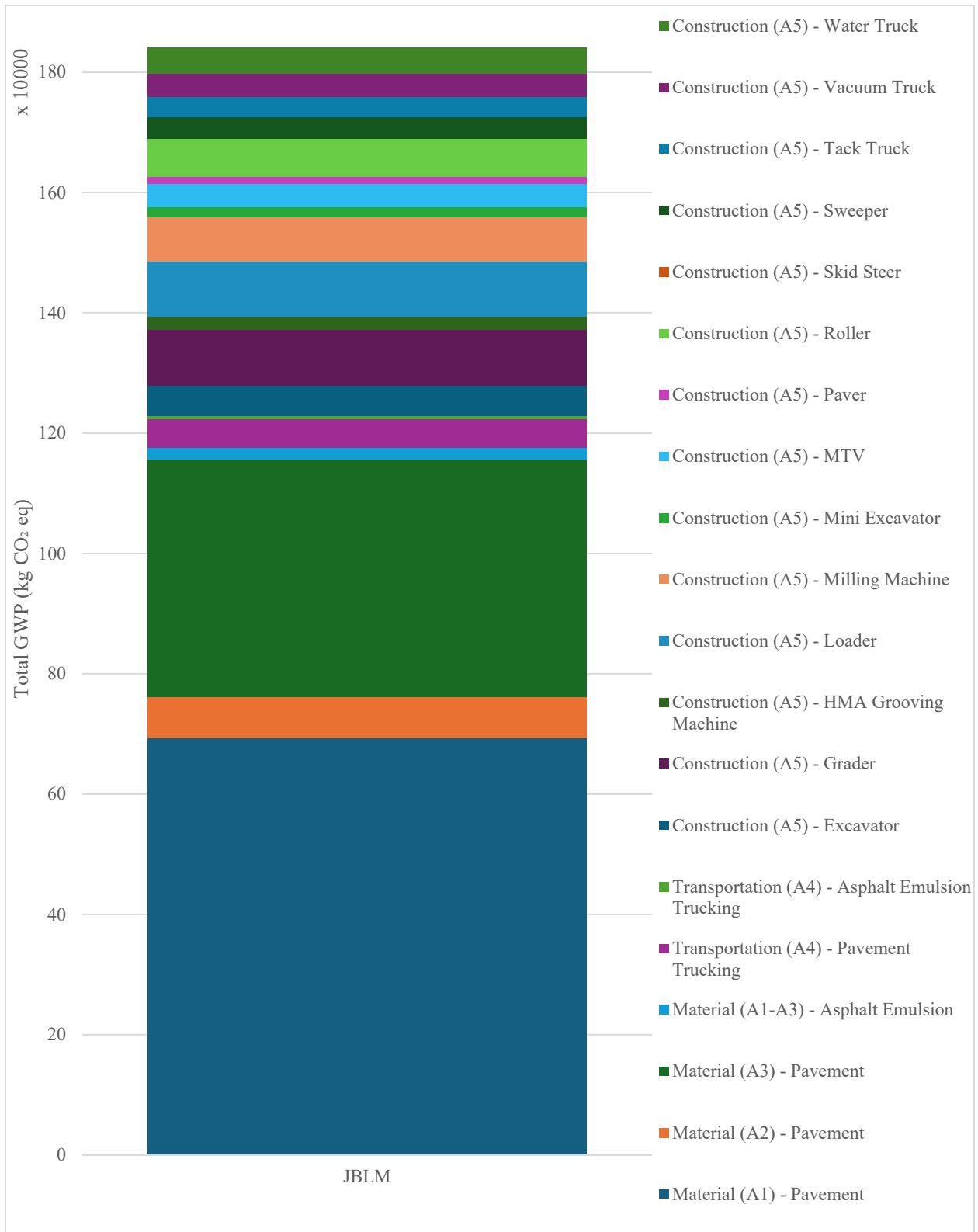


Figure 48 – JBLM Project Total GWP

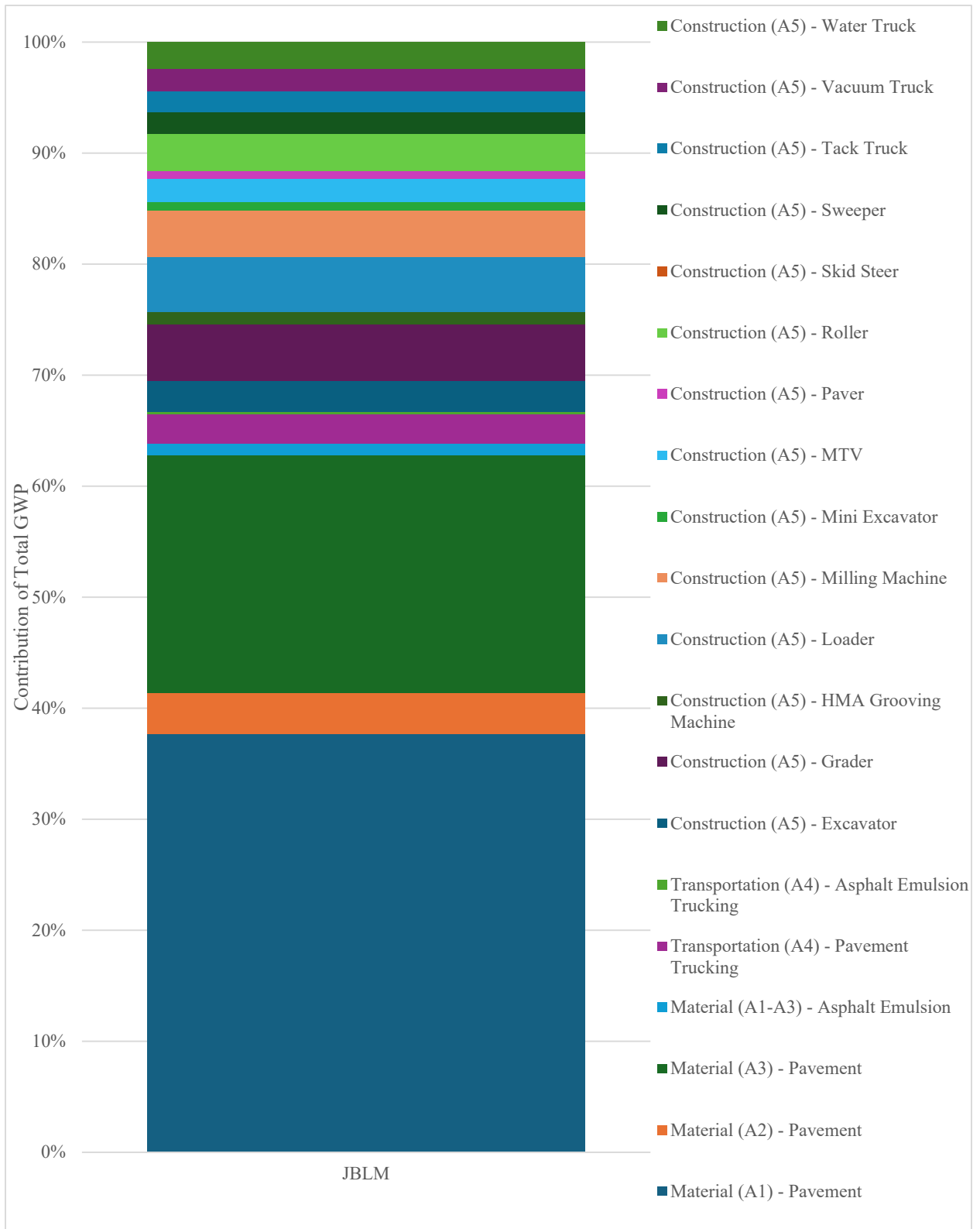


Figure 49 – JBLM Percent Contribution

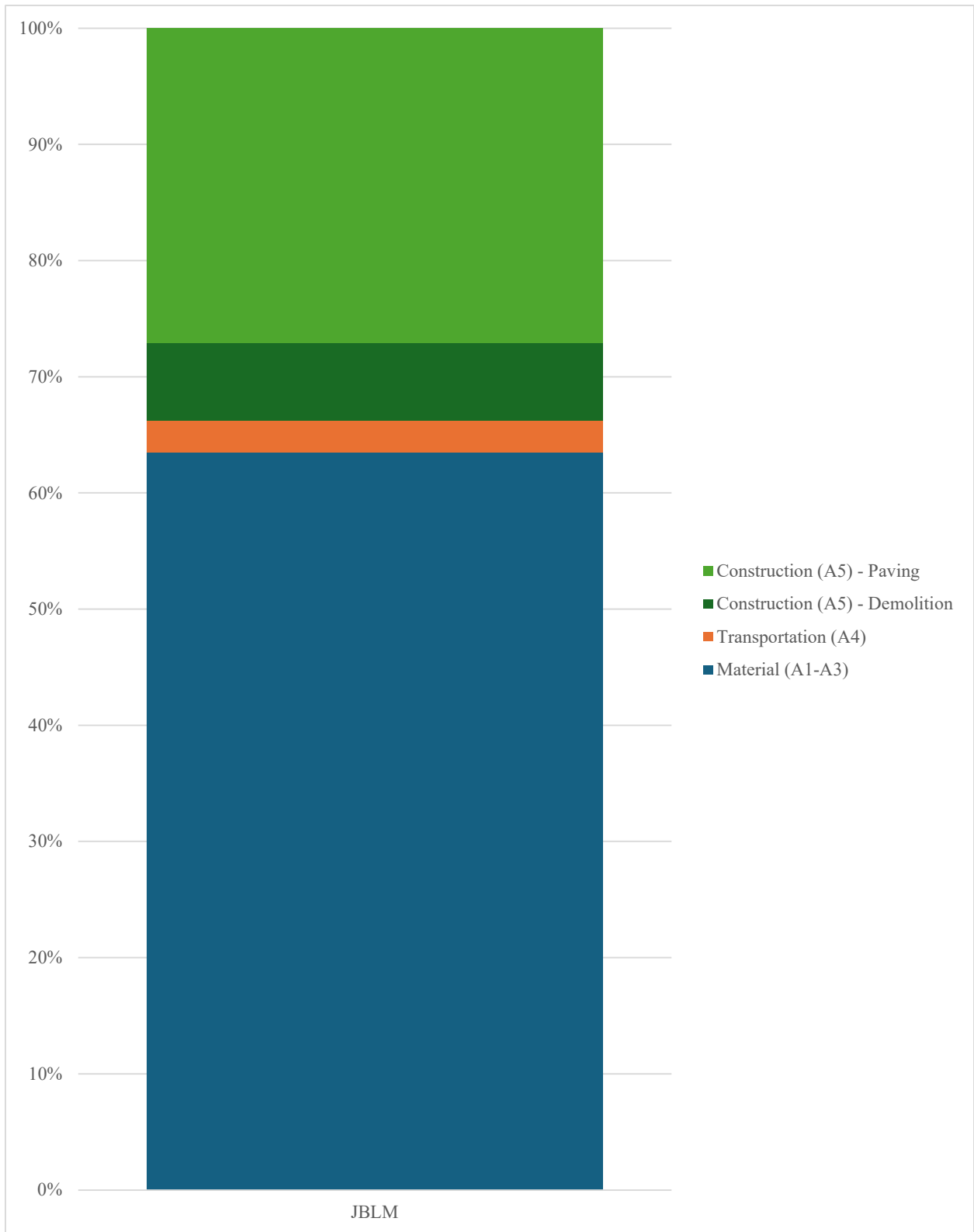


Figure 50 – JBLM GWP by Life Cycle Stage Percent Contribution

8 Appendix B: NASWI Results Figures

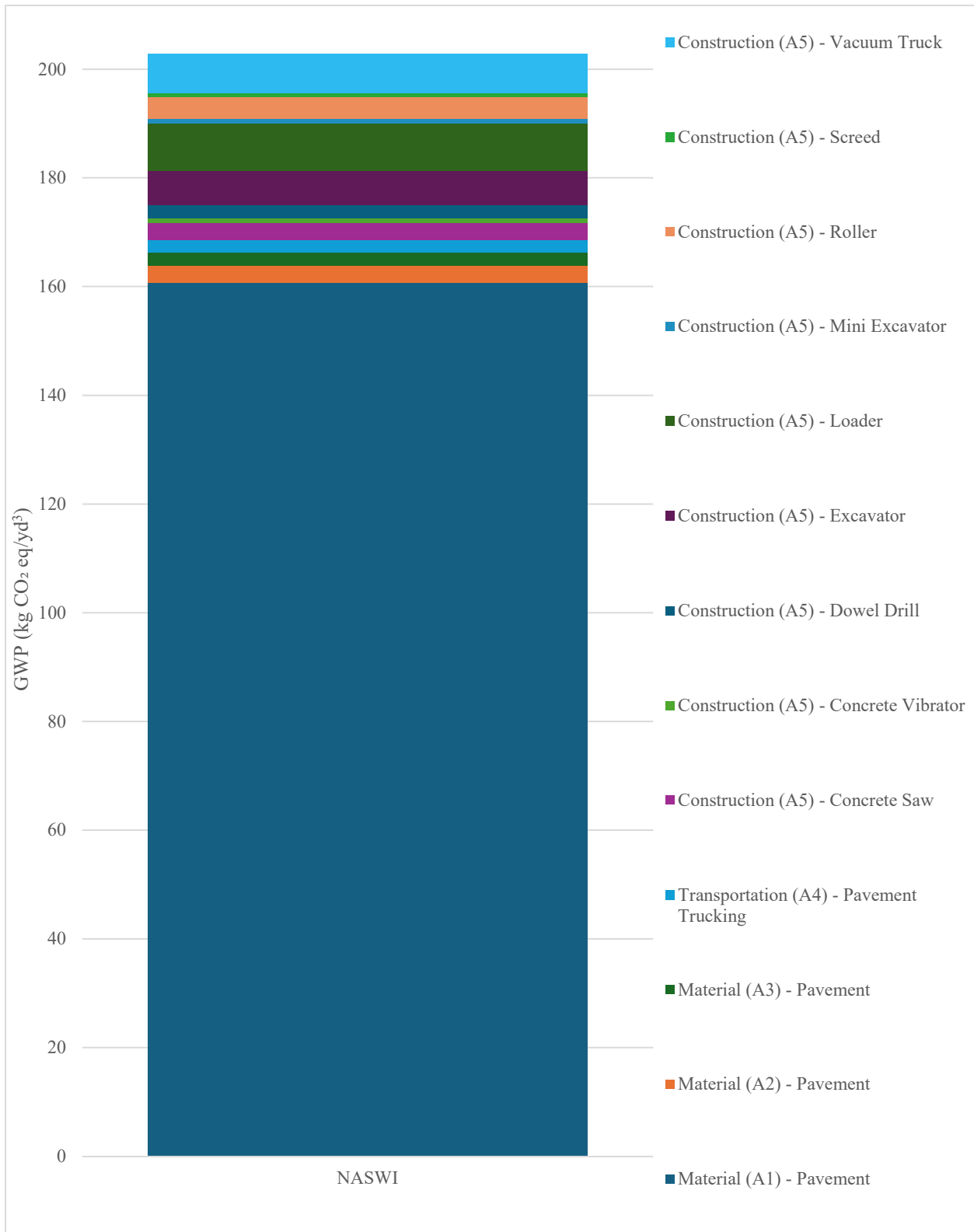


Figure 51 – NASWI GWP (kg CO₂ eq) per Cubic Yard of Concrete

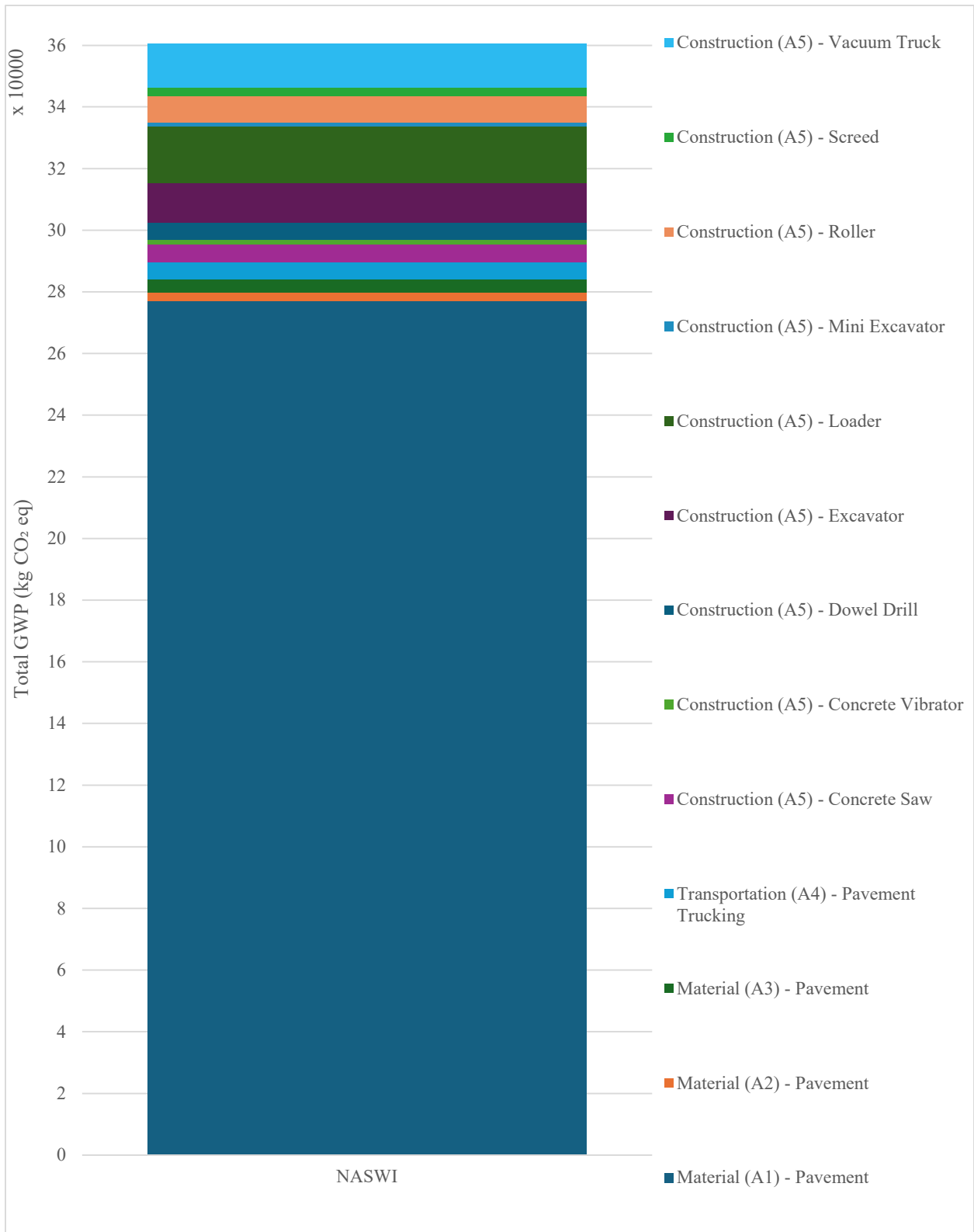


Figure 52 – NASWI Project Total GWP

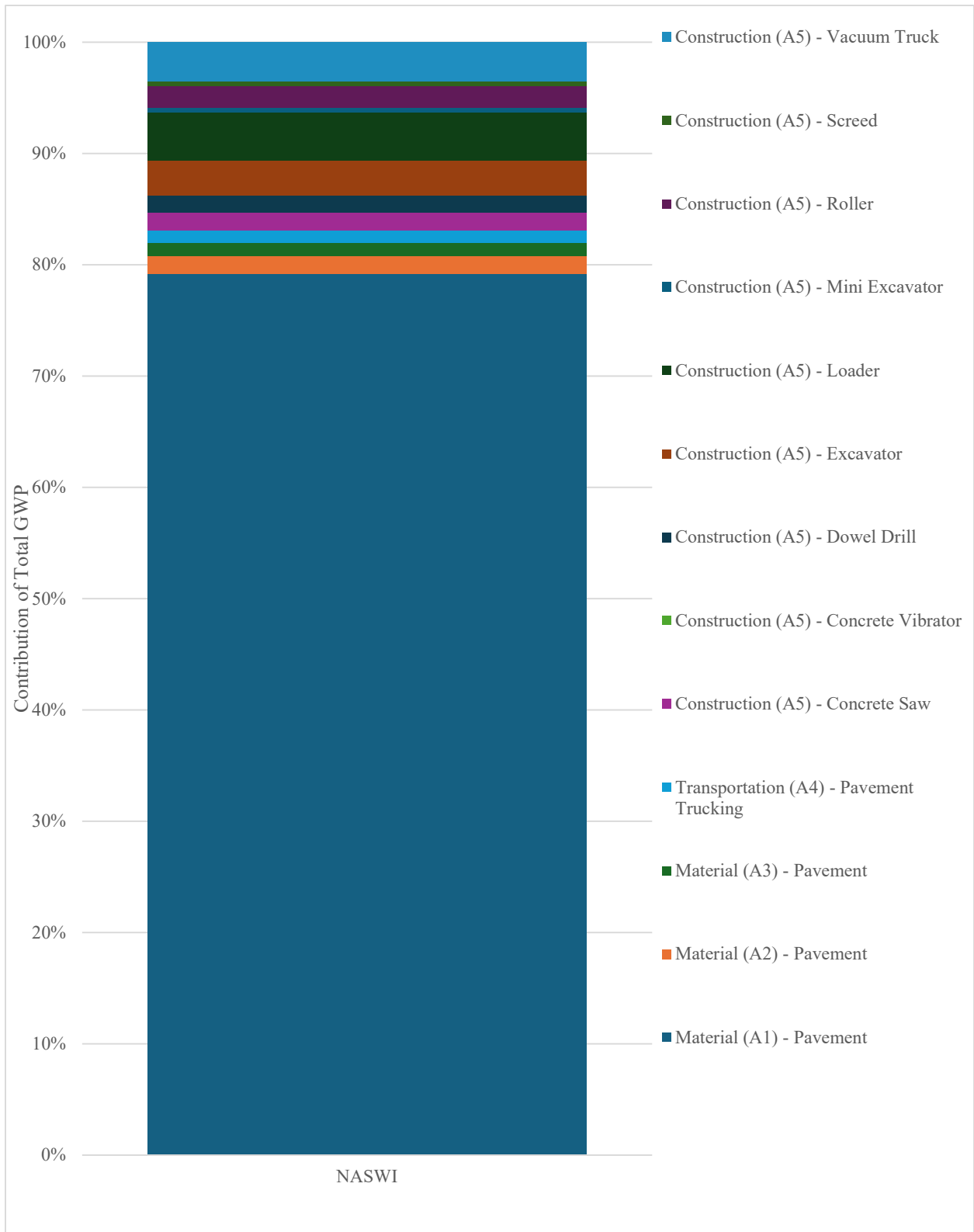


Figure 53 – NASWI Percent Contribution

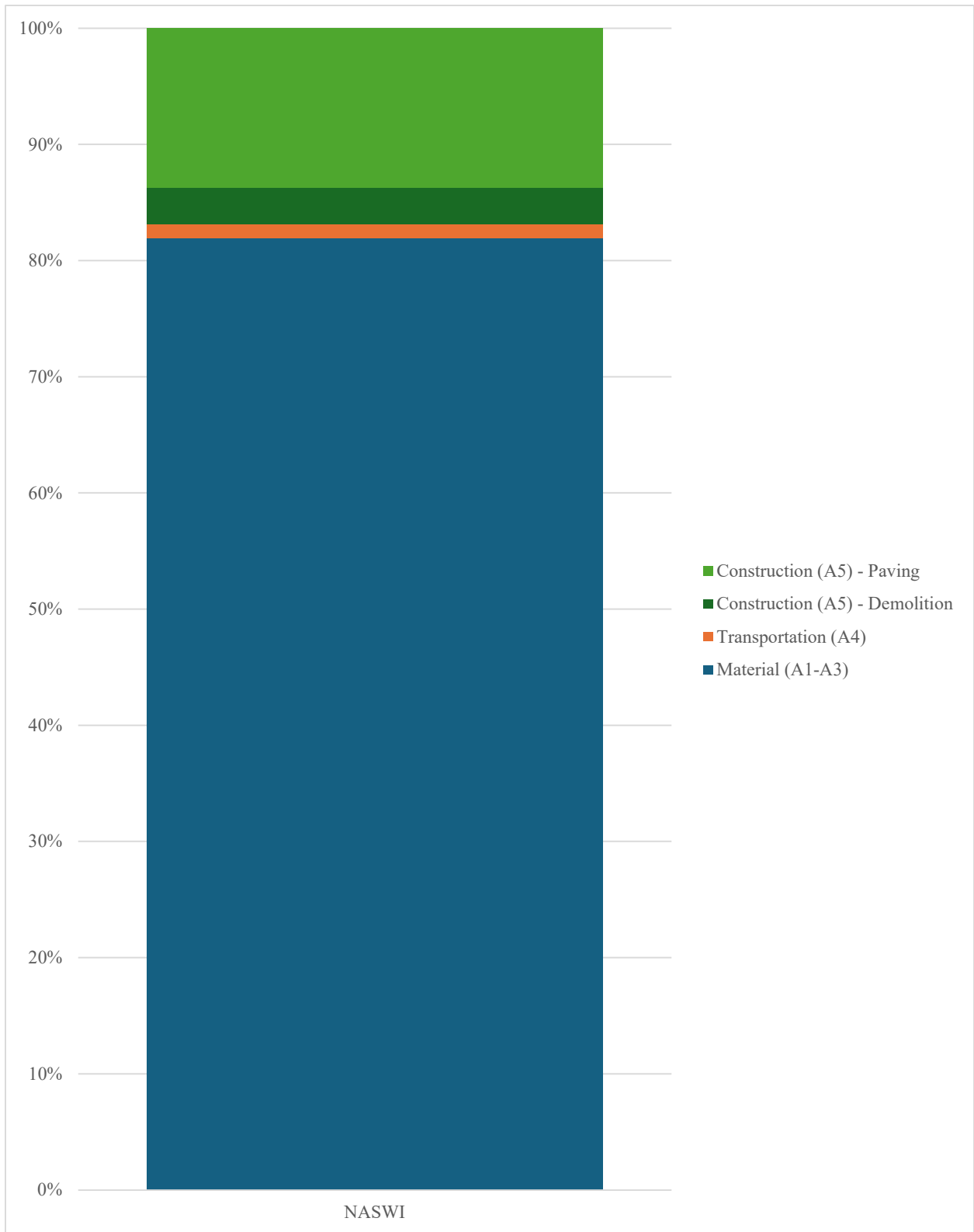


Figure 54 – NASWI GWP by Life Cycle Stage Percent Contribution

9 Appendix C: TAFB Results Figures

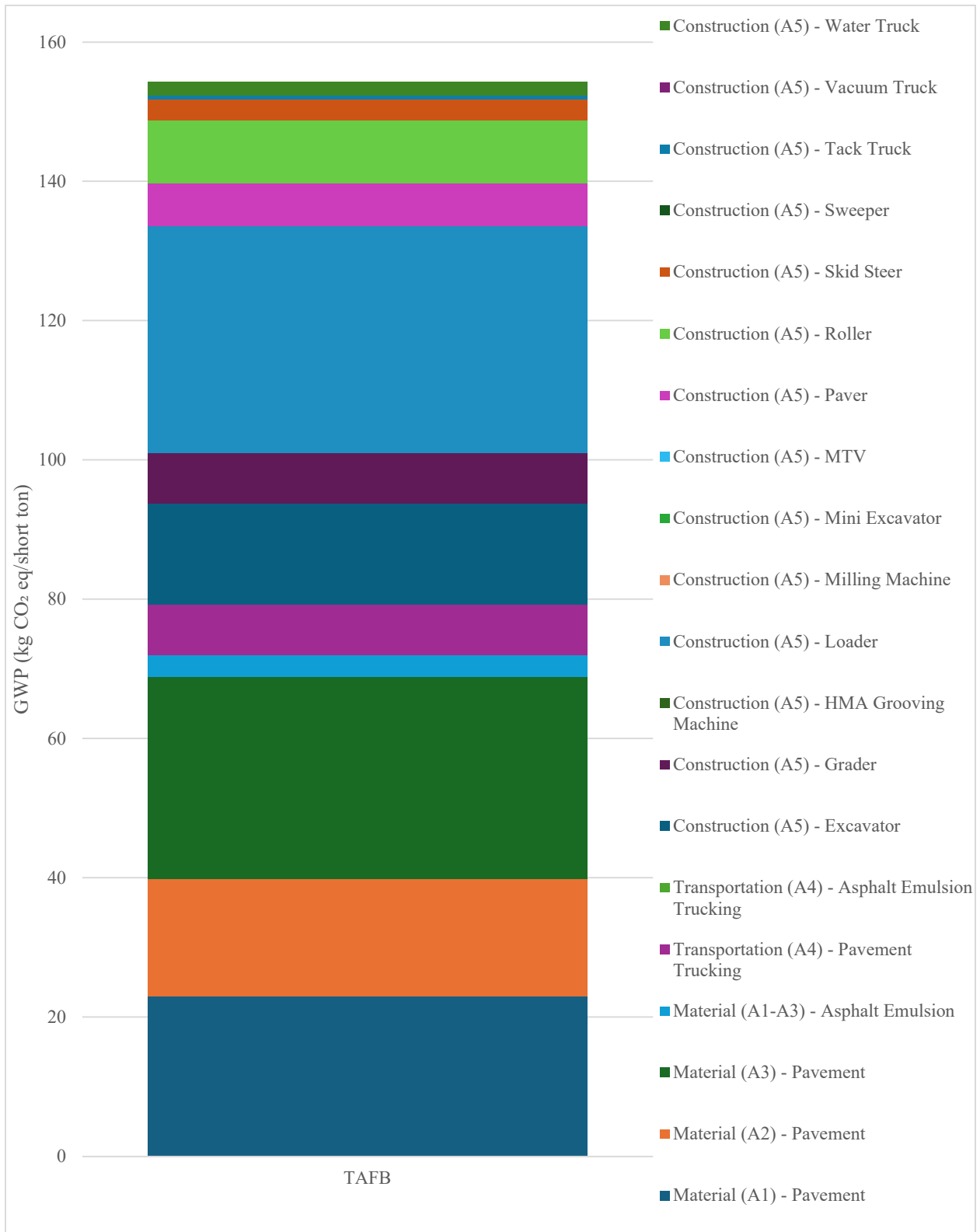


Figure 55 – TAFB GWP (kg CO₂ eq) per Short Ton of Asphalt

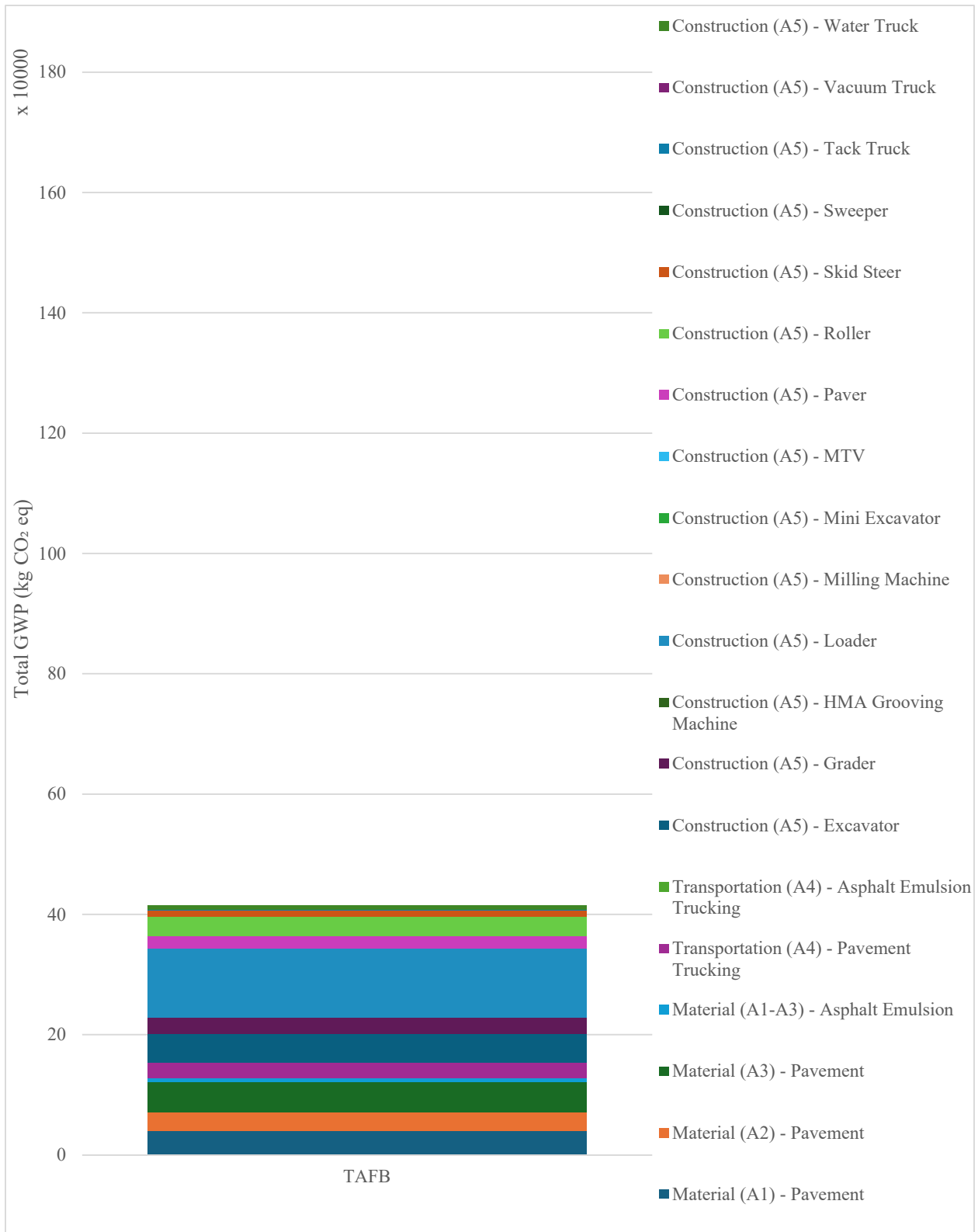


Figure 56 – TAFB Project Total GWP

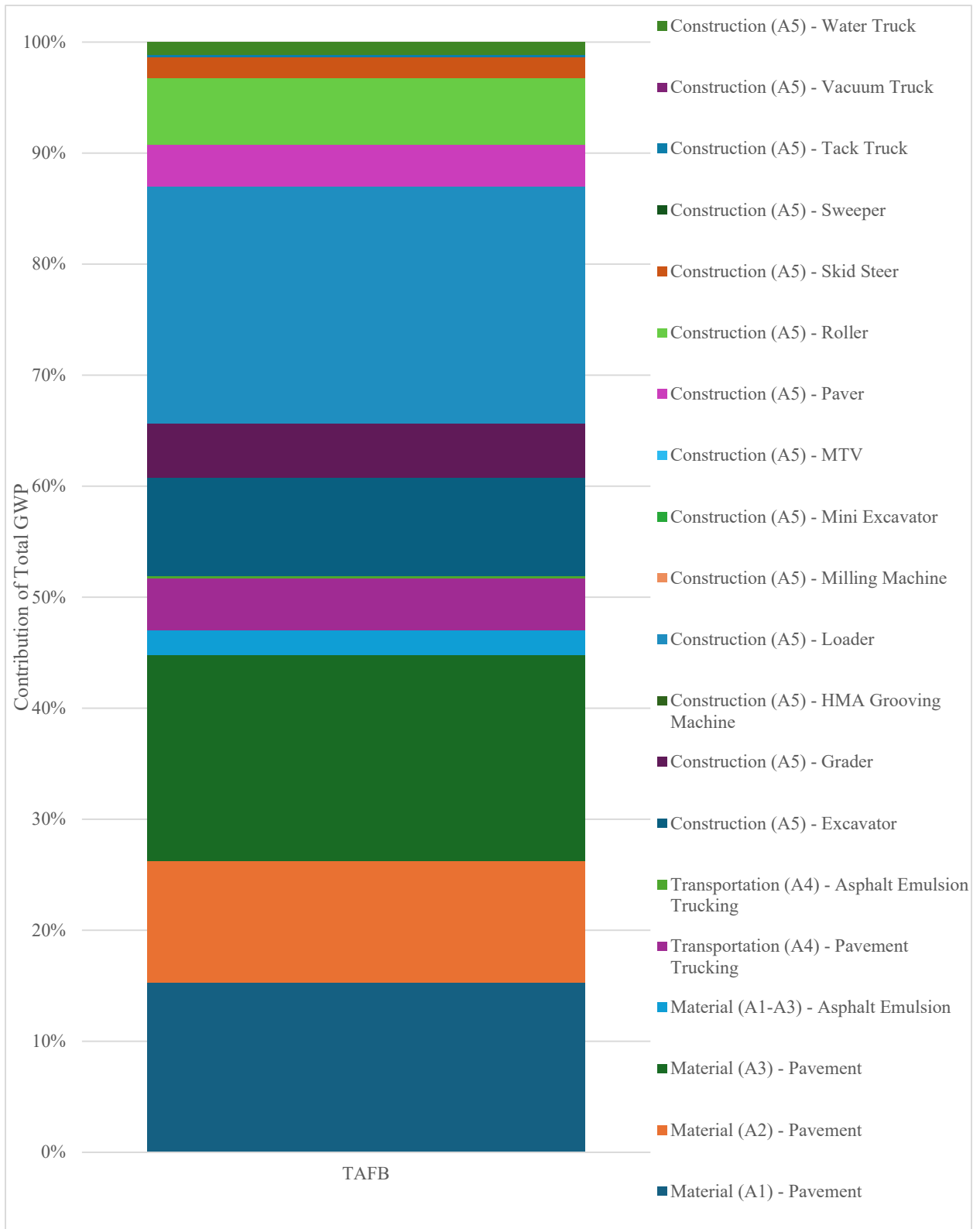


Figure 57 – TAFB Percent Contribution

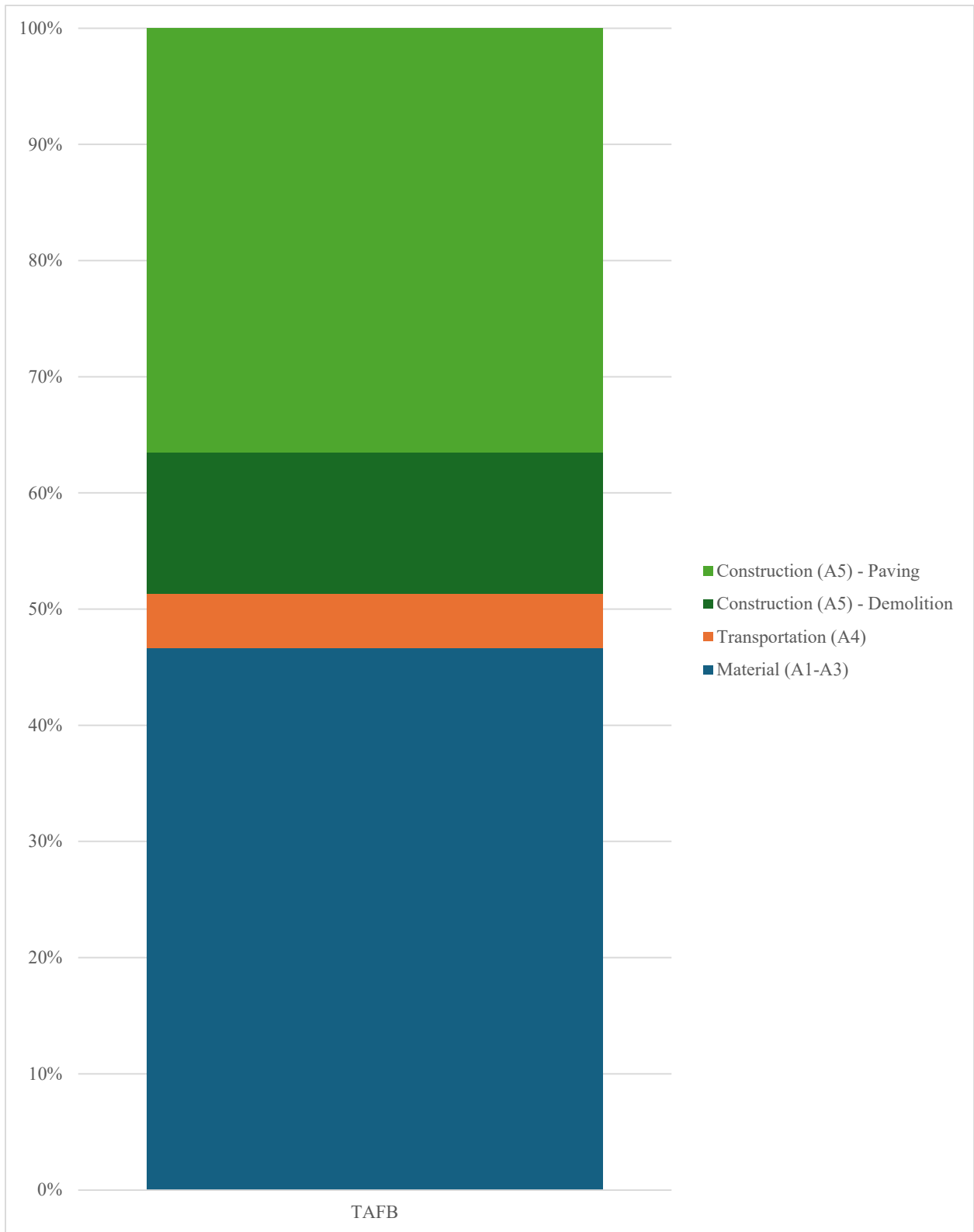


Figure 58 – TAFB GWP by Life Cycle Stage Percent Contribution

10 Appendix D: openLCA Variables

Table 44 – openLCA Input Parameters

Name	Description
