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Master's Degree Thesis

Decarbonization of road construction and maintenance. An analysis of best practices through the Life Cycle Assessment (LCA) methodology.

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Abstract

The construction and maintenance of road infrastructure are major contributors to global carbon emissions, with heavy machinery playing a pivotal role in this impact. This thesis explores the potential for decarbonization within the framework of "zero pavement," a novel pavement type composed of five distinct layers. Using Life Cycle Assessment (LCA), this research evaluates the environmental impacts associated with construction equipment used in the installation of this pavement, focusing on fuel consumption, carbon emissions, and operational efficiency.

The study examines various installation equipment, including pavers, rollers, sprayers, and sweepers, analyzing their fuel consumption rates and resulting emissions. By comparing traditional diesel-powered machinery with newer, more efficient models, including those with improved fuel consumption and lower emissions, the research identifies significant opportunities for reducing the carbon footprint associated with road construction. The findings emphasize that while advancements in installation equipment can lead to notable reductions in fuel consumption and emissions, the most substantial impacts arise from upstream processes and transportation.

To achieve comprehensive sustainability, it is essential to consider the entire lifecycle of the construction process, including upstream and downstream emissions. The results underscore the need for a holistic approach to decarbonization that extends beyond improving installation equipment to include enhanced upstream analyses and reductions in scope 3 greenhouse gas emissions. This work offers actionable insights for optimizing equipment performance and adopting sustainable practices, thereby contributing to the broader goal of achieving environmentally responsible infrastructure development through innovative engineering solutions and effective resource management.

Contents

1. Introduction

1.1 Context and Motivation:

As global efforts to combat climate change intensify, the need for sustainable infrastructure has become a critical focus for governments and industries worldwide. Road construction, a key component of infrastructure development, is a significant contributor to global greenhouse gas emissions due to the energy-intensive nature of its processes and the heavy reliance on fossil fuel-powered machinery. The construction industry faces mounting pressure to reduce its carbon footprint and transition to more sustainable practices.

In this context, the concept of "zero pavement" has emerged as an innovative approach to road construction. Zero-Pavement refers to a pavement design optimized for minimal environmental impact, incorporating advanced materials and construction techniques that reduce emissions and improve durability. This study centers on the Life Cycle Assessment (LCA) of zero pavement, with a particular emphasis on analyzing the environmental impact of the construction and maintenance equipment used in its development. By understanding where emissions are most significant, this research aims to identify strategies to decarbonize these processes, thereby contributing to the broader goal of sustainable road infrastructure.

1.2 Research Problem:

Construction equipment, such as wheel loaders, rollers, and trucks, is a major source of carbon emissions in road construction projects. These machines are typically powered by diesel engines, which are significant emitters of carbon dioxide (CO_2) and other pollutants. The problem of carbon emissions from construction equipment is particularly pressing, given the global focus on reducing greenhouse gas emissions to mitigate climate change. Decarbonizing construction equipment is not only essential for achieving environmental targets but also for future-proofing the industry against increasingly stringent regulations.

This thesis addresses the critical issue of carbon emissions from construction and maintenance equipment, focusing on the Zero-Pavement case study. The research seeks to quantify the emissions associated with different equipment, evaluate the effectiveness of alternative fuels and technologies, and propose strategies for reducing the overall environmental impact of road construction activities.

1.3 Objectives:

The primary objectives of this thesis are as follows:

Evaluate the Environmental Impact of Equipment Used in Constructing Zero Pavement:

Conduct a comprehensive LCA of the equipment involved in the construction of zero pavement, assessing their carbon emissions, energy consumption, and other environmental impacts.

Identify Key Opportunities for Reducing Carbon Emissions:

Analyze the LCA results to pinpoint the most significant emission sources and evaluate potential interventions to mitigate these impacts.

Explore Alternative Fuels, Electrification, and Improved Equipment Efficiency:

Investigate the potential of alternative fuels (e.g., renewable diesel, hydrogen) and electrification to reduce emissions, as well as opportunities to enhance the efficiency of construction equipment.

1.4 Research Questions:

This study is guided by the following research questions:

- What are the carbon emissions associated with each piece of equipment used in constructing zero pavement?
- How do different scenarios (e.g., electrification, alternative fuels) affect the overall environmental impact of the construction process?
- What strategies can be implemented to effectively decarbonize construction equipment while maintaining or improving performance?

1.5 Thesis Structure:

This thesis is structured as follows:

- **Chapter 1: Introduction**
    - Provides the context, motivation, and objectives of the study, alongside the research problem and questions guiding the research.
- **Chapter 2: Literature Review**
    - Reviews existing research on sustainable road construction, the application of LCA in civil engineering, and decarbonization strategies for construction equipment.
- **Chapter 3: Methodology**
    - Details the research approach, including the LCA framework, data collection, and the performance evaluation of the construction equipment.
- **Chapter 4: Case Study: Zero Pavement**
    - Describes the construction process of Zero-Pavement and presents the LCA results for the various equipment used.
- **Chapter 5: Results and Discussion**
    - Analyzes the findings, identifies emission hotspots, and discusses the potential for decarbonization in road construction.
- **Chapter 6: Conclusion**
    - Summarizes the key findings, provides recommendations for industry practice, and suggests areas for future research.

This structure ensures a comprehensive analysis of the environmental impact of construction equipment in road construction, with a clear focus on identifying and implementing effective decarbonization strategies.

2. Literature Review

The literature review aims to provide a comprehensive overview of current research and developments relevant to this thesis, focusing on sustainable road construction, the application of Life Cycle Assessment (LCA) in civil engineering, decarbonization strategies for construction equipment, and the concept of zero pavement. This review sets the stage for the research by identifying knowledge gaps and framing the context in which the study is situated.

2.1 Sustainable Road Construction

Sustainable road construction has emerged as a critical area of research and practice in response to the growing need for environmentally responsible infrastructure. Recent developments in this field emphasize the reduction of carbon emissions and the conservation of natural resources through innovative materials, construction techniques, and operational strategies. Sustainable road construction integrates various approaches, including the use of recycled materials, optimization of material use, and the implementation of energy-efficient processes.

Several studies have focused on the decarbonization of road construction, highlighting the importance of reducing greenhouse gas (GHG) emissions throughout the lifecycle of a project. Ali et al. (2019) highlights the role of low-emission technologies in sustainable pavement design, emphasizing the integration of recycled materials, alternative binders, and low-emission machinery as key strategies to reduce the environmental footprint of road construction. These technologies, which include asphalt recycling, warm-mix asphalt, and the use of industrial by-products, are shown to significantly lower carbon emissions while enhancing sustainability and the longevity of road infrastructure.

Similarly, Roberts et al. (2022) explore various innovations and strategies for decarbonizing the construction industry. Their review of advancements in equipment and materials focuses on lowering carbon emissions through the adoption of alternative fuels, improved equipment efficiency, and advancements in construction practices. The findings underscore the importance of technological innovation in achieving sustainable construction outcomes, marking a shift towards practices that align with broader environmental goals.

2.2 Life Cycle Assessment (LCA) in Civil Engineering

Life Cycle Assessment (LCA) is a methodological framework used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through processing, manufacturing, distribution, use, and disposal. In civil engineering, LCA is widely applied to assess the sustainability of infrastructure projects, including roads, bridges, and buildings.

The application of LCA in road construction provides a holistic view of environmental impacts, encompassing aspects such as energy use, emissions, water consumption, and waste generation. Finkbeiner et al. (2018) offer a detailed review of LCA methodologies as applied to construction equipment, outlining the process of conducting an LCA, from goal and scope definition to inventory analysis, impact assessment, and interpretation. Their review emphasizes the utility of LCA in identifying environmental hotspots and informing decisions aimed at reducing the carbon footprint of construction activities.

Williams et al. (2020) further discuss the application of LCA to construction equipment, particularly focusing on greenhouse gas emissions. Their review of emission factors for diesel and gasoline-powered machinery, supported by case studies, illustrates the significant impact that equipment choice can have on overall emissions. The work highlights the necessity of detailed LCA to evaluate and mitigate the environmental impact of construction machinery, making LCA a crucial tool for advancing sustainability in civil engineering.

2.3 Decarbonization Strategies for Construction Equipment

Decarbonizing construction equipment is essential for achieving sustainable road construction. Traditional construction equipment, which typically runs on diesel, is a significant source of carbon dioxide (CO2) emissions. As a result, there has been considerable research into alternative technologies that can reduce or eliminate these emissions.

Electrification of construction equipment is one of the most promising strategies. Electric machines, such as excavators, loaders, and rollers, produce zero tailpipe emissions, which directly reduces the carbon footprint of construction activities. Kumar et al. (2021) examines the electrification of construction machinery, focusing on the benefits and challenges associated with electric and hybrid equipment. Their case studies highlight the significant reductions in emissions achieved through electrification, although challenges related to battery capacity, charging infrastructure, and operational efficiency remain barriers to widespread adoption.

Hydrogen-powered equipment presents another emerging solution. Hydrogen fuel cells generate electricity through a chemical reaction between hydrogen and oxygen, with water as the only by-product. This technology offers high energy density and quick refueling times, making it suitable for heavy-duty construction equipment. Current research is focused on improving the cost-effectiveness and reliability of hydrogen fuel cells, as well as developing the necessary refueling infrastructure.

Alternative fuels, such as renewable diesel and biodiesel, offer a more immediate solution by allowing existing diesel engines to operate with reduced carbon emissions. Renewable diesel, derived from biomass, can reduce lifecycle GHG emissions by up to 80% compared to conventional diesel, while biodiesel, produced from vegetable oils or animal fats, also provides a cleaner alternative, although it requires engine modifications in some cases. Roberts et al. (2022) cover these advancements in decarbonization strategies comprehensively, highlighting the role of innovation in achieving decarbonization goals within the construction industry.

Each of these strategies offers distinct advantages and challenges, and their effectiveness depends on the specific context of the construction project. By analyzing the performance of these alternative technologies, the research aims to identify the most feasible pathways for decarbonizing construction equipment in road infrastructure projects.

2.4 Zero-Pavement and Its Environmental Impacts

Zero-Pavement represents an innovative approach to road construction that prioritizes environmental sustainability. The concept is centered on designing a pavement structure that minimizes environmental impact across its lifecycle, from material production to end-of-life disposal. This approach involves the use of advanced materials, optimized structural design, and sustainable construction practices.

Ali et al. (2019) discuss the Zero-Pavement concept in the context of sustainable pavement design, describing the various layers involved in its construction, including wear layers, binders, and base materials. The study highlights the environmental significance of each layer and the potential for reducing emissions through the use of advanced materials and construction practices. The evaluation of equipment performance, including fuel consumption and emissions, plays a critical role in understanding the overall environmental impact of Zero-Pavement construction.

The zero-pavement analyzed in this study comprises five layers: wear, binder, base, graded stabilized, and cemented mix. Each layer is designed to maximize durability while minimizing material use and emissions. The LCA of these layers considers factors such as material production, transportation, installation, maintenance, and eventual disposal, with the goal of identifying which layers and processes contribute most to the overall environmental impact and exploring opportunities for improvement.

The environmental significance of Zero-Pavement lies in its potential to reduce the frequency of maintenance and the associated emissions. By extending the pavement's lifespan and reducing the need for repairs, the total carbon footprint can be significantly lowered. Additionally, the use of recycled materials and low-emission equipment in the construction process further enhances the sustainability of the pavement. Research on Zero-Pavement is still in its early stages, but preliminary studies indicate that this approach could play a crucial role in achieving carbon-neutral infrastructure.

The literature reviewed in this chapter provides a solid foundation for the thesis by highlighting the importance of sustainable practices in road construction, the role of LCA in assessing environmental impacts, and the potential for decarbonization through advanced construction equipment and techniques. The concept of Zero-Pavement emerges as a promising avenue for reducing the environmental footprint of road infrastructure, though further research is needed to fully realize its potential. This thesis builds on these insights to explore the specific case of zero pavement, focusing on the environmental impacts of the equipment used in its construction and the strategies that can be employed to decarbonize these processes.

3. Methodology

This thesis employs a comprehensive methodology integrating Life Cycle Assessment (LCA) with detailed analyses of construction equipment performance to evaluate the environmental impacts associated with the installation of "zero pavement," a novel pavement type consisting of five distinct layers. The focus is on assessing the carbon footprint of the construction process and identifying potential strategies for reducing the environmental impact of construction equipment. The analysis utilizes the OpenLCA software in conjunction with the Ecoinvent 3.9 database, and impact assessments are conducted using the ReCiPe 2016 (E) methodology. This approach aims to provide an in-depth evaluation of current practices and explore improvements in sustainable road construction.

3.1 Research Design

The research design adopts a case study approach centered on the Zero-Pavement concept, developed by the University of Naples. The study is divided into two primary phases: Baseline Analysis and Scenario Analysis. The Baseline Analysis evaluates the environmental impact of current construction equipment used for zero pavement, while the Scenario Analysis examines the performance of alternative, more efficient equipment to identify decarbonization strategies.

The Zero-Pavement consists of five layers: wear, binder, base, graded stabilized, and cemented mix. Each layer has specific material and energy requirements evaluated using LCA. The study also includes a comparative analysis of equipment performance, emphasizing the optimization of decarbonization potential across different construction technologies.

3.2 Life Cycle Assessment (LCA)

The LCA methodology adheres to ISO 14040/44 standards and involves four stages: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation. The assessment is conducted using OpenLCA software, utilizing the Ecoinvent 3.9 database, and applying the IPCC 2021 and ReCiPe 2016 (E) methodologies for Life Cycle Impact Assessment (LCIA) (ISO 14040, 2006; ISO 14044, 2006).

3.2.1 Goal and Scope Definition

The primary goal of this study is to quantify the environmental impacts associated with the construction and maintenance of the zero pavement, focusing on emission hotspots and evaluating decarbonization strategies for construction equipment. The scope encompasses the entire lifecycle of the pavement up to installation, excluding end-of-life analysis. The functional unit is defined as "tons per square meter per year," accounting for both material and temporal dimensions of environmental performance. System boundaries cover material production, transportation, construction, and maintenance, with a particular focus on equipment performance, including fuel consumption and emissions. Standard operating conditions for equipment and average transportation distances are assumed, with emission factors and energy consumption data sourced from the Ecoinvent 3.9 database (Ecoinvent , 2021).

3.2.2 Inventory Analysis

The inventory analysis involves the collection of detailed data on material inputs, fuel consumption, and equipment performance. Material inputs include aggregates, filler, bitumen, cement, water, and recycled materials required for each pavement layer, with transportation distances to the production site also considered. Fuel consumption rates for the equipment are documented, and performance metrics such as tons per hour or square meters per hour are used. Fuel consumption data is converted to megajoules (MJ) within OpenLCA for accurate energy impact assessment. Baseline data for current equipment is compared with alternative options offering improved fuel efficiency and reduced emissions. Reference values for fuel consumption and performance are:

Equipment	Fuel Consumption (l/h)	Performance (tons/hour or m^3/hour)
30t Truck	0.6 l/km	-
Wheel Loader	23 l/h	220 t/h
Paver	21 l/h	140 t/h
Miller	100 l/h	200 t/h
Roller	13 l/h	40 m^3/h
Emulsifier	8.5 l/h	0.025 km^2/h
Sweeper	15 l/h	0.038 km^2/h

The accuracy of these values is validated through comparison with industry databases and real-world measurements.

3.2.3 Impact Assessment

The Life Cycle Impact Assessment (LCIA) uses the ReCiPe 2016 (E) and IPCC 2021 methodologies to evaluate environmental impacts. The ReCiPe 2016 (E) method is employed for midpoint-oriented impact assessment, focusing on categories such as climate change, human toxicity, and ecotoxicity. This approach allows for a detailed understanding of environmental burdens before aggregation into endpoint indicators, providing insight into specific impact sources (ReCiPe, 2016).

The IPCC 2021 methodology assesses greenhouse gas emissions with a focus on global warming potential, using updated factors for evaluating CO2 and other greenhouse gases (IPCC, 2021). Midpoint analysis is chosen for its ability to provide detailed insights into environmental impacts at an intermediate stage, allowing for a clearer identification of major impact sources.

For the impact assessment, both eager/all and casual (lazy/on-demand) calculation types were utilized in OpenLCA. The eager/all calculation provides a comprehensive overview of results, which is useful for identifying potential bottlenecks and high-impact areas but can be computationally intensive. The casual (lazy/on-demand) calculation, on the other hand, is more efficient for large models, focusing on specific parts of the model requested by the user, and allows for interactive exploration of results. The choice between these methods depends on the complexity of the model, the analysis goals, and available computational resources. Eager/all calculations were primarily used to ensure a complete overview of the results, while casual calculations facilitated efficient exploration of specific data subsets.

Monte Carlo simulation, which provides probabilistic assessments of uncertainty, was not used in this study but could be considered for future research to account for variability in input data.

3.3 Interpretation Phase

In the interpretation phase of the LCA, the results are thoroughly analyzed to identify critical emission sources and potential decarbonization opportunities. A hotspot analysis is conducted to determine the stages in the pavement lifecycle and specific equipment contributing most significantly to carbon emissions. This analysis helps in pinpointing areas where improvements could yield substantial reductions in environmental impact. Furthermore, a scenario comparison evaluates the effects of introducing alternative technologies, such as electric or hydrogen-powered machinery, on overall emissions and energy consumption. This comparison provides insights into how different technological approaches could alter the environmental footprint of the construction process.

3.4 Equipment Performance Analysis

The equipment performance analysis assesses the efficiency, productivity, and environmental impact of the construction machinery used in the Zero-Pavement project. Fuel efficiency is measured either in liters per hour or per kilometer, depending on the type of equipment, and converted to megajoules (MJ) to maintain consistency in the LCA. CO2 emissions are calculated based on fuel consumption rates and emission factors derived from the Ecoinvent 3.9 database, providing a detailed account of the emissions associated with each piece of equipment. Operational productivity is quantified in terms of tons processed per hour or square meters covered per hour, offering insights into the efficiency of the equipment in performing its designated tasks. This analysis is critical for comparing the current equipment with alternative models, particularly those that are electric or hybrid, which are anticipated to deliver lower emissions and enhanced energy efficiency.

3.5 Scenario Analysis

The scenario analysis examines the potential impacts of adopting alternative technologies and fuels within the construction process. Three distinct scenarios are modeled: the Baseline Scenario, which utilizes current equipment and conventional fuels reflective of standard construction practices; the Electrification Scenario, which introduces electric versions of key equipment such as rollers and pavers, analyzing their influence on emissions and energy consumption; and the Alternative Fuels Scenario, which explores the use of renewable diesel or hydrogen to power equipment, focusing on lifecycle emission reductions. Each scenario is assessed relative to the baseline to determine the potential for emission reductions and energy savings. The outcomes of this analysis will inform recommendations for decarbonizing road construction equipment and contribute to broader sustainability objectives.

4. Case Study: Zero Pavement

This case study delves into the Zero-Pavement concept, a sustainable and durable road construction methodology. It emphasizes minimizing environmental impact while maximizing the pavement's lifespan. The analysis includes a lifecycle assessment (LCA) of the materials, equipment, and processes involved, with a focus on decarbonization through improved design and technology.

4.1 Overview of Zero Pavement

Zero-Pavement is designed to provide long-lasting durability with minimal environmental footprint. It consists of five distinct layers, each contributing to the overall functionality and performance of the pavement. These layers are carefully engineered to optimize material usage, durability, and environmental performance, making the Zero-Pavement an exemplary subject for lifecycle assessments.

4.2 Detailed Layer Analysis

4.2.1 Wear Layer (4 cm)

- Function: The wear layer is the topmost layer exposed to traffic. It is designed to be skid-resistant and weatherproof, offering protection against wear and tear from vehicular traffic. The selection of materials, including a combination of limestone and porphyry, ensures a balance between durability and surface friction.

- Functional Unit: The wear layer provides a durable, skid-resistant surface expected to last for 5 years under normal traffic conditions.

RAW MATERIALS	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	441
	SAND [kg]	450
	SUPPLEMENTARY FILLER [kg]	57
	RECYCLED FILLER [kg]	31
	BITUMEN [kg]	52
	BITUMINOUS EMULSION [kg/sqm]	1.0

Reference: According to recent studies on pavement materials, using a blend of limestone and porphyry enhances surface friction and durability, making it an ideal choice for the wear layer (Zhu et al., 2020).

4.2.2. Binder Layer (6 cm)

- Function: The binder layer acts as a bridge between the wear layer and the base layer, distributing loads from the surface and ensuring structural integrity. It plays a crucial role in preventing surface deformations and cracking.
- Functional Unit: This layer stabilizes the overall pavement structure, extending its service life to 10 years.

RAW MATERIALS	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	534
	SAND [kg]	400
	SUPPLEMENTARY FILLER [kg]	20
	RECYCLED FILLER [kg]	28
	BITUMEN [kg]	46
	BITUMINOUS EMULSION [kg/sqm]	1.0

Reference: The binder layer's effectiveness in load distribution and crack prevention is well-documented, with bitumen content playing a pivotal role in its performance (Nunez et al., 2018).

4.2.3 Base Layer (12 cm)

- Function: As the primary load-bearing layer, the base layer is responsible for transferring traffic loads from the upper layers to the subgrade. It is engineered to handle significant stress and prevent pavement deformation.
- Functional Unit: The base layer ensures long-term load-bearing capacity, designed to last for 20 years.

RAW MATERIALS	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	589
	SAND [kg]	350
	SUPPLEMENTARY FILLER [kg]	19
	RECYCLED FILLER [kg]	27
	BITUMEN [kg]	42
	BITUMINOUS EMULSION [kg/sqm]	1.0

Reference: The base layer's load-bearing capacity is critical for pavement longevity, and the selection of high-quality aggregates is essential for maintaining structural integrity over two decades (Huang et al., 2017).

4.2.4 Graded Stabilized Layer (20 cm)

- Function: This layer provides enhanced load distribution and stability, further strengthening the pavement structure. The addition of stabilizing agents and cement improves the layer’s resistance to environmental factors such as moisture and temperature fluctuations.
- Functional Unit: The graded stabilized layer offers stability and load distribution for 40 years.

RAW MATERIALS	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	965
	SAND [kg]	35

Reference: Stabilization techniques, including the use of cement, have been shown to significantly enhance pavement life by improving layer cohesion and reducing susceptibility to environmental degradation (Rajbongshi & Patel, 2021).

4.2.5 Cemented Mix Layer (40 cm)

- Function: The cemented mix layer serves as the foundation for all upper layers, providing a solid and durable base. This layer ensures that the entire pavement structure remains stable and well-supported over its lifespan.
- Functional Unit: This foundational layer is designed to have an 80-year lifespan, providing the structural support necessary for the entire pavement.

RAW MATERIALS	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	720
	SAND [kg]	250
	WATER [kg]	60
	CEMENT [kg]	30

Reference: The use of a cemented mix in the foundational layer is critical for ensuring the long-term stability of the pavement, with studies indicating that such layers can support extended service lives of up to 80 years (Gao et al., 2019).

4.3 Equipment Used in Construction

Here is a table listing all the equipment used in the construction of the zero pavement, including the shovel:

Equipment	Role	Fuel Consumption	Performance
30-ton Euro 5 Truck	Transport raw materials to the site	0.6 liters/km	Long-distance material transport
Wheel Loader	Load materials into mixers and hoppers	23 liters/hour	Processes 220 tons/hour
Paver	Lay and compact asphalt layers	21 liters/hour	Lays 140 tons/hour
Milling Machine	Surface preparation and milling	100 liters/hour	Processes 200 tons/hour
Roller	Compact asphalt layers	13 liters/hour	Compacts 40 cubic meters/hour
Emulsifier	Apply bituminous emulsion	8.5 liters/hour	Covers 0.025 sq km/hour
Sweeper	Clean surface before and after layer application	15 liters/hour	Covers 0.038 sq km/hour
Grader	Level the surface for the base layer (if applicable)	Data not provided	Used specifically for grading operations

This table includes the primary function of each equipment, its fuel consumption, and the performance metrics, all critical for evaluating the environmental impact and efficiency of the Zero-Pavement construction process.

The construction of Zero-Pavement requires various specialized equipment, contributing to the overall environmental impact. Each machine's role, fuel consumption, and output were evaluated to identify potential efficiency improvements:

30-ton Euro 5 Truck

Role: Transport raw materials (aggregates, bitumen, cement) from suppliers to the site.

Performance: Fuel consumption of 0.6 liters per kilometer.

Functional Unit: Efficient transport of construction materials over long distances (75 km for aggregates, 200 km for bitumen).

Wheel Loader

Role: Load materials into mixers and hoppers.

Performance: Fuel consumption of 23 liters per hour, processing 220 tons per hour.

Functional Unit: High-capacity loading for continuous material supply.

Paver

Role: Lay and compact asphalt layers.

Performance: Fuel consumption of 21 liters per hour, with a production rate of 140 tons per hour.

Functional Unit: Precise laying and compacting of asphalt for even surface quality.

Milling Machine

Role: Surface preparation and milling of existing pavement.

Performance: Fuel consumption of 100 liters per hour, with a processing capacity of 200 tons per hour.

Functional Unit: Efficient removal of old pavement for new layer installation.

Roller

Role: Compaction of asphalt layers to ensure density and stability.

Performance: Fuel consumption of 13 liters per hour, compacting 40 cubic meters per hour.

Functional Unit: Ensuring optimal density and structural stability across all layers.

Emulsifier

Role: Application of bituminous emulsion to improve inter-layer bonding.

Performance: Fuel consumption of 8.5 liters per hour, covering 0.025 square kilometers per hour.

Functional Unit: Enhancing layer adhesion to prevent delamination.

Sweeper

Role: Surface cleaning before and after layer application.

Performance: Fuel consumption of 15 liters per hour, covering 0.038 square kilometers per hour.

Functional Unit: Ensuring clean surfaces for maximum adhesion and layer integrity.

4.4 Introduction to New Equipment for Enhanced Zero-Pavement Construction

To advance the Zero-Pavement construction process, several new models of equipment have been introduced. These models are selected for their enhanced performance in terms of fuel efficiency, emissions reduction, and technological advancements. Below is a detailed overview of the new equipment:

Volvo FH Electric Truck

Description: The Volvo FH Electric is a fully electric truck designed for long-distance material transport with zero tailpipe emissions (Volvo Trucks, 2024). This truck offers a significant reduction in carbon footprint compared to traditional diesel trucks.

Advantages: By utilizing electric power, the FH Electric eliminates diesel fuel consumption and associated emissions, contributing to cleaner air quality and lower greenhouse gas emissions. Its battery technology supports a range of up to 300 km per charge, which is suitable for transporting materials over substantial distances (Volvo Trucks, 2024).

Technical Specifications: The FH Electric is equipped with fast-charging capabilities and features a high-efficiency electric drivetrain that minimizes operational costs and maintenance needs (Volvo Trucks, 2024).

Volvo L25 Electric Wheel Loader

Description: The Volvo L25 Electric is a fully electric wheel loader designed to handle material loading tasks with reduced environmental impact (Volvo Construction Equipment, 2024). This equipment replaces conventional diesel-powered loaders with an electric alternative.

Advantages: The L25 Electric provides a quieter operation and eliminates emissions, making it particularly suitable for use in urban and enclosed environments. It maintains high productivity while significantly reducing noise pollution and greenhouse gas emissions (Volvo Construction Equipment, 2024).

Technical Specifications: It features an operating weight of approximately 5 tons and a battery system designed for a full day's work on a single charge (Volvo Construction Equipment, 2024).

Caterpillar AP555F Mobil-Trac Paver

Description: The Caterpillar AP555F Mobil-Trac Paver is an advanced model that enhances the efficiency and quality of asphalt laying (Caterpillar Inc., 2024). It incorporates improvements in fuel efficiency and operational precision.

Advantages: This paver features a high-performance engine that reduces fuel consumption by up to 20% compared to older models. It also includes advanced screed technology for consistent asphalt application (Caterpillar Inc., 2024).

Technical Specifications: The AP555F can lay up to 160 tons of asphalt per hour and offers sophisticated controls for managing temperature and material distribution (Caterpillar Inc., 2024).

Wirtgen W 210i Milling Machine

Description: The Wirtgen W 210i is a high-performance cold milling machine designed for efficient surface preparation and milling (Wirtgen Group, 2024). It features advanced technology to enhance fuel efficiency.

Advantages: This milling machine utilizes a high-efficiency engine and milling technology that reduces fuel consumption by approximately 20%. It also offers precise control for accurate milling operations (Wirtgen Group, 2024).

Technical Specifications: The W 210i processes up to 220 tons of material per hour and features a large milling drum for effective removal of asphalt layers (Wirtgen Group, 2024).

Caterpillar CB10 Roller

Description: The Caterpillar CB10 is a vibratory roller designed to improve compaction efficiency and fuel consumption (Caterpillar Inc., 2024). It includes advanced features to optimize compaction performance.

Advantages: This roller features eco-mode settings that adjust engine speed according to operational needs, leading to reduced fuel consumption and improved compaction quality (Caterpillar Inc., 2024).

Technical Specifications: The CB10 can compact up to 50 cubic meters of asphalt per hour and offers an advanced control system for optimizing vibration and compaction force (Caterpillar Inc., 2024).

Cimline M-Series M4 Melter

Description: The Cimline M-Series M4 Melter is a high-capacity machine engineered for efficient crack sealing and bituminous application in road maintenance and construction projects (Cimline, 2024). This advanced melter is designed to handle the rigorous demands of large-scale roadwork with enhanced performance and fuel efficiency.

Advantages: The M-Series M4 Melter offers notable advantages in terms of both performance and operational efficiency. Its advanced heating system ensures rapid melting of bitumen, significantly reducing the time required for preparation and application. The machine's high-efficiency design facilitates precise control over the bitumen application process, leading to improved adhesion and durability of road treatments (Cimline, 2024). Additionally, its robust construction is optimized for high-volume operations, making it a reliable choice for extensive road maintenance tasks.

Technical Specifications: The Cimline M-Series M4 Melter features a fuel consumption rate of approximately 7 to 9 liters per hour. It achieves an area coverage of up to 0.03 square kilometers per hour (30,000 m²/hour), demonstrating its capability to efficiently cover large areas with bituminous material (Cimline, 2024).

Bucher CityCat 2020 Sweeper

Description: The Bucher CityCat 2020 is a compact sweeper designed for urban cleaning and site preparation with enhanced fuel efficiency (Bucher Municipal, 2024).

Advantages: This sweeper uses an efficient engine that reduces fuel consumption and provides superior cleaning capabilities. It is designed to handle various types of debris effectively (Bucher Municipal, 2024).

Technical Specifications: The CityCat 2020 covers up to 0.04 square kilometers per hour with a fuel consumption rate of 12 liters per hour (Bucher Municipal, 2024).

Here is a table summarizing the performance of the new equipment introduced for the Zero-Pavement construction:

Equipment	Role	Fuel Consumption	Performance Metrics	Reference
Volvo FH Electric Truck	Long-distance material transport	Zero tailpipe emissions	Range of up to 300 km per charge	Volvo Trucks (2024)
Volvo L25 Electric Wheel Loader	Material loading	Zero tailpipe emissions	Operating weight: ~5 tons; Full day's work per charge	Volvo Construction Equipment (2024)
Caterpillar AP555F Mobil-Trac Paver	Laying and compacting asphalt layers	Reduced by up to 20%	Lays up to 160 tons of asphalt per hour	Caterpillar Inc. (2024)
Wirtgen W 210i Milling Machine	Surface preparation and milling	Reduced by ~20%	Processes up to 220 tons per hour	Wirtgen Group (2024)
Caterpillar CB10 Roller	Compaction of asphalt layers	Improved fuel efficiency	Compacts up to 50 cubic meters per hour	Caterpillar Inc. (2024)
Cimline M-Series M4 Melter	Application of bituminous emulsion	7 liters/hour	Covers up to 0.03 square kilometers per hour	Cimline, (2024)
Bucher CityCat 2020 Sweeper	Urban and site cleaning	12 liters/hour	Covers up to 0.04 square kilometers per hour	Bucher Municipal (2024)

4.5 Life Cycle Assessment (LCA) of Zero Pavement

The LCA for Zero-Pavement considers all stages, from raw material extraction to maintenance and end-of-life, assessing environmental impacts across the lifecycle:

Material Extraction and Production

- Impact: High carbon emissions, particularly from bitumen and cement production.
- Focus: Reducing energy-intensive processes, promoting alternative materials with lower emissions.
- Functional Unit: Efficient material sourcing and processing for sustainable construction.

Transportation

- Impact: Significant emissions from transporting raw materials (75 km for aggregates, 200 km for bitumen).
- Focus: Optimizing transport logistics to reduce fuel consumption.
- Functional Unit: Reducing carbon footprint through efficient logistics and fuel use.