concretesaw_total_fuel_use_gal	Total fuel use over entirety of project in gallons
concretevibrator_total_fuel_use_gal	Total fuel use over entirety of project in gallons
doweldrill_total_fuel_use_gal	Total fuel use over entirety of project in gallons
dumptruck_end_total_fuel_use_gal	Total fuel use over entirety of project in gallons
excavator_end_total_fuel_use_gal	Total fuel use over entirety of project in gallons
grader_total_fuel_use_gal	Total fuel use over entirety of project in gallons
HMAgroover_total_fuel_use_gal	Total fuel use over entirety of project in gallons
loader_total_fuel_use_gal	Total fuel use over entirety of project in gallons
millingmachine_total_fuel_use_gal	Total fuel use over entirety of project in gallons
miniexcavator_end_total_fuel_use_gal	Total fuel use over entirety of project in gallons
mtv_total_fuel_use_gal	Total fuel use over entirety of project in gallons
one_way_trucking_dist_mil	One-way trucking distance from plant to project site
paver_total_fuel_use_gal	Total fuel use over entirety of project in gallons
roller_19to56kW_total_fuel_use_gal	Total fuel use over entirety of project in gallons
roller_56to560kW_total_fuel_use_gal	Total fuel use over entirety of project in gallons
screed_total_fuel_use_gal	Total fuel use over entirety of project in gallons
skidsteer_total_fuel_use_gal	Total fuel use over entirety of project in gallons
sweeper_total_fuel_use_gal	Total fuel use over entirety of project in gallons
tack_coat_gal	Gallons of emulsion used (tack coat, CSS-1)
tack_coat_travel_dist_mi	Approximate travel distance of emulsion
tacktruck_total_fuel_use_gal	Total fuel use over entirety of project in gallons
tons_of_asphalt	Total asphalt use per project
cubic_yards_concrete	Total concrete use per project
vacuumtruck_total_fuel_use_gal	Total fuel use over entirety of project in gallons
watertruck_total_fuel_use_gal	Total fuel use over entirety of project in gallons

Table 45 – openLCA Dependent Parameters

Name	Formula	Description
concretesaw_MJ	$(\text{concretesaw_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic_yards_concrete}$	Energy consumption in MJ converted from total gallons of diesel used
concretevibrator_MJ	$(\text{concretevibrator_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic_yards_concrete}$	Energy consumption in MJ converted from total gallons of diesel used

doweldrill_MJ	$(\text{doweldrill_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic yards concrete}$	Energy consumption in MJ converted from total gallons of diesel used
dumptruck_end_MJ	$(\text{dumptruck_end_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
	$(\text{dumptruck_end_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic yards concrete}$	
excavator_MJ	$(\text{excavator_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
	$(\text{excavator_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic yards concrete}$	
grader_MJ	$(\text{grader_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
HMAgroover_MJ	$(\text{HMAgroover_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
loader_MJ	$(\text{loader_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons of pavement}$	Energy consumption in MJ converted from total gallons of diesel used
	$(\text{loader_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic yards concrete}$	
millingmachine_MJ	$(\text{millingmachine_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
miniexcavator_MJ	$(\text{miniexcavator_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
	$(\text{miniexcavator_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic yards concrete}$	
mtv_MJ	$(\text{mtv_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
paver_MJ	$(\text{paver_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
roller_19to56kW_MJ	$(\text{roller_19to56kW_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used

roller_56to560kW_MJ	$(\text{roller_56to560kW_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
	$(\text{roller_56to560kW_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic_yards_concrete}$	
screed_MJ	$(\text{screed_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic_yards_concrete}$	Energy consumption in MJ converted from total gallons of diesel used
skidsteer_MJ	$(\text{skidsteer_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
sweeper_MJ	$(\text{sweeper_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
tack_coat_tons	$(\text{tack_coat_gal} / \text{css_1_per_ton})$	Value of tack coat used on job in tons
tack_coat_tons_per_ton_asphalt	$(\text{tack_coat_tons} / \text{tons_of_asphalt})$	Value of tack coat used on job in tons per ton of asphalt
tack_coat_travel_per_ton_asphalt	$(\text{tack_coat_tons} * \text{tack_coat_travel_dist_mi}) / \text{tons_of_asphalt}$	Tack coat in (ton-miles) per ton of asphalt