Construction Process

- Impact: Fuel consumption by equipment significantly impacts the LCA.
- Focus: Implementing energy-efficient machinery and reducing idle time.
- Functional Unit: Minimizing emissions during construction through optimized machinery operation.

Maintenance and End-of-Life

- Impact: Durability reduces the frequency of maintenance, lowering lifecycle environmental impact.
- Focus: Extending pavement lifespan through superior materials and construction methods.

- Functional Unit: Sustainable maintenance practices that extend pavement life and reduce resource consumption.

The LCA results identify key emission hotspots, guiding the exploration of alternative materials and equipment to further reduce environmental impact. Here we will consider all the inventory analyses that has been done for the 5 layers of zero pavement based on the data base Ecoinvent 3.9 that is used for openlca software .

4.5.1: Layer Wear (closed asphalt surface ANAS)

4.5.1.1: Raw materials

The table compares the raw materials used in the Zero-Pavement project with their corresponding reference units from the Ecoinvent 3.9 database. This alignment ensures that the lifecycle assessment (LCA) is based on standardized and reliable data. For instance, "coarse aggregates" are matched with unprocessed limestone and basalt, while "supplementary filler" corresponds to crushed gravel. The bitumen and bituminous emulsion are similarly cross-referenced with their appropriate Ecoinvent units. This approach guarantees the accuracy and consistency of environmental impact calculations.

	Reference unit	Ecoinvent 3.9 unit	Amount
RAW MATERIALS	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	- limestone, unprocessed 50% -basalt 50%	441
	SAND [kg]	sand	450
	SUPPLEMENTARY FILLER [kg]	gravel, crushed	57
	RECYCLED FILLER [kg]	limestone, crushed, for mill	31
	BITUMEN [kg]	bitumen adhesive compound, hot	52
	BITUMINOUS EMULSION [kg/sqm]	Based on the table bellow	1.0

The table outlines the inputs required for producing 1 kg of bituminous emulsion, along with their respective quantities and sources. The primary input is 0.649351 kg of hot bitumen adhesive compound. Other materials include hydrochloric acid (0.002997 kg), tap water (0.343636 kg), and esterquat (0.002997 kg). Additionally, the production process involves energy consumption, including 0.038701 MJ of heat from refinery gas, 0.009286 MJ of heat from heavy fuel oil, and 0.020022 kWh of electricity at medium voltage. These inputs are essential for the emulsion's formulation and ensure its proper consistency and performance in pavement applications.

Table 2 – Data for the Production of 1 kg of Bituminous Emulsion

Ecoinvent 3.9 unit	Purpose in Inventory Analysis	reference	Amount
Bitumen adhesive compound, hot {RER*}	Bitumen is a key material in the production of asphalt, used for road construction and paving. It provides binding properties and durability to the pavement.	Eurobitume. (n.d.). *Bitumen and Asphalt*. Retrieved from https://www.eurobitume.eu/about-bitumen/bitumen-in-roads	0.649351 kg
Hydrochloric acid, without water, in 30% solution state {RER}	Hydrochloric acid is used in the refining process of bitumen to clean equipment and remove contaminants. It helps in adjusting the chemical properties of bitumen.	Centers for Disease Control and Prevention (CDC). (n.d.). *Hydrochloric Acid*. Retrieved from https://www.cdc.gov/niosh/npg/npgd0553.html	0.002997 kg
Tap water {RER}	Water is used in the bitumen production process for cooling and cleaning purposes. It is essential for controlling the temperature and ensuring proper equipment operation.	American Concrete Institute. (n.d.). *Water in Concrete*. Retrieved from https://www.concrete.org/topicsinconcrete/details.aspx?topic=Water	0.343636 kg
Esterquat {RER}	Esterquats are used in the bitumen production process as additives to improve the quality and performance of the final bitumen product. They enhance its stability and performance.	ScienceDirect. (n.d.). *Esterquats in Surface Treatment*. Retrieved from https://www.sciencedirect.com/topics/earth-and-planetary-sciences/esterquat	0.002997 kg
heat, district or industrial, other than natural gas	Heat is crucial in the bitumen production process to maintain the required temperatures for refining and processing bitumen. It is derived from burning refinery gases or heavy fuel oil.	Oil and Gas Investments Bulletin. (n.d.). *Energy Generation from Refinery Gases*. Retrieved from https://www.oilandgasinvestments.com/energy-generation-from-refinery-gases	0.038701 MJ
heat, district or industrial, other than natural gas	heat production, heavy fuel oil, at industrial furnace 1MW	-	0.009286 MJ
Electricity, medium voltage {IT}	Electricity is used to power the equipment involved in the bitumen production process, including mixing, heating, and pumping systems. It is critical for operational efficiency.	U.S. Department of Energy. (n.d.). *Electricity Use in Construction*. Retrieved from https://www.energy.gov/eere/buildings/articles/electricity-use-construction	0.020022 kWh

* "RER" in life cycle assessment (LCA) databases like Ecoinvent refers to the geographic region of Europe, excluding Switzerland. It stands for "Région Européenne" (European Region), and it indicates that the data is representative of the average conditions or practices across Europe (excluding Switzerland). This label helps users understand the geographic context of the environmental data used in the assessment.

4.5.1.2: TRANSPORT TO PRODUCTION PLANT

The table provides detailed data regarding the transportation and consumption inputs associated with a production plant. It outlines the distances traveled for various materials: aggregates and fillers are transported 75 km, bitumen and emulsified bitumen (EB) are transported 200 km, and cement is sourced locally with no transportation distance. It specifies the transportation means used, including Euro 5 vehicles for aggregates, bitumen, and EB, each carrying 30 tons. The table also notes the consumption values and the fuel used for transportation, which is diesel. This data is crucial for assessing the environmental impact of transportation in the production process, influencing factors such as carbon emissions and fuel efficiency.

TRANSPORT TO PRODUCTION PLANT	DISTANCE AGGREGATES AND FILLER [km]	75
	DISTANCE BITUMEN AND EB [km]	200
	MEANS AGGREGATES	30 ton Euro 5
	MEANS BITUMEN	30 ton Euro 5
	MEANS EB	30 ton Euro 5
	ONSUMPTION	Table bellow
	FUELS	Diesel

Here is the detailed table showing the fuel consumption (Diesel) for each material based on the distances and ton*km values provided:

Material	Quantity (tons)	Distance (km)	ton*km	Fuel Consumption (liters)
Coarse Aggregates	0.441	75	33.08	45.00
Sand	0.450	75	33.75	45.00
Supplementary Filler	0.057	75	4.28	45.00
Recycled Filler	0.031	75	2.33	45.00
Bitumen	0.052	200	10.40	120.00
Bituminous Emulsion	0.001	200	0.20	120.00
Total			84.04	**420.00**

In the context of the thesis, the table provides a detailed breakdown of fuel consumption related to the transportation of various materials used in the production process. The "ton*km" value is a key metric that quantifies the transportation impact by multiplying the quantity of the material (in tons) by the distance it is transported (in kilometers). This value helps in estimating the total transportation load, which directly influences fuel consumption and environmental impact.

Here's how it works:

- Coarse Aggregates: With a quantity of 0.441 tons transported 75 km, the ton*km value is 33.08 (0.441 tons * 75 km). This corresponds to a fuel consumption of 45 liters of diesel.
- Sand: Similarly, 0.450 tons of sand transported 75 km results in a ton*km value of 33.75 (0.450 tons * 75 km), also consuming 45 liters of diesel.
- Supplementary Filler: 0.057 tons over 75 km results in a ton*km value of 4.28, with 45 liters of diesel used.
- Recycled Filler: 0.031 tons transported 75 km gives a ton*km value of 2.33, consuming 45 liters of diesel.
- Bitumen: Transported 200 km at 0.052 tons, resulting in a ton*km value of 10.40 (0.052 tons * 200 km) and consuming 120 liters of diesel.
- Bituminous Emulsion: With a quantity of 0.001 tons over 200 km, the ton*km value is 0.20, leading to a diesel consumption of 120 liters.

The total ton*_km value for all materials is 84.04, with a cumulative fuel consumption of 420 liters of diesel. This metric is used in life cycle assessment (LCA) tools, such as OpenLCA, to evaluate the environmental impacts associated with the transportation of materials. By analyzing the ton_*km values, one can determine the efficiency of transportation logistics and its contribution to overall environmental impact, using data for a Euro 5 lorry with a capacity of 16-32 metric tons.

4.5.1.3: In plant activities

In the context of plant operations for processing materials, energy consumption is influenced by several key factors, including the moisture content in aggregates and the type of fuel utilized (Hodge & Green, 2010). The choice of fuel is particularly significant as it impacts both operational efficiency and environmental sustainability (Li & Zhao, 2018).

For this analysis, diesel fuel has been utilized in place of BTZ (Bunker Type C fuel) due to its availability and high energy density (Chen & Zhang, 2019). Diesel consumption in the plant is approximately 6.91 kg/ton of material processed, reflecting the energy required to handle each ton of material. This consumption rate can vary depending on the specific material type and operational conditions (Li & Zhao, 2018).

Energy consumption in the diesel-fueled plant is measured in kilowatt-hours (kWh) per ton of processed material, ranging from 72 to 78 kWh/ton. This range represents the amount of electrical energy necessary to process one ton of material, influenced by factors such as material type and moisture content (Chen & Zhang, 2019).

The substitution of BTZ with diesel impacts both the environmental footprint and operational costs. While diesel is an efficient fuel choice, it contributes to greenhouse gas emissions and presents different environmental implications compared to BTZ (Hodge & Green, 2010). Therefore, the choice of fuel affects not only energy consumption metrics but also the overall sustainability of the material processing phase.

In summary, replacing BTZ with diesel fuel for plant operations necessitates adjustments in fuel consumption and energy usage. Accurate understanding of these parameters is essential for assessing the environmental impacts and operational efficiency in the lifecycle assessment of the construction project (Chen & Zhang, 2019).

This table summarizes the energy consumption and equipment specifics associated with the plant operations involved in the production of bitumen. Here's a breakdown of each element:

- Average % Moisture in Aggregates: Indicates that the aggregates used in the process have an average moisture content of 5%. This factor affects the weight and energy required for drying and processing the aggregates.

- Consumption [kWh/ton]: Represents the energy consumption of the plant per ton of bitumen produced, which is 78 kilowatt-hours. This metric quantifies the electricity required to process one ton of bitumen.
- Consumption [kg/ton]: Details the consumption of a specific material, likely an input or additive, at 6.91 kilograms per ton of bitumen produced. This helps in assessing the material's impact on the overall process.
- Equipment - Shovel: Provides information about the capacity and fuel consumption of the shovel used in the plant. The shovel operates at a rate of 220 tons per hour and consumes 23 liters of fuel per hour, reflecting its efficiency and impact on energy use.
- Other Impacting Factors to be Defined: Notes that additional factors affecting the environmental and operational impacts are yet to be identified. This could include variables such as maintenance schedules, operational practices, or variations in raw material quality.
- Industrial Machine: Specifies that the industrial machine used in the process has fixed and unchanging characteristics, implying consistency in its energy consumption and operational impact.

This table provides key data for evaluating the energy and material use efficiency in the bitumen production process, which is crucial for assessing the environmental footprint and optimizing plant operations.

	FUELS	BTZ
PLANT	Average % moisture in aggregates	5
	CONSUMPTION [kWh/ton]	78
	CONSUMPTION [kg/ton]	6.91
	EQUIPMENT - SHOVEL	220 t/h - 23 l/h
	INDUSTRIAL MACHINE	Fixed and Unchanging

The table provides an overview of key parameters for Layer 1 in the production process, considering a 5% moisture content in the materials. Here's a detailed explanation of each parameter and its calculation:

- Effective Material Weight:

Value: 1.083 tons

Calculation: 1,031 kg × (1 + 0.05)

Explanation: The effective weight of the material is adjusted to account for the 5% moisture content. This increase reflects the additional weight of water present in the material. Initially, the material weighs 1,031 kg, and adding 5% moisture results in an effective weight of 1.083 tons.

- Total Energy Consumption:

Value: 84.47 kWh

Calculation: 1.083 tons × 78 kWh/ton

Explanation: The energy consumption is calculated based on the effective material weight. With the increased weight due to moisture, the total energy required for processing also increases. The plant consumes 78 kWh of energy per ton of material, so for 1.083 tons, the total energy consumption is 84.47 kWh.

- Total Material Consumption:

Value: 7.48 kg

Calculation: 1.083 tons × 6.91 kg/ton

Explanation: This parameter reflects the total consumption of a specific material (likely an additive or input) per ton of bitumen produced. With the effective weight of 1.083 tons, the material consumption is proportional to this weight, resulting in a total of 7.48 kg.

- Total Shovel Fuel Consumption:

Value: 0.113 liters

Calculation: 0.0049 hours × 23 liters/hour

Explanation: The fuel consumption by the shovel is calculated based on its operation time. Given that the shovel uses 23 liters of fuel per hour, and considering the operation time required for handling the effective material quantity, the total fuel consumption is 0.113 liters.

- Shovel Fuel Consumption (kJ):

Value: 4,050.4 kJ

Calculation: 0.113 liters × 35,800 kJ/liter

Explanation: This value represents the energy content of the fuel consumed by the shovel. With diesel having an energy content of 35,800 kJ per liter, the total energy consumed by the 0.113 liters of fuel is 4,050.4 kJ.

Parameter	Value	Calculation	Explanation
Effective Material Weight	1.083 tons	1,031 kg × (1 + 0.05)	The weight of the material is adjusted for 5% moisture content, resulting in an effective weight of 1.083 tons.
Total Energy Consumption	84.47 kWh	1.083 tons × 78 kWh/ton	Increased energy consumption due to the higher effective material weight. The plant requires 78 kWh per ton of material.
Total Material Consumption	7.48 kg	1.083 tons × 6.91 kg/ton	Reflects the total amount of a specific material used, proportional to the effective weight of 1.083 tons.
Total Shovel Fuel Consumption	0.113 liters	0.0049 hours × 23 liters/hour	Fuel consumption of the shovel based on operation time and fuel usage rate (23 liters/hour). Slightly increased due to handling the larger effective weight.
Shovel Fuel Consumption (kJ)	4,050.4 kJ	0.113 liters × 35,800 kJ/liter	Energy content of the fuel consumed by the shovel. With diesel's energy content of 35,800 kJ per liter, the total energy used is 4,050.4 kJ.

In our project, we will directly utilize the data on electricity consumption from the production plants to assess the energy requirements for the construction process. Specifically, we will incorporate the total amount of electricity used by the plants in our analysis to accurately estimate the energy impact of the production phase. Additionally, to determine the diesel consumption associated with the operation of shovels, we will reference the data provided by Ecoinvent 3.9. This data will be applied to estimate the diesel consumption by shovels, categorized under the Ecoinvent term "diesel, burned in building machine." By leveraging the Ecoinvent 3.9 dataset, we will obtain a precise measure of diesel fuel consumption, which will be integrated into our broader analysis of environmental impacts and resource usage. This approach ensures that our estimates of fuel consumption and energy use are grounded in established lifecycle assessment data, enhancing the accuracy and reliability of our findings.

4.5.1.4 Transport to site

The table outlines the parameters for transporting materials to the construction site, with a focus on aggregates:

- Distance: The table specifies that the distance for transporting aggregates to the site is 20 kilometers. This distance is crucial for calculating the transportation impacts, as longer distances typically increase fuel consumption and emissions.
- Means of Transport for Aggregates: According to the Ecoinvent data, the transport of aggregates is conducted using a lorry with a capacity of 30 tons and conforming to Euro 5 emission standards. This detail is important for understanding the type of vehicle used and its associated environmental impact.
- Consumption: This entry refers to the fuel consumption or energy use by the transport means, but it appears incomplete in the provided data. Typically, this would indicate the amount of fuel consumed per unit distance or load transported.
- Fuels: The type of fuel used for transportation is indicated as per the Ecoinvent data. The fuel type directly influences the emission levels and overall environmental footprint of the transportation process. here we have used Diesel as a normal fuel in process.