tacktruck_MJ	$(\text{tacktruck_total_fuel_use_gal} * \text{MJ_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
truck_travel_miles	$(\text{tons_of_asphalt} * \text{one_way_trucking_dist_mil})$	Approximate number of short ton miles that trucks traveled
	$(\text{cubic_yards_concrete} * \text{one_way_trucking_dist_mil})$	Approximate number of cubic yard miles that trucks traveled
vacuumtruck_MJ	$(\text{vacuumtruck_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used
	$(\text{vacuumtruck_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{cubic_yards_concrete}$	
watertruck_MJ	$(\text{watertruck_total_fuel_use_gal} * \text{mj_per_gal_diesel}) / \text{tons_of_asphalt}$	Energy consumption in MJ converted from total gallons of diesel used

11 Appendix E: Equipment Summary

Table 46 – Cumulative Equipment Summary List

Project	Equipment Type	Make and Models	Engine Size (kW)	Engine Size Range (kW)
JBLM	Breakdown roller	HAMM HD+ 120VO	100	56 - 560
NASWI	Concrete saw	*Not specified	*Not specified	19 - 56
NASWI	Concrete vibrator	*Not specified	*Not specified	19 - 56
NASWI	Dowel Drill	*Not specified	*Not specified	56 - 560
JBLM	Excavator	John Deere 160	90	56 - 560
TAFB	Excavator	Volvo D6H	128	56 - 560