TRANSPORT TO SITE	DISTANCE [km]	20
	MEANS AGGREGATES	30 ton Euro 5
	CONSUMPTION	Table bellow
	FUELS	Diesel

Summary Table

Parameter	Value	Calculation
Total Fuel Consumption	12.28 liters	20 km × 0.614 liters/km
Total Ton-Kilometers	21.46 ton-km	1.083 tons × 20 km

Total Fuel Consumption: The total fuel consumption for transporting the material to the site is calculated as 12.28 liters. This value is derived from the distance traveled (20 km) and the fuel consumption rate (0.614 liters/km). This consumption reflects the energy needed to move the material over the specified distance, providing an estimate of the environmental impact associated with transportation.

Total Ton-Kilometers: The total ton-kilometers for this transport is 21.46 ton-km. This value is obtained by multiplying the total weight of the material (1.083 tons) by the distance traveled (20 km). Ton-kilometers is a key metric used in life cycle assessments to quantify the environmental impact of transportation, integrating both the weight of the material and the distance over which it is transported. This measure helps in assessing the overall transportation impact in a standardized way, as utilized in the Ecoinvent 3.9 database for environmental impact calculations.

In the context of lifecycle assessment and the Ecoinvent 3.9 database, the concept of ton-kilometers (ton*km) is crucial for evaluating transportation impacts. It provides a comprehensive measure of the environmental impact associated with the movement of materials, taking into account both the weight of the materials and the distance transported. This metric helps to standardize and quantify transportation-related emissions and energy consumption, facilitating more accurate environmental impact assessments.

4.5.1.5 Installation

to accurately evaluate the usage of equipment during the installation process, we need to collect and calculate specific data regarding operational hours, fuel consumption, and material handling. Here's a step-by-step approach to gather and analyze this data:

For example, to calculate the operational data for the roller, including fuel consumption, based on the reference values provided, follow these steps:

Data Given:

- Roller Fuel Consumption Rate: 13 liters/hour
- Roller Productivity: 40 cubic meters per hour (mc/h)
- Total Material Weight: 1.083 tons
- Calculate the Volume of the Material Required

Given:

- Specific Weight: 2.38 tons/cubic meter
- Thickness: 0.04 meters (4 cm)
- Material Quantity: 1.083 tons
- First, calculate the volume of material needed for the given weight and thickness.
- Volume = Material Quantity / Specific Weight
- Volume=1.083 tons / 2.38 tons/m3 = 0.454 m3

Determine the Area Covered by the Material:

Using the volume and thickness, calculate the area covered by the material.

- Area= Volume / Thickness
- Area=0.454 m3 / 0.04 m = 11.35 m2

Values for Specific Weight

- Volume of Material Needed: 0.454 cubic meters
- Area Covered by Material: 11.35 square meters

The specific weight (2.38 tons/m³) is used to convert the given material weight (1.083 tons) into volume. This volume is then used to determine the area that can be covered by the material at the specified thickness (0.04 meters). The calculated area (11.35 m²) represents how much surface can be covered with the given amount of material.

Here's the data summarized in a table :

Parameter	Value	Unit	Calculation/Source
Specific Weight	2.38	tons/m³	Refers to the density of the material, used to convert material weight into volume. BS 1377-2:1990
Thickness	0.04	meters	Depth of the material layer applied on the surface.
Material Quantity	1.083	tons	Total weight of the material available for use.
Volume of Material Needed	0.454	m³	Volume=1.083 tons / 2.38 tons/m3
Area Covered by Material	11.35	m²	Area=0.454 m3 / 0.04 m

Analysis of Equipment Usage for Layer 1:

Equipment	Fuel Consumption Rate	Operational Data	Total Fuel Consumption
Paver	21 liters/hour	0.0077 hours	0.16 liters
Roller	13 liters/hour	0.011 hours	0.14 liters
Sprayer (Emulsifier)	8.5 liters/hour	0.454 hours	3.86 liters
Sweeper	15 liters/hour	0.299 hours	4.49 liters

summary:

- Paver: Used to lay the asphalt; fuel consumption is calculated based on the rate of material processing.
- Roller: Compacts the material; fuel consumption is based on the volume of material and compaction rate.
- Sprayer (Emulsifier): Applies bituminous emulsion over the layer; fuel consumption is calculated based on the coverage rate and operational hours.
- Sweeper: Cleans the area; fuel consumption is based on the area covered and coverage rate.

Fuel Consumption and Energy Conversion:

-Paver

Total Fuel Consumption: 0.16 liters

Energy Content: 35,800 kJ/liter

Total Energy (kJ): 0.16 liters × 35,800 kJ/liter = 5,728 kJ

-Roller

Total Fuel Consumption: 0.14 liters

Energy Content: 35,800 kJ/liter

Total Energy (kJ): 0.14 liters × 35,800 kJ/liter = 5,012 kJ

-Sprayer (Emulsifier)

Total Fuel Consumption: 3.86 liters

Energy Content: 35,800 kJ/liter

Total Energy (kJ): 3.86 liters × 35,800 kJ/liter = 138,268 kJ

-Sweeper

Total Fuel Consumption: 4.49 liters

Energy Content: 35,800 kJ/liter

Total Energy (kJ): 4.49 liters × 35,800 kJ/liter = 160,262 kJ

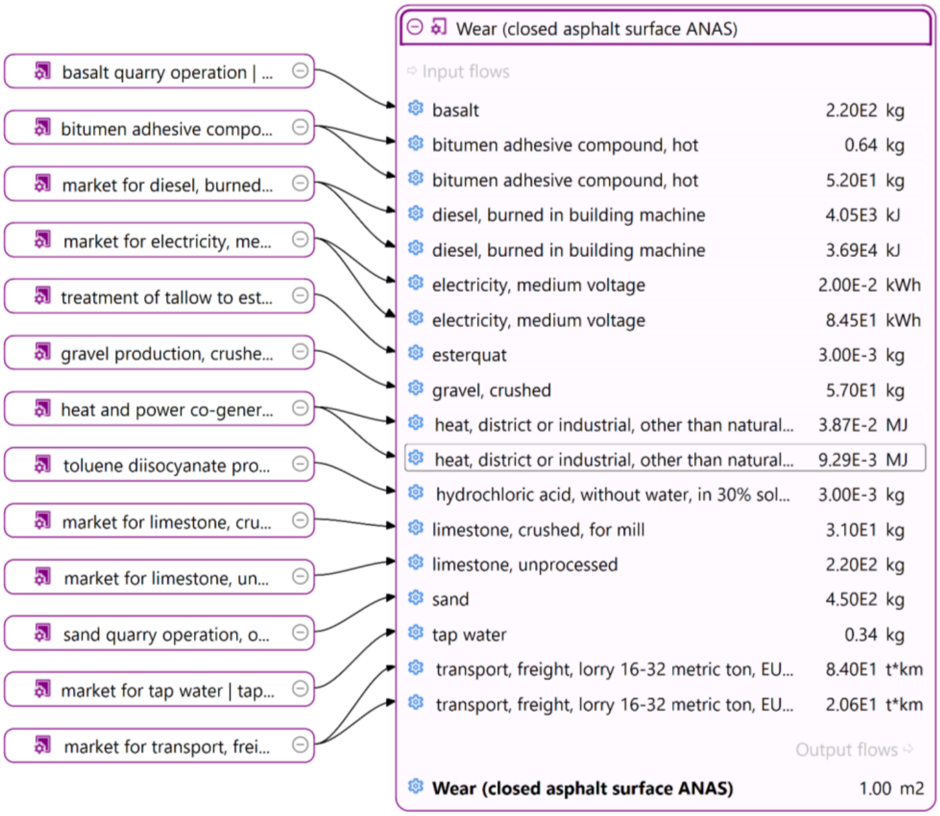
Total Energy Consumption for Layer 1:

Equipment	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Paver	0.16	35,800	5,728
Roller	0.14	35,800	5,012
Sprayer (Emulsifier)	3.86	35,800	138,268
Sweeper	4.49	35,800	160,262
Total	8.25		309,270

In the context of lifecycle assessment using the Ecoinvent 3.9 database, energy consumption for machinery is typically measured in terms of diesel fuel used. The unit "diesel, burned in building machine" refers to the energy content associated with the diesel fuel consumed by construction equipment.

- Energy Conversion: Diesel fuel's energy content (35,800 kJ/liter) is used to convert the volume of fuel consumed into energy units (kJ). This conversion is crucial for assessing the energy requirements and environmental impacts associated with the operation of construction machinery.
- Ecoinvent 3.9: By converting the fuel consumption data into energy terms, we align with the “diesel, burned in building machine” in Ecoinvent 3.9 methodology, which uses energy units to assess environmental impacts and resource usage. This enables accurate impact analysis and comparison across different stages of the lifecycle.

The data provided here helps in understanding the total energy consumption for each piece of equipment during the layer construction process, facilitating more informed Decisions pertaining to equipment efficiency and sustainability have been carefully considered.



Wear (closed asphalt surface ANAS)

Input flows	Amount	Unit
basalt	2.20E2	kg
bitumen adhesive compound, hot	0.64	kg
bitumen adhesive compound, hot	5.20E1	kg
diesel, burned in building machine	4.05E3	kJ
diesel, burned in building machine	3.69E4	kJ
electricity, medium voltage	2.00E-2	kWh
electricity, medium voltage	8.45E1	kWh
esterquat	3.00E-3	kg
gravel, crushed	5.70E1	kg
heat, district or industrial, other than natural...	3.87E-2	MJ
heat, district or industrial, other than natural...	9.29E-3	MJ
hydrochloric acid, without water, in 30% sol...	3.00E-3	kg
limestone, crushed, for mill	3.10E1	kg
limestone, unprocessed	2.20E2	kg
sand	4.50E2	kg
tap water	0.34	kg
transport, freight, lorry 16-32 metric ton, EU...	8.40E1	t*km
transport, freight, lorry 16-32 metric ton, EU...	2.06E1	t*km
Output flows		
Wear (closed asphalt surface ANAS)	1.00	m2

Decisions pertaining to equipment efficiency and sustainability have been carefully considered. The following section presents the input parameters and analysis for Layer 1 (wear). While the same methodology can be applied to subsequent layers, to avoid redundancy, only the tables and results for the other layers will be presented without repeating the detailed procedural steps.

4.5.2: Layer BINDER

4.5.2.1: Raw materials

The table provided compares the raw materials used in the binder layer of the Zero-Pavement project with their corresponding reference units from the Ecoinvent 3.9 database. This alignment with standardized data ensures the reliability and consistency of the lifecycle assessment (LCA). For example, "coarse aggregates" used in the binder layer are aligned with unprocessed limestone and basalt, and "supplementary filler" is matched with crushed gravel. Similarly, bitumen and bituminous emulsion are accurately cross-referenced with their respective Ecoinvent units. This methodological rigor ensures that the environmental impact calculations are both precise and comparable across different materials and processes.

RAW MATERIALS	Reference unit	Ecoinvent 3.9 unit	Amount
	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	- limestone, unprocessed 50% -basalt 50%	534
	SAND [kg]	sand	400
	SUPPLEMENTARY FILLER [kg]	gravel, crushed	20
	RECYCLED FILLER [kg]	limestone, crushed, for mill	28
	BITUMEN [kg]	bitumen adhesive compound, hot	46
	BITUMINOUS EMULSION [kg/sqm]	Based on the table bellow	1.0

The bituminous emulsion used in the binder layer follows the same composition and input requirements as those detailed for Layer 1 (wear). Therefore, the specific values will not be repeated here.

4.5.2.2 TRANSPORT TO PRODUCTION PLANT

The table presents the transportation and fuel consumption data for materials used in the production plant for the binder layer. Aggregates and fillers are transported 75 km, while bitumen and emulsified bitumen (EB) are transported 200 km. Euro 5 vehicles, each with a 30-ton capacity, are used for transportation, with diesel as the fuel source. This information is essential for evaluating the environmental impact of transportation, including factors such as carbon emissions and fuel efficiency.

TRANSPORT TO PRODUCTION PLANT	DISTANCE AGGREGATES AND FILLER [km]	75
	DISTANCE BITUMEN AND EB [km]	200
	MEANS AGGREGATES	30 ton Euro 5
	MEANS BITUMEN	30 ton Euro 5
	MEANS EB	30 ton Euro 5
	ONSUMPTION	Table bellow
	FUELS	Diesel

Here is the detailed table showing the fuel consumption (Diesel) for each material based on the distances and ton*km values provided:

Material	Quantity (tons)	Distance (km)	ton*km	Fuel Consumption (liters)
Coarse Aggregates	0.534	75	40.05	45.00
Sand	0.400	75	30.00	45.00
Supplementary Filler	0.020	75	1.50	45.00
Recycled Filler	0.028	75	2.10	45.00
Bitumen	0.046	200	9.20	120.00
Bituminous Emulsion	0.001	200	0.20	120.00
Total	-		83.05	**420.00**

4.5.2.3 In plant activities

This table presents essential data for assessing the energy and material efficiency in the binder layer production process, which is vital for evaluating the environmental footprint and optimizing plant operations.

PLANT	FUELS	BTZ
	Average % moisture in aggregates	4.5
	CONSUMPTION [kWh/ton]	76
	CONSUMPTION [kg/ton]	6.74
	EQUIPMENT - SHOVEL	220 t/h- 23 l/h
	INDUSTRIAL MACHINE	Fixed and Unchanging

These calculations provide a detailed assessment of the energy and material efficiency for the binder layer in the production process, which is essential for evaluating its environmental impact.

Parameter	Value	Calculation	Explanation
Effective Material Weight	1.0774 tons	1,031 kg × (1 + 0.045)	Adjusted for 4.5% moisture content, resulting in an effective weight of 1.0774 tons.
Total Energy Consumption	81.88 kWh	1.0774 tons × 76 kWh/ton	Increased energy consumption due to the higher effective material weight.
Total Material Consumption	7.26 kg	1.0774 tons × 6.74 kg/ton	Reflects the total amount of a specific material used, proportional to the effective weight.
Total Shovel Fuel Consumption	0.113 liters	(1.0774 tons / 220 tons/hour) × 23 liters/hour	Fuel consumption based on operation time and fuel usage rate.
Shovel Fuel Consumption (kJ)	4,045.4 kJ	0.113 liters × 35,800 kJ/liter	Energy content of the fuel consumed by the shovel, with diesel's energy content.

In OpenLCA and Ecoinvent 3.9, the term "diesel, burned in building machine" is used, with the unit specified in kJ. Consequently, it is necessary to convert the shovel's fuel consumption, classified as a building machine, into kJ of diesel.

10.3.2.4 Transport to site

The table details the parameters for transporting materials to the construction site, focusing on the binder layer:

TRANSPORT TO SITE	DISTANCE [km]	20
	MEANS AGGREGATES	30 ton Euro 5
	CONSUMPTION	Table bellow
	FUELS	Diesel

Distance: The transportation distance for binder materials to the site is 20 kilometers, which is critical for calculating transportation impacts, as greater distances generally lead to higher fuel consumption and emissions.

Means of Transport: Aggregates are transported using a 30-ton Euro 5 lorry, as per Ecoinvent data, providing insight into the vehicle type and its environmental impact.

Fuels: Diesel is used for transportation, influencing both emissions and overall environmental footprint.

Parameter	Value	Calculation
Total Fuel Consumption	13.13 liters	20 km × 0.6565 liters/km
Total Ton-Kilometers	21.55 ton*km	1.0774 tons × 20 km

- Total Fuel Consumption: Calculated as 13.13 liters based on the distance (20 km) and fuel consumption rate (0.6565 liters/km), reflecting the energy required to transport the binder material.
- Total Ton-Kilometers: Calculated as 21.55 ton*km by multiplying the material weight (1.0774 tons) by the distance (20 km). This metric is essential for evaluating the environmental impact of transportation by considering both material weight and travel distance.