TAFB	Excavator	Kobelco SK350LC	198	56 - 560
NASWI	Excavator	*Not specified	*Not specified	56 - 560
JBLM	Finish roller	IR DD120B	148	56 - 560
JBLM	Grader	John Deere 672	190	56 - 560
TAFB	Grader	Volvo G930	152	56 - 560
TAFB	Grader	CAT 120M	103	56 - 560
JBLM	HMA grooving machine	DP Groover	200	56 - 560
JBLM	Loader	John Deere 744	236	56 - 560
TAFB	Loader	John Deere 544	123	56 - 560
TAFB	Loader	CAT 963D	141	56 - 560
NASWI	Loader	*Not specified	*Not specified	56 - 560
JBLM	Milling machine	Wirtgen 210i	537	56 - 560
JBLM	Mini excavator	John Deere 50	26.8	19 - 56
NASWI	Mini excavator	*Not specified	*Not specified	19 - 56
JBLM	MTV	Roadtec SB-2500B	224	56 - 560
JBLM	MTV	Weiler e2850	223	56 - 560
JBLM	Paver	CAT AP1055F	168	56 - 560
TAFB	Paver	CAT AP600	129	56 - 560
JBLM	Pneumatic roller	Sakai GW750	79	56 - 560
TAFB	Roller	CAT CB13	106	56 - 560
TAFB	Roller	Volvo DD90	97	56 - 560
TAFB	Roller	Volvo PT125	63	56 - 560
NASWI	Roller	*Not specified	*Not specified	56 - 560
NASWI	Screed	*Not specified	*Not specified	0 - 19
TAFB	Skid steer	CAT 289D	54	19 - 56
TAFB	Skid steer	Bobcat S650	54	19 - 56
JBLM	Sweeper	Elgin	*Not specified	56 - 560
JBLM	Tack truck	International	*Not specified	56 - 560