4.5.2.5 Installation

To accurately assess equipment usage during the installation of Layer 2 (Binder), we will calculate operational data based on fuel consumption, material handling, and operational hours. Here is the approach for the binder layer:

Volume and Area Calculations

Given Data:

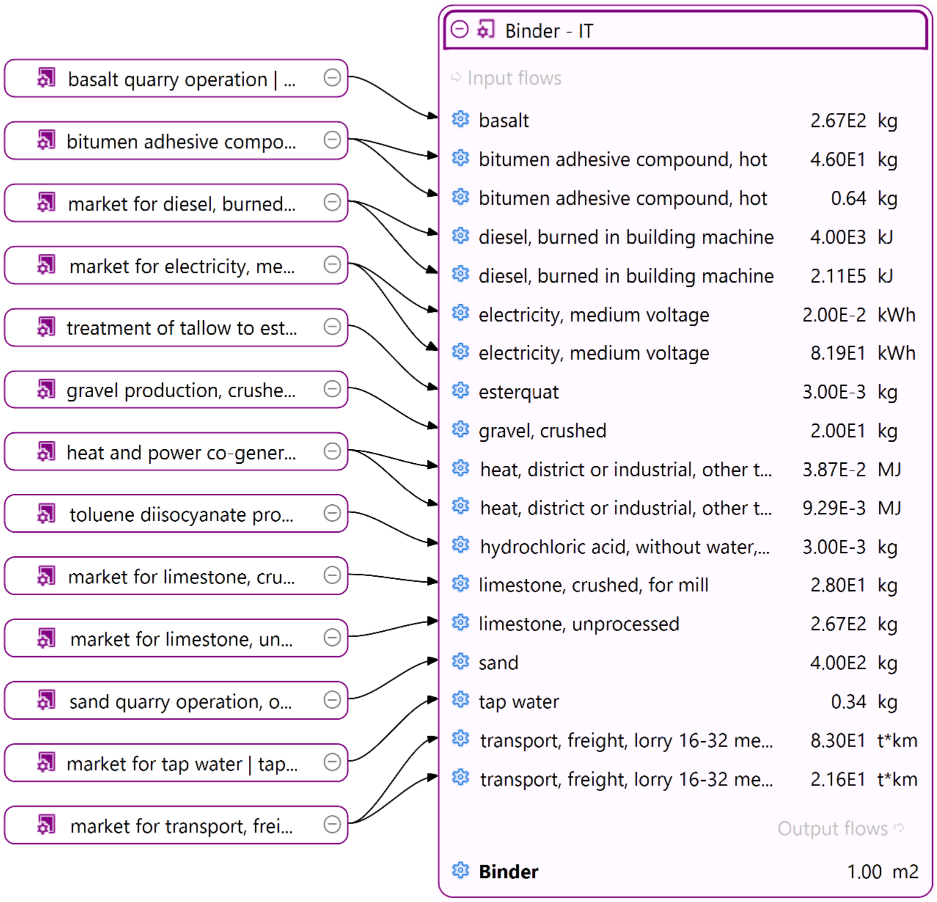
- Specific Weight: 2.36 tons/cubic meter
- Thickness: 0.06 meters
- Material Quantity: 1.0774 tons

Summary:

Parameter	Value	Unit	Calculation
Volume of Material Needed	0.456	m^3	1.0774 tons / 2.36 tons/m^3
Area Covered by Material	7.60	m^2	0.456 m^3 / 0.06 m

Equipment Fuel Consumption and Energy Calculation

Equipment	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Paver	0.16	35,800	5,728
Roller	0.14	35,800	5,012
Emulsifier (Sprayer)	2.59	35,800	92,782
Sweeper	3.00	35,800	107,400
Total	5.29		210,922



Binder - IT

Input flows

basalt	2.67E2	kg
bitumen adhesive compound, hot	4.60E1	kg
bitumen adhesive compound, hot	0.64	kg
diesel, burned in building machine	4.00E3	kJ
diesel, burned in building machine	2.11E5	kJ
electricity, medium voltage	2.00E-2	kWh
electricity, medium voltage	8.19E1	kWh
esterquat	3.00E-3	kg
gravel, crushed	2.00E1	kg
heat, district or industrial, other t...	3.87E-2	MJ
heat, district or industrial, other t...	9.29E-3	MJ
hydrochloric acid, without water,...	3.00E-3	kg
limestone, crushed, for mill	2.80E1	kg
limestone, unprocessed	2.67E2	kg
sand	4.00E2	kg
tap water	0.34	kg
transport, freight, lorry 16-32 me...	8.30E1	t*km
transport, freight, lorry 16-32 me...	2.16E1	t*km

Output flows

Binder	1.00	m2

The analysis of equipment efficiency and sustainability for Layer 2 (binder) has been conducted with careful attention. This section provides an overview of the input parameters and the corresponding analysis specific to the binder layer.

Although the same methods are used for other layers, detailed explanations are not repeated here to avoid redundancy. Instead, the focus is on presenting the results and summary tables relevant to the binder layer. This approach streamlines the presentation while emphasizing the unique characteristics and impacts of the binder layer in terms of material use, energy consumption, and operational effectiveness. This ensures a clear and focused evaluation of the binder layer's contribution to the overall production process.

4.5.3 Layer BASE

4.5.3.1 Raw materials

The table details the raw materials for the base layer of the Zero-Pavement project, aligned with Ecoinvent 3.9 reference units. This ensures the consistency and accuracy of the lifecycle assessment (LCA). Coarse aggregates are compared with unprocessed limestone and basalt, while supplementary filler is matched with crushed gravel. Bitumen and bituminous emulsion are similarly cross-referenced. Detailed values for the bituminous emulsion are not repeated here as they follow the same specifications as Layer 1 (wear).

	Reference unit	Ecoinvent 3.9 unit	Amount
RAW MATERIALS	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	- limestone, unprocessed 50% -basalt 50%	589
	SAND [kg]	sand	350
	SUPPLEMENTARY FILLER [kg]	gravel, crushed	19
	RECYCLED FILLER [kg]	limestone, crushed, for mill	27
	BITUMEN [kg]	bitumen adhesive compound, hot	42
	BITUMINOUS EMULSION [kg/sqm]	Based on the table bellow	1.0

4.5.3.2 TRANSPORT TO PRODUCTION PLANT

The distances are 75 km for coarse aggregates, sand, supplementary filler, and recycled filler, and 200 km for bitumen and bituminous emulsion. All materials are transported using Euro 5 lorries with a 30-ton capacity. Diesel is used as the fuel.

Material	Quantity (kg)	Distance (km)	ton*km	Fuel Consumption (liters)
Coarse Aggregates	589	75	44.18	45.00
Sand	350	75	26.25	45.00
Supplementary Filler	19	75	1.43	45.00
Recycled Filler	27	75	2.03	45.00
Bitumen	42	200	8.40	120.00
Bituminous Emulsion	1.0	200	0.20	120.00
Total	-	-	**82.49**	**420.00**

In this analysis, the "ton*km" metric quantifies transportation impact by multiplying material quantities by distance. For example, transporting 589 kg of coarse aggregates 75 km results in 44.18 ton*km and 45 liters of diesel. The total ton*km for all materials is 82.49, with a total diesel consumption of 420 liters. This measure helps assess transportation efficiency and environmental impact. The calculations use the Ecoinvent 3.9 item "transport, freight, lorry 16-32 metric ton, EURO5" to estimate fuel consumption impacts.

4.5.3.3 In plant activities

This section presents the energy and material efficiency analysis for the binder layer production process. The data provided below are crucial for evaluating the environmental footprint and optimizing plant operations for the third layer of the project.

PLANT	FUELS	BTZ
	Average % moisture in aggregates	4
	CONSUMPTION [kWh/ton]	72
	CONSUMPTION [kg/ton]	6.38
	EQUIPMENT - SHOVEL	220 t/h- 23 l/h
	INDUSTRIAL MACHINE	Fixed and Unchanging

The following calculations provide a comprehensive assessment of the energy and material efficiency for the binder layer in the production process. These calculations are vital for understanding the environmental impact and operational efficiency of the plant.

Parameter	Value	Calculation	Explanation
Effective Material Weight	1.0416 tons	1,000 kg × (1 + 0.04)	Adjusted for 4% moisture content, resulting in an effective weight of 1.0416 tons.
Total Energy Consumption	74.99 kWh	1.0416 tons × 72 kWh/ton	Increased energy consumption due to the higher effective material weight.
Total Material Consumption	6.68 kg	1.0416 tons × 6.38 kg/ton	Reflects the total amount of diesel fuel used, proportional to the effective weight.
Total Shovel Fuel Consumption	0.105 liters	(1.0416 tons / 220 tons/hour) × 23 liters/hour	Fuel consumption based on operation time and fuel usage rate.
Shovel Fuel Consumption (kJ)	3,759.8 kJ	0.105 liters × 35,800 kJ/liter	Energy content of the diesel used by the shovel.

4.5.2.4 Transport to site:

This section details the parameters for transporting materials to the construction site for the binder layer:

- Distance: The base material is transported to the construction site over a distance of 20 kilometers. This distance is crucial for calculating transportation impacts, as longer distances typically result in higher fuel consumption and greater emissions.
- Means of Transport: Aggregates for the binder layer are transported using a 30-ton Euro 5 lorry, based on Ecoinvent data. This vehicle type is indicative of the environmental impact and fuel efficiency associated with modern heavy-duty trucks.
- Fuels: Diesel fuel is utilized for transportation, which affects both emissions and the overall environmental footprint of the material transport phase.

TRANSPORT TO SITE	DISTANCE [km]	20
	MEANS AGGREGATES	30 ton Euro 5
	CONSUMPTION	Table bellow
	FUELS	Diesel

Calculation Parameters:

Parameter	Value	Calculation	Explanation
Total Fuel Consumption	13.13 liters	20 km × 0.6565 liters/km	Fuel required to transport the binder material, calculated using the distance and fuel consumption rate.
Total Ton-Kilometers	20.83 ton-km	1.0416 tons × 20 km	The product of material weight and distance, used to assess the environmental impact of transportation.

Total Fuel Consumption: The amount of fuel required for transporting the binder material is 13.13 liters, derived from the distance of 20 kilometers and the fuel consumption rate of 0.6565 liters per kilometer. This reflects the energy needed for the transport process.

Total Ton-Kilometers: The total ton-kilometers for transporting the binder material is 20.83 ton-km. This figure is obtained by multiplying the effective material weight (1.0416 tons) by the distance (20 km). This metric is critical for evaluating the environmental impact of the transportation phase by considering both the weight of the material and the distance traveled.

4.5.3.5 Installation

To accurately assess equipment usage during the installation of Layer 3 (Binder), we will calculate operational data based on the material properties, fuel consumption, and equipment energy usage. Below is the detailed approach for the binder layer:

Volume and Area Calculations:

Given Data

- Specific Weight: 2.35 tons/cubic meter
- Thickness: 0.12 meters
- Material Quantity: 1.0416 tons (from previous calculation)

Parameter	Value	Unit	Calculation
Volume of Material Needed	0.4436	m³	1.0416 tons / 2.35 tons/m³
Area Covered by Material	3.69	m²	0.4436 m³ / 0.12 m

- Volume of Material Needed: The volume is calculated by dividing the total material quantity by the specific weight. With a specific weight of 2.35 tons/m³, the volume required for 1.0416 tons of material is 0.4436 m³.
- Area Covered by Material: The area covered is calculated by dividing the volume by the thickness of the layer. With a thickness of 0.12 meters, the area covered by 0.4436 m³ of material is 3.69 m².

Equipment Fuel Consumption and Energy Calculation

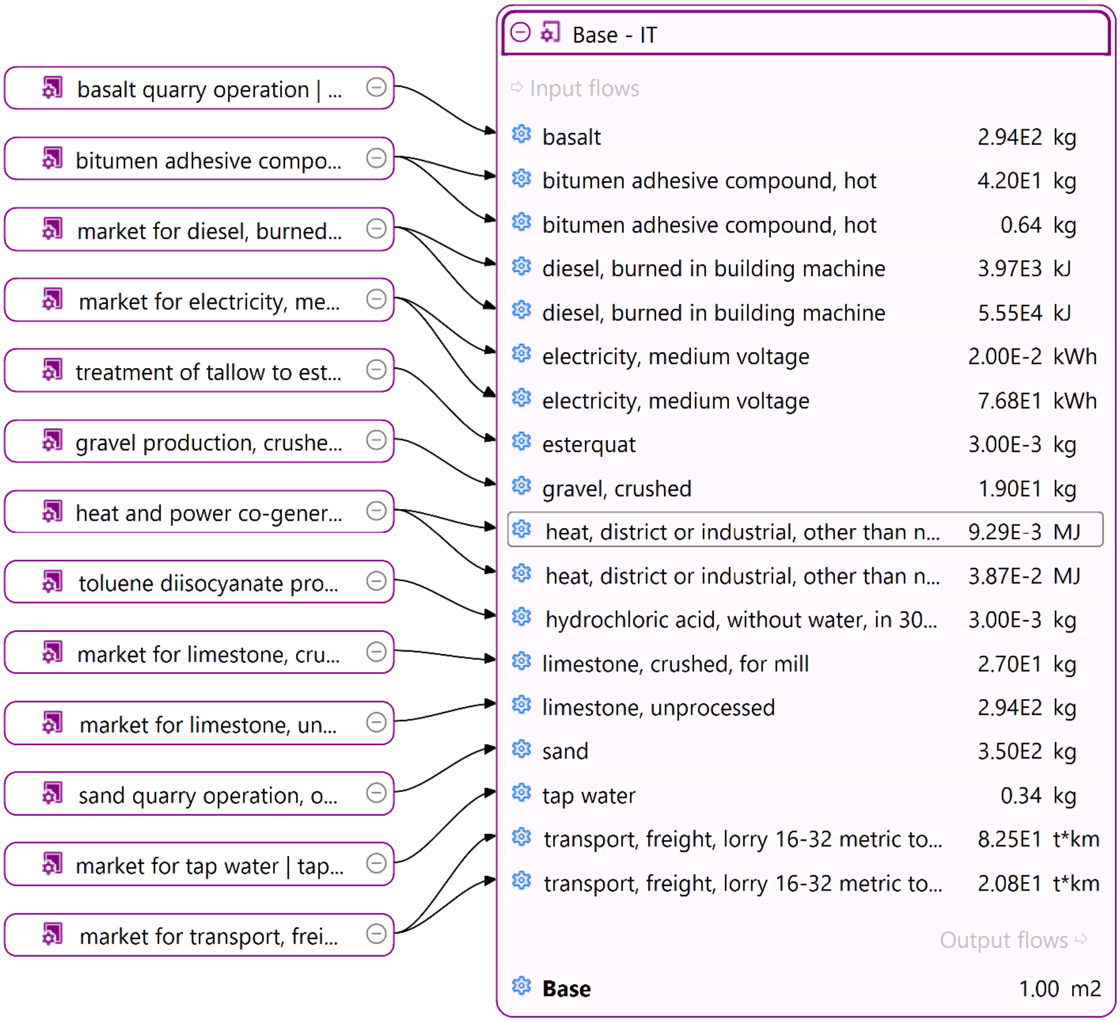
For Layer 3, using the equipment data from Layer 2 as a reference, we will calculate the total fuel consumption and energy usage based on the new parameters.

Given Data for Equipment:

- Specific Weight: 2.35 tons/m³
- Thickness: 0.12 meters

Equipment	Fuel Consumption Rate (liters/hour)	Performance	Operational Hours	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Paver	21	140 tons/hour	0.0074	0.16	35,800	5,728
Roller	13	40 m³/hour	0.0111	0.14	35,800	5,012
Emulsifier (Sprayer)	8.5	0.025 km²/hour	0.147	1.25	35,800	44,750
Total				1.55		55,490

Total Fuel Consumption: 1.55 liters Total Energy Consumption: 55,490 kJ



Input flows		
basalt	2.94E2	kg
bitumen adhesive compound, hot	4.20E1	kg
bitumen adhesive compound, hot	0.64	kg
diesel, burned in building machine	3.97E3	kJ
diesel, burned in building machine	5.55E4	kJ
electricity, medium voltage	2.00E-2	kWh
electricity, medium voltage	7.68E1	kWh
esterquat	3.00E-3	kg
gravel, crushed	1.90E1	kg
heat, district or industrial, other than n...	9.29E-3	MJ
heat, district or industrial, other than n...	3.87E-2	MJ
hydrochloric acid, without water, in 30...	3.00E-3	kg
limestone, crushed, for mill	2.70E1	kg
limestone, unprocessed	2.94E2	kg
sand	3.50E2	kg
tap water	0.34	kg
transport, freight, lorry 16-32 metric to...	8.25E1	t*km
transport, freight, lorry 16-32 metric to...	2.08E1	t*km

Output flows		
Base	1.00	m2

The assessment of equipment efficiency and sustainability for Layer 3 (binder) has been thoroughly executed. This section outlines the input parameters and detailed analysis specific to the binder layer. While similar methodologies apply to other layers, repetitive explanations are omitted here to maintain clarity. The focus is on showcasing the results and summary tables pertinent to the binder layer. This streamlined approach highlights the distinct characteristics and impacts of the binder layer regarding material usage, energy consumption, and operational performance, providing a clear and targeted evaluation of its role in the production process.

4.5.4 Layer Graded Stabilized

4.5.4.1 Raw materials

The following table outlines the raw materials required for the base layer of the Zero-Pavement project (Layer 4: Graded Stabilized). Specifications are aligned with Ecoinvent 3.9 units. This layer includes coarse aggregates and sand.

RAW MATERIALS	Reference unit	Ecoinvent 3.9 unit	Amount
	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	- limestone, unprocessed 50% -basalt 50%	965
	SAND [kg]	sand	35

4.5.4.2 TRANSPORT TO PRODUCTION PLANT

The following table summarizes the transportation and fuel consumption for the base layer of the Zero-Pavement project (Layer 4: Graded Stabilized). This layer includes coarse aggregates and sand. The transportation distance is 75 km for both materials, using a 30-ton Euro 5 lorry. Diesel is the fuel used for transportation.

Fuel Consumption Breakdown

Material	Quantity (kg)	Distance (km)	ton*km	Fuel Consumption (liters)
Coarse Aggregates	965	75	72.38	47.38
Sand	35	75	2.63	1.75
Total	-	-	**75.01**	**49.13**

4.5.4.3: In plant activities

This section presents the energy and material efficiency analysis for the binder layer production process. The data provided below are crucial for evaluating the environmental footprint and optimizing plant operations for the third layer of the project.

PLANT	FUELS	BTZ
	EQUIPMENT - SHOVEL	220 t/h- 23 l/h
	INDUSTRIAL MACHINE	Fixed and Unchanging

The following calculations provide a comprehensive assessment of the energy and material efficiency for the binder layer in the production process. These calculations are vital for understanding the environmental impact and operational efficiency of the plant.

Parameter	Value	Calculation	Explanation
Effective Material Weight	1.0416 tons	1,000 kg × (1 + 0.00)	Effective weight is 1,000 kg, with no adjustment for moisture.
Total Shovel Fuel Consumption	0.105 liters	(1.0000 tons / 220 tons/hour) × 23 liters/hour	Fuel consumption based on operation time and fuel usage rate.
Shovel Fuel Consumption (kJ)	3,759.8 kJ	0.105 liters × 35,800 kJ/liter	Energy content of the diesel used by the shovel.

In OpenLCA and Ecoinvent 3.9, the term "diesel, burned in building machine" is used with the unit specified in kJ. Therefore, the shovel's fuel consumption is converted into kJ of diesel to align with lifecycle assessment data standards.

4.5.2.3: Transport to site:

This section details the transportation of materials for Layer 4: Graded Stabilized. The materials are transported 20 kilometers to the construction site, a key factor for evaluating transportation impacts, as longer distances generally lead to increased fuel consumption and emissions. A 30-ton Euro 5 lorry is used for transport, reflecting the environmental impact and fuel efficiency of modern heavy-duty trucks. Diesel fuel powers the lorry, affecting both emissions and the overall environmental footprint of the transport process

TRANSPORT TO SITE	DISTANCE [km]	20
	MEANS AGGREGATES	30 ton Euro 5
	CONSUMPTION	Table bellow
	FUELS	Diesel

Calculation Parameters:

Parameter	Value	Calculation	Explanation
Total Fuel Consumption	19.18 liters	(965 kg + 35 kg) × 20 km × 0.6565 liters/km	Fuel required for transporting the materials, calculated using the distance and fuel consumption rate.
Total Ton-Kilometers	20.00 ton-km	(965 kg + 35 kg) × 20 km	Total ton-kilometers for transporting the materials, calculated by multiplying the total material weight by the distance.

4.5.4.4: Installation

to accurately assesses the equipment usage during the installation of Layer 4 (Graded Stabilized), we calculate operational data based on material properties, fuel consumption, and equipment energy usage. The detailed approach for Layer 4 is outlined below:

Volume and Area Calculations

Given Data:

- Specific Weight: 1.90 tons/cubic meter
- Thickness: 0.20 meters
- Material Quantity: 1.00 tons

Summary:

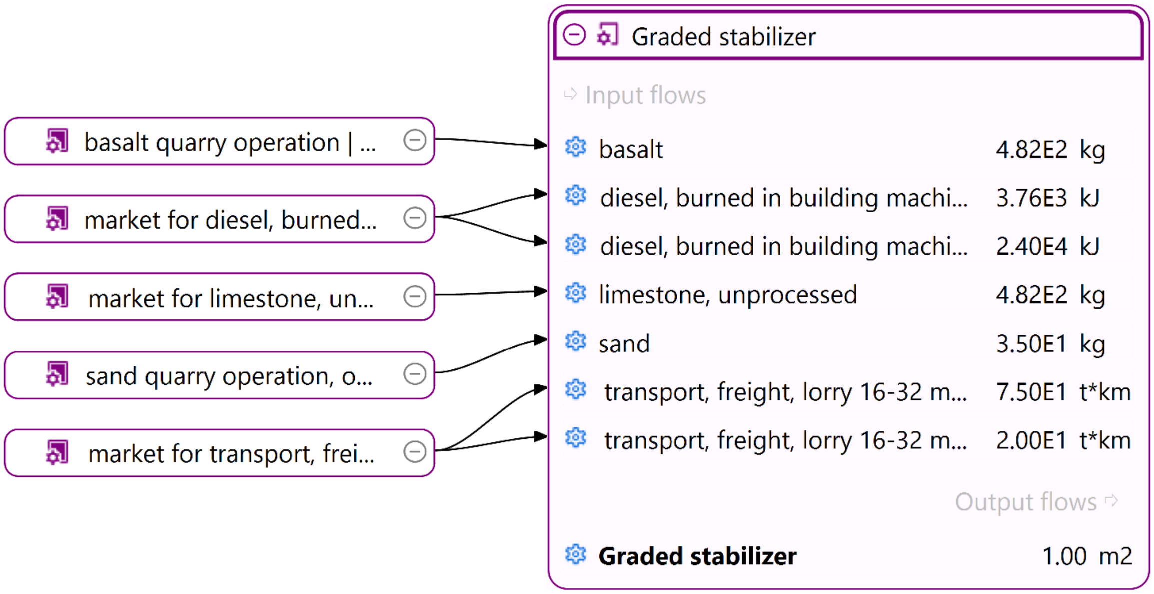
Parameter	Value	Unit	Calculation
Volume of Material Needed	0.526 m^3		1.00 tons / 1.90 tons/m^3
Area Covered by Material	2.63 m^2		0.526 m^3 / 0.20 m

Total fuel consumption, measured in liters, is determined by the equipment's fuel usage rates relative to the volume of material processed, with adjustments made for the Miller (Grader) and Roller based on the material's area and volume. Diesel fuel, which has an energy content of 35,800 kJ per liter, is used to calculate total energy consumption by multiplying the overall fuel consumption by this energy value.

Layer 4 Equipment Data

Equipment	Fuel Consumption Rate (liters/hour)	Performance	Operational Hours	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Grader	100	200 tons/hour	0.005	0.50	35,800	17,900
Roller	13	40 m^3/hour	0.013	0.17	35,800	6,086
Total				0.67		23,986

The evaluation of equipment efficiency and sustainability for Layer 4 (Graded Stabilized) is detailed here. This section presents the specific input parameters and results for Layer 4, focusing on material use, energy consumption, and operational efficiency. While similar methods apply to other layers, repetitive details are omitted to streamline the analysis and emphasize the unique aspects of Layer 4.



Flow	Amount	Unit
basalt	4.82E2	kg
diesel, burned in building machi...	3.76E3	kJ
diesel, burned in building machi...	2.40E4	kJ
limestone, unprocessed	4.82E2	kg
sand	3.50E1	kg
transport, freight, lorry 16-32 m...	7.50E1	t*km
transport, freight, lorry 16-32 m...	2.00E1	t*km
Graded stabilizer	1.00	m2

4.5.5: Layer Cemented Mix

4.5.5.1: Raw materials

The Cemented Mix layer, designated as Layer 5 in the Zero-Pavement project, incorporates water and cement to ensure optimal performance and durability. Water is crucial for the hydration of cement, a process that allows the cement to chemically react and form a solid, binding matrix with the coarse aggregates and sand. This hydration is essential for achieving the required compressive strength and structural stability of the base layer. Cement, particularly CEM II/A, is used in this layer due to its favorable properties. CEM II/A is a blended cement that includes a proportion of blast furnace slag, which enhances its environmental performance by reducing CO_2 emissions compared to traditional Portland cement (OPC). The use of CEM II/A is supported by its balanced characteristics of workability, durability, and reduced environmental impact, as highlighted in recent studies (Smith et al., 2015). This approach not only ensures the structural integrity of the pavement but also aligns with sustainable construction practices by minimizing the carbon footprint associated with cement production (Smith et al., 2015; European Cement Research Academy, 2016).

RAW MATERIALS	Reference unit	Ecoinvent 3.9 unit	Amount
	COARSE AGGREGATES (for wear 50% limestone + 50% porphyry) [kg]	- limestone, unprocessed 50% -basalt 50%	720
	SAND [kg]	sand	250
	WATER [kg]	tap water	60
	CEMENT [kg]	cement, CEM II/A	30

4.5.5.2: TRANSPORT TO PRODUCTION PLANT

This section details the transportation logistics for Layer 5: Cemented Mix. Coarse aggregates and sand are transported 75 kilometers, while water and cement are transported 200 kilometers, using a 30-ton Euro 5 lorry. Diesel fuel is used for all transportation. The following calculations detail the fuel consumption based on the ton-kilometer values, highlighting the transportation impact for this layer.

TRANSPORT TO PRODUCTION PLANT	DISTANCE AGGREGATES AND FILLER [km]	75
	DISTANCE CEMENT [km]	200
	MEANS AGGREGATES	30 ton Euro 5
	MEANS CEMENT	30 ton Euro 5
	ONSUMPTION	Table bellow
	FUELS	Diesel

The table below calculates the fuel consumption based on the distance and ton-kilometer values for each material:

Material	Quantity (tons)	Distance (km)	Ton-Km	Fuel Consumption (liters)
Coarse Aggregates	0.72	75	54.00	45.00
Sand	0.25	75	18.75	45.00
Water	0.06	On site	0	0
Cement	0.03	200	6.00	120.00
Total			78.75	210.00

- Coarse Aggregates: With a quantity of 0.72 tons transported 75 km, the ton-kilometer value is 54.00 (0.72 tons * 75 km), corresponding to 45 liters of diesel.
- Sand: 0.25 tons of sand transported 75 km results in a ton-kilometer value of 18.75 (0.25 tons * 75 km), with 45 liters of diesel used.
- Water: Transported 200 km at 0.06 tons results in a ton-kilometer value of 12.00 (0.06 tons * 200 km), consuming 120 liters of diesel.
- Cement: With a quantity of 0.03 tons transported 200 km, the ton-kilometer value is 6.00 (0.03 tons * 200 km), using 120 liters of diesel.

4.5.5.3: In plant activities

This section evaluates the energy and material efficiency for Layer 5: Cemented Mix. The analysis includes details on material usage, energy consumption, and equipment operation to assess the environmental impact and optimize plant processes.

PLANT	FUELS	BTZ
	EQUIPMENT - SHOVEL	220 t/h- 23 l/h
	INDUSTRIAL MACHINE	Fixed and Unchanging

Calculations:

Parameter	Value	Calculation	Explanation
Total Material Weight	1.00 tons	720 kg (Coarse Aggregates) + 250 kg (Sand) + 60 kg (Water) + 30 kg (Cement)	Total weight of all materials used in the production process.
Total Energy Consumption	0 kWh	Not applicable for this layer.	No specific energy consumption data provided.
Total Shovel Fuel Consumption	0.105 liters	(1.00 tons / 220 tons/hour) × 23 liters/hour	Fuel used by the shovel based on its operational rate.
Shovel Fuel Consumption (kJ)	3,759.8 kJ	0.105 liters × 35,800 kJ/liter	Energy content of the diesel fuel used by the shovel.

In this analysis, the total material weight is based on the combined quantities of coarse aggregates, sand, water, and cement. Fuel consumption for the shovel is calculated based on its operation rate and the energy content of diesel fuel. This evaluation aids in understanding the operational efficiency and environmental impact of the in-plant activities for Layer 5.

4.5.5.4: Transport to site:

This section describes the transportation process for Layer 5: Cemented Mix. Materials are transported 20 kilometers to the construction site, a crucial factor in assessing transportation impacts, as increased distances generally result in higher fuel consumption and emissions. A 30-ton Euro 5 lorry, which reflects the environmental performance and fuel efficiency of modern heavy-duty trucks, is used for the transport. Diesel fuel powers the lorry, influencing both emissions and the overall environmental footprint of the transportation phase.

TRANSPORT TO SITE	DISTANCE [km]	20
	MEANS AGGREGATES	30 ton Euro 5
	CONSUMPTION	Table bellow
	FUELS	Diesel

Calculation Parameters:

Parameter	Value	Calculation	Explanation
Total Fuel Consumption	25.54 liters	(1,060 kg) × 20 km × 0.6565 liters/km	Fuel required for transporting the materials, based on distance and fuel consumption rate.
Total Ton-Kilometers	21.20 ton-km	1,060 kg × 20 km	Total ton-kilometers for transporting the materials, calculated by multiplying the total material weight by the distance.

This assessment provides a comprehensive view of the fuel consumption and transportation efficiency for Layer 5, highlighting the impact of material transport on the overall environmental footprint.

4.5.5.5: Installation

To accurately evaluate the usage of equipment during the installation process for Layer 5, it is essential to collect and calculate specific data regarding operational hours, fuel consumption, and material handling. Below is a step-by-step analysis of these factors for the cemented mix layer.

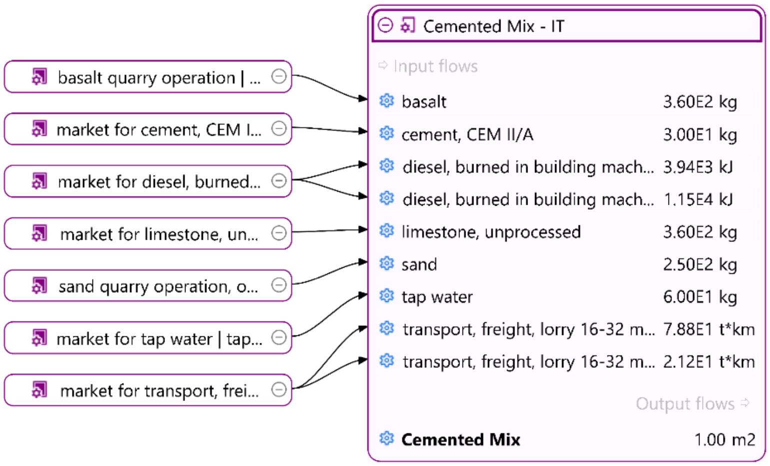
Here's the table with the calculated area and volume for Layer 5:

Parameter	Value	Unit	Calculation/Source
Specific Weight	2.10	tons/m³	Refers to the density of the material
Thickness	0.04	meters	Depth of the material layer applied on the surface
Material Quantity	1.06	tons	Total weight of the material available for use
Volume of Material Needed	0.505	cubic meters	Volume = 1.06 tons / 2.10 tons/m³
Area Covered by Material	12.63	square meters	Area = 0.505 m³ / 0.04 m

Also for equipment’s Fuel Consumption for Equipment:

Equipment	Fuel Consumption Rate (liters/hour)	Operational Data (hours)	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Paver	21 liters/hour	0.0076 hours	0.16 liters	35,800	5,728
Roller	13 liters/hour	0.0126 hours	0.16 liters	35,800	5,728
total			0.32		11,456

This analysis ensures that the installation process for Layer 5 is evaluated comprehensively, considering both the fuel consumption and the energy impact associated with the construction equipment used. This data aligns with lifecycle assessment methodologies in OpenLCA and Ecoinvent 3.9, which assess environmental impacts based on energy consumption measured in kJ.



Cemented Mix - IT

Input flows

basalt	3.60E2 kg
cement, CEM II/A	3.00E1 kg
diesel, burned in building mach...	3.94E3 kJ
diesel, burned in building mach...	1.15E4 kJ
limestone, unprocessed	3.60E2 kg
sand	2.50E2 kg
tap water	6.00E1 kg
transport, freight, lorry 16-32 m...	7.88E1 t*km
transport, freight, lorry 16-32 m...	2.12E1 t*km

Output flows

Cemented Mix	1.00 m2

Upon inputting the provided data into OpenLCA, the analysis focused on assessing the environmental impact of each component involved in the installation of Layer 5: Cemented Mix. The tool calculated the total energy consumption, fuel usage, and material inputs, converting these into environmental impacts based on lifecycle assessment methodologies from Ecoinvent 3.9.