TAFB	Tack truck	International	*Not specified	56 - 560
JBLM	Vacuum truck	Isuzu	*Not specified	56 - 560
NASWI	Vacuum truck	*Not specified	*Not specified	56 - 560
JBLM	Water truck	International 10,000 gal	*Not specified	56 - 560
TAFB	Water truck	West-Mark 500T	*Not specified	56 - 560

12 Appendix F: Data Quality Analysis by Project

Table 47 – JBLM Data Quality Analysis

	Very Good (5)	Good (4)	Fair (3)	Poor (2)	Very Poor (1)
Technological Representative- ness	Technology aspects have been modelled exactly as described in the title and metadata, without any significant need for improvement.	Technology aspects are very similar to what is described in the title and metadata with need for limited improvements. For example: use of generic technologies' data instead of modelling all the single plants.	Technology aspects are similar to what is described in the title and metadata but merits improvements. Some of the relevant processes are not modelled with specific data but using proxies.	Technology aspects are different from what described in the title and metadata. Requires major improvements.	Technology aspects are completely different from what is described in the title and metadata. Substantial improvement is necessary.
Time Representative- ness	The data (collection date) can be maximum 2 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the dataset.	The data (collection date) is older than 8 years with respect to the "reference year" of the dataset.
Geographical Representative- ness	The processes included in the dataset are fully representative for the geography stated in the "location" indicated in the metadata.	The processes included in the dataset are well representative for the geography stated in the "location" indicated in the metadata.	The processes included in the dataset are sufficiently representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.	The processes included in the dataset are only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different	The processes included in the dataset are not representative for the geography stated in the "location" indicated in the metadata.

				electricity grid mix profile.	
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations.	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations.	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods.	Representative data from only one site relevant for the market considered or some sites but from shorter periods.	Representative ness unknown or data from a small number of sites and from shorter period.
Precision	Measured / calculated and verified. Very low uncertainty (< 7%).	Measured / calculated / literature and plausibility checked by reviewer.	Measured / calculated / literature and plausibility not checked by reviewer OR Qualified estimate based on calculations plausibility checked by reviewer.	Qualified estimate based on calculations, plausibility not checked by reviewer.	Rough estimate with known deficits.
Methodological Appropriateness and Consistency	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact in comparison to an ideal situation.
Overall Quality	Meets the criterium to a very high degree, having	Meets the criterium to a high degree, having little	Meets the criterium to a sufficient degree, having	Does not meet the criterium to a sufficient degree, having	Does not at all meet the criterium, having the

	or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
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Table 48 – NASWI Data Quality Analysis

	Very Good (5)	Good (4)	Fair (3)	Poor (2)	Very Poor (1)
Technological Representativeness	Technology aspects have been modelled exactly as described in the title and metadata, without any significant need for improvement.	Technology aspects are very similar to what is described in the title and metadata with need for limited improvements. For example: use of generic technologies' data instead of modelling all the single plants.	Technology aspects are similar to what is described in the title and metadata but merits improvements. Some of the relevant processes are not modelled with specific data but using proxies.	Technology aspects are different from what described in the title and metadata. Requires major improvements.	Technology aspects are completely different from what is described in the title and metadata. Substantial improvement is necessary.
Time Representativeness	The data (collection date) can be maximum 2 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the dataset.	The data (collection date) is older than 8 years with respect to the "reference year" of the dataset.
Geographical Representativeness	The processes included in the dataset are	The processes included in the dataset are	The processes included in the dataset are	The processes included in the dataset are	The processes included in the dataset are not

	fully representative for the geography stated in the "location" indicated in the metadata.	well representative for the geography stated in the "location" indicated in the metadata.	sufficiently representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.	only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different electricity grid mix profile.	representative for the geography stated in the "location" indicated in the metadata.
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations.	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations.	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods.	Representative data from only one site relevant for the market considered or some sites but from shorter periods.	Representativeness unknown or data from a small number of sites and from shorter period.
Precision	Measured / calculated and verified. Very low uncertainty (< 7%).	Measured / calculated / literature and plausibility checked by reviewer.	Measured / calculated / literature and plausibility not checked by reviewer OR Qualified estimate based on calculations plausibility checked by reviewer.	Qualified estimate based on calculations, plausibility not checked by reviewer.	Rough estimate with known deficits.
Methodological Appropriateness and Consistency	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's	Meets the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's

	contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	contribution to the data set's potential overall environmental impact an in comparison to an ideal situation.
Overall Quality	Meets the criterium to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterium to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterium, having the need for very substantial improvement. This is to be judged in view of the criterium's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.

Table 49 – TAFB Data Quality Analysis

	Very Good (5)	Good (4)	Fair (3)	Poor (2)	Very Poor (1)
Technological Representativeness	Technology aspects have been modelled exactly as described in the title and metadata, without any significant need for improvement.	Technology aspects are very similar to what is described in the title and metadata with need for limited improvements. For example: use of generic technologies' data instead of modelling all	Technology aspects are similar to what is described in the title and metadata but merits improvements. Some of the relevant processes are not modelled with specific data but using proxies.	Technology aspects are different from what described in the title and metadata. Requires major improvements.	Technology aspects are completely different from what is described in the title and metadata. Substantial improvement is necessary.

		the single plants.			
Time Representativeness	The data (collection date) can be maximum 2 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 4 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 6 years old with respect to the "reference year" of the dataset.	The data (collection date) can be maximum 8 years old with respect to the "reference year" of the dataset.	The data (collection date) is older than 8 years with respect to the "reference year" of the dataset.
Geographical Representativeness	The processes included in the dataset are fully representative for the geography stated in the "location" indicated in the metadata.	The processes included in the dataset are well representative for the geography stated in the "location" indicated in the metadata.	The processes included in the dataset are sufficiently representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs but has a very similar electricity grid mix profile.	The processes included in the dataset are only partly representative for the geography stated in the "location" indicated in the metadata. E.g. the represented country differs and has a substantially different electricity grid mix profile.	The processes included in the dataset are not representative for the geography stated in the "location" indicated in the metadata.
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations.	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations.	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods.	Representative data from only one site relevant for the market considered or some sites but from shorter periods.	Representativeness unknown or data from a small number of sites and from shorter period.
Precision	Measured / calculated and verified. Very low uncertainty (< 7%).	Measured / calculated / literature and plausibility checked by reviewer.	Measured / calculated / literature and plausibility not checked by reviewer OR Qualified estimate based on	Qualified estimate based on calculations, plausibility not checked by reviewer.	Rough estimate with known deficits.

			calculations plausibility checked by reviewer.		
Methodological Appropriate- ness and Consistency	Meets the criterion to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterion to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterion to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterion to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterion, having the need for very substantial improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact an in comparison to an ideal situation.
Overall Quality	Meets the criterion to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterion to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Meets the criterion to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not meet the criterion to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.	Does not at all meet the criterion, having the need for very substantial improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.

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