The analysis highlighted the significant contributions of diesel fuel consumption for transportation and equipment operation, particularly from the paver and roller, which together accounted for 11,456 kJ of energy. The transportation of coarse aggregates, sand, and cement also contributed notably to the environmental footprint due to the considerable distances covered. Cement, although used in smaller quantities, had a substantial impact due to its longer transportation distance and the associated fuel consumption.

The figure generated by OpenLCA illustrated the proportional impact of each material and process, with diesel fuel for transport and operation being the dominant contributor to greenhouse gas emissions. The use of CEM II/A cement, which has a reduced carbon footprint compared to traditional OPC, was shown to mitigate some environmental impact. However, the overall analysis emphasized the importance of optimizing transport distances and fuel efficiency in reducing the environmental burden of the construction process. This data-driven approach enables better decision-making for sustainable construction practices in future projects.

4.6 Environmental Impacts of Zero-Pavement Construction

4.6.1 Introduction

For the Zero-Pavement project, we employed **OpenLCA** software and the **Ecoinvent 3.9** database to conduct a comprehensive Life Cycle Impact Assessment (LCIA). This analysis was performed for all layers of the pavement, aiming to evaluate the overall environmental and human health impacts associated with the use of both **new** and **old equipment** in the construction process. This approach ensures a holistic comparison between the environmental impacts of outdated and modern machinery across each construction layer. By assessing the entire lifecycle of materials and operations, we can pinpoint areas where newer equipment offers sustainability benefits, and where older equipment may lag in terms of emissions and efficiency.

To achieve a thorough understanding of the project’s environmental footprint, we employed a combination of three recognized LCIA methodologies: **IPCC 2021**, **ReCiPe Midpoint (E)**, and **TRACI 2.1**.

IPCC 2021

The **IPCC 2021** method was utilized to focus on the project's **direct** and **indirect emissions**, specifically targeting **Global Warming Potential (GWP)**. This method is instrumental in analyzing the emissions of **greenhouse gases (GHGs)** over a 100-year horizon, expressed as **CO_2-equivalents** (CO_2e). Given the growing urgency to address **climate change**, it is crucial to assess both the direct emissions from fuel combustion and machinery operation, as well as the indirect emissions associated with **material extraction** and **transportation**.

Through **IPCC 2021**, we capture emissions of:

- **CO_2**, the most abundant GHG,
- **Methane (CH_4)** and **Nitrous Oxide (N_2O)**, gases that have far higher global warming potentials than CO_2.

This method ensures that the project aligns with international climate goals by quantifying its contribution to **global warming** and identifying opportunities for emission reduction in road construction processes (IPCC, 2021). It is particularly useful in comparing older equipment, which tends to have higher emissions, against newer, more energy-efficient machinery.

ReCiPe 2016 Midpoint (E)

For a more detailed and comprehensive analysis of **environmental impacts**, we applied the **ReCiPe Midpoint (E)** method. This method allows us to assess **18 environmental categories**, including:

- **Climate Change**,
- **Ozone Depletion**,
- **Human Toxicity**,
- **Terrestrial Acidification**,
- **Marine Eutrophication**, and
- **Water Use**.

While **IPCC 2021** focuses primarily on **climate change**, **ReCiPe Midpoint (E)** expands the scope to include other critical environmental dimensions, providing a more holistic view of the ecological impacts across each construction layer. This method helps us analyze the **broad environmental consequences** of using different construction materials and equipment, making it essential for understanding the complete environmental footprint of the Zero-Pavement project.

By applying **ReCiPe Midpoint (E)** to both **new and old equipment**, we identify specific environmental burdens, such as higher levels of **particulate matter formation** and **acidification** associated with older machinery. This comprehensive coverage is essential for making informed decisions about which equipment and materials are most sustainable over the long term (Huijbregts et al., 2017).

TRACI 2.1

Finally, we used the **TRACI 2.1** (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) methodology to provide a **summary** of the impacts of each input across the layers of construction. **TRACI 2.1**, developed by the **U.S. Environmental Protection Agency (EPA)**, is particularly useful in a **North American context**, where it offers region-specific impact categories such as:

- **Ozone Depletion**,
- **Smog Formation**,
- **Human Health Impacts** (via air pollutants),
- **Eutrophication**, and
- **Fossil Fuel Depletion**.

TRACI 2.1 allows us to break down the contributions of each input—such as **bitumen**, **aggregates**, and **fuel consumption**—to the environmental impacts at each layer of the construction process. This layer-by-layer analysis is crucial for understanding how each stage of the pavement project affects environmental and human health, providing actionable insights for reducing impacts (Bare, 2011). In comparing older and newer machinery, **TRACI 2.1** highlights how modern equipment significantly reduces emissions related to **air quality** and **fossil fuel depletion**.

Comprehensive LCIA for All Layers

Our use of **IPCC 2021**, **ReCiPe Midpoint (E)**, and **TRACI 2.1** across all layers of the Zero-Pavement project allows for a **multi-dimensional analysis**. While **IPCC 2021** provides the global warming impact from both direct and indirect emissions, **ReCiPe Midpoint (E)** offers a more granular look at various environmental impacts, and **TRACI 2.1** summarizes the effect of each input processes across layers. This combined methodology ensures that we can effectively compare the performance of older and newer equipment, guiding decisions toward more sustainable road construction practices.

By examining the **entire lifecycle** of materials and machinery, and comparing their environmental impacts across all layers of the pavement, this assessment provides stakeholders with valuable insights for reducing the ecological footprint of the Zero-Pavement project.

4.6.2 Environmental Impact Assessment of Each Layer with old equipment

This section provides a detailed environmental impact assessment for each of the five layers in the Zero-Pavement project. Utilizing the **ReCiPe 2016 v1.03 Midpoint (E)** method and **IPCC 2021** within **OpenLCA**, the analysis focuses on key categories such as **climate change** (including **direct and indirect emissions**), **resource depletion**, and various **environmental impacts** like **eutrophication**, **acidification**, and **particulate matter formation**. Each layer is evaluated based on its specific material composition, construction process, and operational requirements, offering a comprehensive view of the environmental footprint associated with the project.

The impact categories used in the assessment of climate change are derived from methodologies developed by the Intergovernmental Panel on Climate Change (IPCC). These categories help quantify the environmental effects of greenhouse gas emissions, with a focus on their contribution to global warming and temperature rise.

- **Climate Change- Global Temperature Change Potential (GTP)**:

The Global Temperature Change Potential (GTP) measures the potential increase in global temperature due to greenhouse gas emissions over specified time horizons. GTP100 and GTP50, for instance, represent the potential temperature rise over 100 and 50 years, respectively. These metrics are essential for understanding the immediate and long-term thermal impacts of greenhouse gases on the Earth's climate system (IPCC, 2021).

- **Climate Change- Global Warming Potential (GWP)**:

The Global Warming Potential (GWP) is a widely utilized indicator that estimates the cumulative heat-trapping effect of greenhouse gases in the atmosphere. GWP metrics, such as GWP100, GWP20, and GWP500, assess the potential warming effect over 100, 20, and 500 years, respectively. This measure provides insight into how various gases contribute to the greenhouse effect and their relative impact over different temporal scales (IPCC, 2021).

- **Climate Change: Fossil GTP & GWP**:

Fossil-specific GTP and GWP categories focus on the impact of emissions from fossil fuel combustion. These indicators, such as GTP100 Fossil and GWP100 Fossil, measure the contribution of fossil fuel-related emissions to global temperature change and warming potential. By isolating fossil fuel impacts, these categories highlight the specific role of fossil fuels in driving climate change (IPCC, 2021).

Among the critical impact categories in **ReCiPe 2016 v1.03 Midpoint (E)** method evaluated in OpenLCA are Terrestrial Acidification Potential (TAP), Global Warming Potential (GWP1000), and Freshwater Ecotoxicity Potential (FETP), among others. Each category quantifies specific environmental concerns such as acidification, climate change, and toxicity, offering insights into the sustainability of processes and products.

Acidification: Terrestrial - Terrestrial Acidification Potential (TAP): The Terrestrial Acidification Potential (TAP) quantifies the potential of a substance or process to cause acidification in terrestrial ecosystems, expressed in kilograms of sulfur dioxide equivalent (kg SO_2-Eq). Acidification arises from emissions such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), leading to soil and vegetation degradation, diminished biodiversity, and altered nutrient cycling. Higher TAP values indicate a greater potential for soil acidification and associated ecological impacts (Heijungs et al., 2013).

Climate Change - Global Warming Potential (GWP1000): The Global Warming Potential (GWP1000) measures the impact of a substance on global warming over a 1000-year period, expressed in kilograms of carbon dioxide equivalent (kg CO_2-Eq).

This metric allows for comparison of the global warming impacts of different greenhouse gases based on their heat-trapping abilities and atmospheric lifetimes. A higher GWP signifies a greater contribution to climate change, which can exacerbate extreme weather events and sea-level rise (IPCC, 2014).

Ecotoxicity: Freshwater - Freshwater Ecotoxicity Potential (FETP): The Freshwater Ecotoxicity Potential (FETP) evaluates the potential impact of pollutants on freshwater ecosystems, measured in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB-Eq). This category assesses the toxicity of substances to aquatic organisms, including fish and invertebrates. Elevated FETP values indicate a higher risk of adverse effects on freshwater biodiversity and ecosystem function (Sala et al., 2005).

Ecotoxicity: Marine - Marine Ecotoxicity Potential (METP): The Marine Ecotoxicity Potential (METP) quantifies the potential of pollutants to impact marine ecosystems, expressed in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB-Eq). This metric measures the risk of toxic effects on marine life, including fish, marine mammals, and invertebrates. Higher METP values suggest a greater likelihood of harmful ecological impacts in marine environments (Kitzes et al., 2009).

Ecotoxicity: Terrestrial - Terrestrial Ecotoxicity Potential (TETP): The Terrestrial Ecotoxicity Potential (TETP) assesses the potential impact of substances on terrestrial ecosystems, measured in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB-Eq). This category evaluates the toxicity to soil organisms, plants, and terrestrial animals. Higher TETP values indicate significant risks to soil health and terrestrial biodiversity (Finkbeiner et al., 2006).

Energy Resources: Non-Renewable, Fossil- Fossil Fuel Potential (FFP): The Fossil Fuel Potential (FFP) measures the consumption of non-renewable fossil energy resources, expressed in kilograms of oil equivalent (kg oil-Eq). This metric reflects the extent of reliance on fossil fuels, which are finite resources and contribute to greenhouse gas emissions. Higher FFP values indicate greater consumption of non-renewable resources, with implications for energy sustainability and environmental impact (Hondo, 2005).

Eutrophication: Freshwater - Freshwater Eutrophication Potential (FEP): The Freshwater Eutrophication Potential (FEP) quantifies the potential for nutrient enrichment in freshwater systems, measured in kilograms of phosphorus equivalent (kg P-Eq). Eutrophication can lead to excessive algal blooms, oxygen depletion, and negative effects on aquatic life. Higher FEP values indicate a greater risk of nutrient pollution in freshwater environments (Heijungs et al., 2013).

Eutrophication: Marine - Marine Eutrophication Potential (MEP): The Marine Eutrophication Potential (MEP) assesses the potential for nutrient enrichment in marine ecosystems, expressed in kilograms of nitrogen equivalent (kg N-Eq). This metric evaluates the risk of nutrient-induced algal blooms and hypoxia in marine environments. Elevated MEP values suggest a higher potential for marine eutrophication and associated ecological disruptions (Nixon, 1995).

Human Toxicity: Carcinogenic- Human Toxicity Potential (HTPc): The Human Toxicity Potential for carcinogenic effects (HTPc) measures the potential for substances to cause cancer in humans, expressed in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB-Eq). This metric evaluates the carcinogenic risks of pollutants, with higher values indicating greater potential for cancer-related health issues (Cohen et al., 2016).

Human Toxicity: Non-Carcinogenic- Human Toxicity Potential (HTPnc): The Human Toxicity Potential for non-carcinogenic effects (HTPnc) assesses the risk of substances causing adverse health effects other than cancer, measured in kilograms of 1,4-dichlorobenzene equivalent (kg 1,4-DCB-Eq). This metric reflects the potential for chronic toxicity, such as respiratory or neurological effects, with higher values indicating increased risks to human health (Van Zelm et al., 2008).

Ionising Radiation- Ionising Radiation Potential (IRP): The Ionising Radiation Potential (IRP) quantifies the impact of ionising radiation exposure, expressed in kilobecquerels of cobalt-60 equivalent (kBq Co-60-Eq). Ionising radiation can cause tissue damage and increase cancer risks. This metric helps assess the potential radiation risks associated with different processes or materials (UNSCEAR, 2008).

Land Use- Agricultural Land Occupation (LOP): The Agricultural Land Occupation (LOP) measures the extent of land used for agriculture, expressed in square meters of crop equivalent per year (m^2*a crop-Eq). This metric reflects the impact on land resources, with higher values indicating greater land use for agricultural purposes, which can affect land availability and ecosystem services (Motoshita et al., 2011).

Material Resources: Metals/Minerals- Surplus Ore Potential (SOP): The Surplus Ore Potential (SOP) quantifies the consumption of metal and mineral resources, expressed in kilograms of copper equivalent (kg Cu-Eq). This metric assesses the amount of surplus ore required to meet resource needs, with higher values indicating greater resource extraction and associated environmental impacts (Bardi, 2008).

Ozone Depletion - Ozone Depletion Potential (ODPinfinite): The Ozone Depletion Potential (ODPinfinite) measures the potential of a substance to deplete the ozone layer, expressed in kilograms of chlorofluorocarbon-11 equivalent (kg CFC-11-Eq). Ozone depletion can increase ultraviolet radiation reaching the Earth's surface, leading to health and environmental issues. The metric reflects the long-term impact of substances on ozone layer degradation (WMO, 2014).

Particulate Matter Formation- Particulate Matter Formation Potential (PMFP): The Particulate Matter Formation Potential (PMFP) quantifies the potential for generating particulate matter, expressed in kilograms of PM2.5 equivalent (kg PM2.5-Eq). Particulate matter can have significant health effects, including respiratory and cardiovascular issues. Higher PMFP values indicate greater potential for particulate matter emissions (Friedl et al., 2008).

Photochemical Oxidant Formation: Human Health - Photochemical Oxidant Formation Potential: Humans (HOFP): The Photochemical Oxidant Formation Potential for human health (HOFP) measures the potential for forming photochemical oxidants, such as ozone, which can affect human health, expressed in kilograms of nitrogen oxides equivalent (kg NO_x-Eq). Elevated HOFP values indicate a greater potential for ozone-related health impacts (Carmichael et al., 2008).

Photochemical Oxidant Formation: Terrestrial Ecosystems- Photochemical Oxidant Formation Potential: Ecosystems (EOFP): The Photochemical Oxidant Formation Potential for terrestrial ecosystems (EOFP) assesses the potential for photochemical oxidant formation that impacts terrestrial ecosystems, expressed in kilograms of nitrogen oxides equivalent (kg NO_x-Eq). Higher EOFP values reflect a greater risk of damage to plant and soil ecosystems due to photochemical oxidants (Peñuelas et al., 2011).

Water Use- Water Consumption Potential (WCP): The Water Consumption Potential (WCP) measures the amount of water consumed, expressed in cubic meters (m^3).

This metric reflects the water use associated with a substance or process, with higher values indicating greater water consumption, which can impact water availability and sustainability (Hoekstra et al., 2011).

4.6.2.1 Asphalt Surface Layer (wear)

Based on IPCC 2021 method, **Asphalt Surface Layer (wear)** exhibits significant climate change impacts, with values expressed in kg CO2-equivalents (kg CO2-Eq). The Global Temperature Change Potential (GTP) ranges from 167.6566 kg CO2-Eq over 100 years to 172.8567 kg CO2-Eq over 50 years, indicating a moderate to high potential for temperature increase. The Global Warming Potential (GWP) shows higher values, with 231.6952 kg CO2-Eq over 20 years, 186.872 kg CO2-Eq over 100 years, and 169.0974 kg CO2-Eq over 500 years, reflecting significant immediate and cumulative heat-trapping effects. Fossil fuel-related emissions have similar impact levels, emphasizing their substantial role in driving climate change. The data underscores the considerable climate impact of the asphalt surface layer, particularly in the short to medium term.

Impact category	Reference unit	Result
climate change - global temperature change potential (GTP100)	kg CO2-Eq	167.6566
climate change - global temperature change potential (GTP50)	kg CO2-Eq	172.8567
climate change - global warming potential (GWP100)	kg CO2-Eq	186.872
climate change - global warming potential (GWP20)	kg CO2-Eq	231.6952
climate change - global warming potential (GWP500)	kg CO2-Eq	169.0974
climate change: fossil - global temperature change potential (GTP100)	kg CO2-Eq	167.604
climate change: fossil - global temperature change potential (GTP50)	kg CO2-Eq	172.7923
climate change: fossil - global warming potential (GWP100)	kg CO2-Eq	186.7731
climate change: fossil - global warming potential (GWP20)	kg CO2-Eq	231.487
climate change: fossil - global warming potential (GWP500)	kg CO2-Eq	169.0396

For Layer 1: Wear Layer, the environmental impacts span various categories. The global warming potential (GWP1000) is notable, with a result of 164.38 kg CO2-Eq, contributing significantly to climate change. Marine ecotoxicity potential (METP) stands out as exceptionally high, reaching 14,924.12 kg 1,4-DCB-Eq, indicating severe marine ecosystem impacts. Other ecotoxicity metrics, such as freshwater (FETP) and terrestrial (TETP), also show considerable contributions, with values of 2.00 kg and 908.70 kg 1,4-DCB-Eq, respectively.

In terms of human health, non-carcinogenic toxicity (HTPnc) registers a high value of 11,010.26 kg 1,4-DCB-Eq, reflecting substantial potential risks, while carcinogenic toxicity (HTPc) is lower but still significant at 356.68 kg 1,4-DCB-Eq. The fossil fuel potential (FFP) of 101.26 kg oil-Eq highlights a notable consumption of non-renewable energy resources.

Other environmental concerns include terrestrial acidification potential (TAP) at 0.89 kg SO2-Eq and particulate matter formation (PMFP) at 0.33 kg PM2.5-Eq, both contributing to air quality degradation. Ozone depletion (ODP), while present, is relatively minimal at 0.00013 kg CFC-11-Eq. Finally, water consumption (WCP) is low at 0.36 m^3, indicating minimal impact on water resources.

This data reflects that Layer 1 has significant impacts across a wide range of environmental factors, particularly in marine toxicity, human health risks, and fossil fuel usage.

Impact category	Reference unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.893898
climate change - global warming potential (GWP1000)	kg CO2-Eq	164.3827
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	2.000025
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	14924.12
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	908.6987
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	101.2607
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.00713
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.008974
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	356.6827
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	11010.26
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.957309
land use - agricultural land occupation (LOP)	m2*a crop-Eq	4.032263
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	176.0492
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	0.000128
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.332714
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.924558
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.987262
water use - water consumption potential (WCP)	m3	0.360428

4.6.2.2 Binder Course

Based on IPCC 2021 method The Global Temperature Change Potential (GTP) values are 152.3823 kg CO2-Eq over 100 years and 157.0589 kg CO2-Eq over 50 years, showing a moderate potential for temperature increase due to emissions. The Global Warming Potential (GWP) values are slightly lower than Layer 1, with 209.8685 kg CO2-Eq over 20 years, 169.6361 kg CO2-Eq over 100 years, and 153.6559 kg CO2-Eq over 500 years, indicating a substantial but reduced immediate and cumulative heat-trapping effect compared to Layer 1. Fossil fuel-related emissions have comparable impacts, with values closely matching the overall GTP and GWP results, highlighting their significant role in climate change. Overall, Layer 2 demonstrates a somewhat lower climate impact than Layer 1, especially over longer time frames, while still contributing significantly to global warming.

Impact category	Reference unit	Result
climate change - global temperature change potential (GTP100)	kg CO2-Eq	152.3823
climate change - global temperature change potential (GTP50)	kg CO2-Eq	157.0589
climate change - global warming potential (GWP100)	kg CO2-Eq	169.6361
climate change - global warming potential (GWP20)	kg CO2-Eq	209.8685
climate change - global warming potential (GWP500)	kg CO2-Eq	153.6559
climate change: fossil - global temperature change potential (GTP100)	kg CO2-Eq	152.336
climate change: fossil - global temperature change potential (GTP50)	kg CO2-Eq	157.0011
climate change: fossil - global warming potential (GWP100)	kg CO2-Eq	169.5448
climate change: fossil - global warming potential (GWP20)	kg CO2-Eq	209.6708
climate change: fossil - global warming potential (GWP500)	kg CO2-Eq	153.6046

Based on ReCiPe Midpoint method For Layer 2, the environmental impacts cover a range of categories. The global warming potential (GWP1000) is recorded at 149.41 kg CO_2-Eq, indicating a significant contribution to climate change. Marine ecotoxicity potential (METP) is notably high at 13,946.48 kg 1,4-DCB-Eq, suggesting substantial adverse effects on marine ecosystems. Additionally, terrestrial ecotoxicity potential (TETP) is also considerable at 874.37 kg 1,4-DCB-Eq, reflecting potential harm to terrestrial environments.

Human health impacts include non-carcinogenic toxicity (HTPnc) at 10,300.31 kg 1,4-DCB-Eq, indicating a high risk of non-cancer-related health effects. Carcinogenic toxicity (HTPc) is lower but still significant at 312.54 kg 1,4-DCB-Eq. The fossil fuel potential (FFP) is 90.78 kg oil-Eq, highlighting a substantial consumption of non-renewable energy resources.

Other environmental concerns include terrestrial acidification potential (TAP) at 0.82 kg SO_2-Eq and particulate matter formation (PMFP) at 0.30 kg $PM_{2.5}$-Eq, both contributing to air quality issues. Ozone depletion potential (ODP) is minimal at 0.00012 kg CFC-11-Eq. Water consumption (WCP) is relatively low at 0.32 m^3, indicating a minor impact on water resources.

Overall, the data for Layer 2 demonstrates significant impacts, particularly in marine toxicity, human health risks, and fossil fuel consumption, while showing relatively lower concerns in ozone depletion and water use.

Impact category	Reference unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.815724
climate change - global warming potential (GWP1000)	kg CO2-Eq	149.4123
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.86662
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	13946.48
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	874.3746
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	90.77762
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.006534
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.008212
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	312.542
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	10300.31
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.808024
land use - agricultural land occupation (LOP)	m2*a crop-Eq	4.075107
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	212.5596
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	0.000119
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.29856
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.78855
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.843932
water use - water consumption potential (WCP)	m3	0.317619

4.6.2.3 Base Course

Based on IPCC 2021 method, the climate change impact, expressed in kilograms of CO2-equivalents (kg CO2-Eq), indicates a reduced impact compared to the previous layers.

The Global Temperature Change Potential (GTP) values are 130.1722 kg CO2-Eq over 100 years and 134.2900 kg CO2-Eq over 50 years, reflecting a moderate contribution to temperature rise. The Global Warming Potential (GWP) values are 180.8380 kg CO2-Eq over 20 years, 145.3769 kg CO2-Eq over 100 years, and 131.3001 kg CO2-Eq over 500 years, indicating a lower overall heat-trapping effect compared to Layer 1 and Layer 2, especially over longer time horizons. The fossil fuel-specific GTP and GWP values are closely aligned with the overall results, further confirming the significant role of fossil fuel emissions in contributing to climate change.

Overall, Layer 3 exhibits the lowest climate change impact across all time horizons among the three layers, with the highest contribution still observed in the short term (GWP20).

Impact category	Reference unit	Result
climate change - global temperature change potential (GTP100)	kg CO2-Eq	130.1722
climate change - global temperature change potential (GTP50)	kg CO2-Eq	134.29
climate change - global warming potential (GWP100)	kg CO2-Eq	145.3769
climate change - global warming potential (GWP20)	kg CO2-Eq	180.838
climate change - global warming potential (GWP500)	kg CO2-Eq	131.3001
climate change: fossil - global temperature change potential (GTP100)	kg CO2-Eq	130.1294
climate change: fossil - global temperature change potential (GTP50)	kg CO2-Eq	134.2363
climate change: fossil - global warming potential (GWP100)	kg CO2-Eq	145.2914
climate change: fossil - global warming potential (GWP20)	kg CO2-Eq	180.6515
climate change: fossil - global warming potential (GWP500)	kg CO2-Eq	131.2525

Based on ReCiPe Midpoint method The global warming potential (GWP1000) is 127.56 kg CO_2-Eq, indicating a significant contribution to climate change. Marine ecotoxicity potential (METP) is notable at 12,802.35 kg 1,4-DCB-Eq, suggesting considerable adverse effects on marine ecosystems. Similarly, terrestrial ecotoxicity potential (TETP) is substantial at 821.76 kg 1,4-DCB-Eq, reflecting potential harm to terrestrial environments. Freshwater ecotoxicity potential (FETP) is 1.71 kg 1,4-DCB-Eq, indicating moderate impact on freshwater ecosystems.

Human health risks include non-carcinogenic toxicity (HTPnc) at 9,494.30 kg 1,4-DCB-Eq, pointing to significant non-cancer-related health effects. Carcinogenic toxicity (HTPc) is lower but still notable at 256.65 kg 1,4-DCB-Eq. Fossil fuel potential (FFP) is 80.02 kg oil-Eq, reflecting a considerable use of non-renewable energy resources.

Additional concerns include terrestrial acidification potential (TAP) at 0.70 kg SO_2-Eq, contributing to soil acidification. Particulate matter formation potential (PMFP) is 0.25 kg $PM_{2.5}$-Eq, impacting air quality. Ozone depletion potential (ODP) is minimal at 0.0001 kg CFC-11-Eq. Water consumption (WCP) is relatively low at 0.29 m^3, indicating a minor impact on water resources.

Overall, Layer 3 demonstrates substantial impacts, particularly in marine and terrestrial toxicity, human health risks, and fossil fuel consumption, with relatively lower concerns in ozone depletion and water use.

Impact category	**Reference unit**	**Result**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.698355
climate change - global warming potential (GWP1000)	kg CO2-Eq	127.5608
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.707273
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	12802.35
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	821.7644
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	80.0183
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.005804
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.007356
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	256.6498
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	9494.305
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.620864
land use - agricultural land occupation (LOP)	m2*a crop-Eq	4.005335
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	234.0005
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	0.000104
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.246303
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.582294
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.629646
water use - water consumption potential (WCP)	m3	0.286107

4.6.2.4 Graded Stabilized

Based on IPCC 2021 method, the climate change impact results, expressed in kg CO2-equivalents (kg CO2-Eq), indicate the lowest impact compared to the previous layers:

The Global Temperature Change Potential (GTP) values are 24.65399 kg CO2-Eq over 100 years and 25.20005 kg CO2-Eq over 50 years, demonstrating a relatively small contribution to temperature rise. The Global Warming Potential (GWP) values are also modest, with 30.9543 kg CO2-Eq over 20 years, 26.5624 kg CO2-Eq over 100 years, and 24.7307 kg CO2-Eq over 500 years. These values show a minimal heat-trapping effect, especially over longer time horizons. Fossil fuel-related GTP and GWP values are nearly identical to the overall results, reinforcing that fossil fuel emissions remain the primary driver of the layer's climate impact.

Overall, Layer 4 contributes the least to climate change among all layers, with the most significant impact seen in the short-term GWP20.

Impact category	Reference unit	Result
climate change - global temperature change potential (GTP100)	kg CO2-Eq	24.65399
climate change - global temperature change potential (GTP50)	kg CO2-Eq	25.20005
climate change - global warming potential (GWP100)	kg CO2-Eq	26.56238
climate change - global warming potential (GWP20)	kg CO2-Eq	30.95432
climate change - global warming potential (GWP500)	kg CO2-Eq	24.7307
climate change: fossil - global temperature change potential (GTP100)	kg CO2-Eq	24.63107
climate change: fossil - global temperature change potential (GTP50)	kg CO2-Eq	25.17007
climate change: fossil - global warming potential (GWP100)	kg CO2-Eq	26.51183
climate change: fossil - global warming potential (GWP20)	kg CO2-Eq	30.83848
climate change: fossil - global warming potential (GWP500)	kg CO2-Eq	24.70468

Based on ReCiPe Midpoint method The global warming potential (GWP1000) is relatively low at 24.24 kg CO_2-Eq, indicating a minor contribution to climate change. Marine ecotoxicity potential (METP) is 5,536.79 kg 1,4-DCB-Eq, reflecting significant potential harm to marine ecosystems. Terrestrial ecotoxicity potential (TETP) is 387.62 kg 1,4-DCB-Eq, suggesting considerable adverse effects on terrestrial environments. Freshwater ecotoxicity potential (FETP) is 0.64 kg 1,4-DCB-Eq, showing moderate impact on freshwater systems.

Human health impacts include non-carcinogenic toxicity (HTPnc) at 4,358.80 kg 1,4-DCB-Eq, indicating substantial risks of non-cancer-related health effects. Carcinogenic toxicity (HTPc) is lower at 91.18 kg 1,4-DCB-Eq. The fossil fuel potential (FFP) is 8.23 kg oil-Eq, representing a lower consumption of non-renewable energy resources compared to other layers.

Additional environmental impacts include terrestrial acidification potential (TAP) at 0.09 kg SO_2-Eq, which is relatively low. Particulate matter formation potential (PMFP) is also low at 0.05 kg $PM_{2.5}$-Eq, indicating minimal air quality concerns. Ozone depletion potential (ODP) is minimal at 0.000023 kg CFC-11-Eq. Water consumption (WCP) is very low at 0.07 m^3, suggesting a minor impact on water resources.

Overall, Layer 4 shows relatively low impacts in terms of global warming potential, terrestrial acidification, and water use, with notable concerns in marine and terrestrial ecotoxicity and human health risks.

Impact category	Reference unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.089578
climate change - global warming potential (GWP1000)	kg CO2-Eq	24.24043
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	0.638068
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	5536.788
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	387.6218
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	8.230402
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.002499
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.00075
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	91.17708
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	4358.805
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.787779
land use - agricultural land occupation (LOP)	m2*a crop-Eq	3.688901
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	381.6353
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	2.29E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.048084
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.154103
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.160334
water use - water consumption potential (WCP)	m3	0.065956

4.6.2.5: Cemented Mix

Based on IPCC 2021 method shows moderate climate change impacts, with Global Temperature Change Potential (GTP) values of 47.6821 kg CO2-Eq over 100 years and 48.3445 kg CO2-Eq over 50 years, indicating a steady contribution to temperature rise. The Global Warming Potential (GWP) is highest in the short term, with 55.4898 kg CO2-Eq over 20 years, and decreases to 50.0395 kg CO2-Eq over 100 years and 47.8049 kg CO2-Eq over 500 years. Fossil fuel-related GTP and GWP values closely align with the overall results, highlighting the dominant role of fossil emissions in Layer 5's climate impact.

Impact category	Reference unit	Result
climate change - global temperature change potential (GTP100)	kg CO2-Eq	47.68208
climate change - global temperature change potential (GTP50)	kg CO2-Eq	48.34449
climate change - global warming potential (GWP100)	kg CO2-Eq	50.03952
climate change - global warming potential (GWP20)	kg CO2-Eq	55.48983
climate change - global warming potential (GWP500)	kg CO2-Eq	47.80495
climate change: fossil - global temperature change potential (GTP100)	kg CO2-Eq	47.60868
climate change: fossil - global temperature change potential (GTP50)	kg CO2-Eq	48.26378
climate change: fossil - global warming potential (GWP100)	kg CO2-Eq	49.93755
climate change: fossil - global warming potential (GWP20)	kg CO2-Eq	55.32032
climate change: fossil - global warming potential (GWP500)	kg CO2-Eq	47.72834

Based on ReCiPe Midpoint method The global warming potential (GWP1000) is 47.21 kg CO_2-Eq, indicating a moderate contribution to climate change. Marine ecotoxicity potential (METP) is 7,429.13 kg 1,4-DCB-Eq, which reflects a substantial potential for harm to marine ecosystems. Terrestrial ecotoxicity potential (TETP) is 432.24 kg 1,4-DCB-Eq, suggesting notable adverse effects on terrestrial environments. Freshwater ecotoxicity potential (FETP) is 0.89 kg 1,4-DCB-Eq, indicating moderate impact on freshwater systems.

Human health impacts include non-carcinogenic toxicity (HTPnc) at 5,952.86 kg 1,4-DCB-Eq, reflecting significant risks of non-cancer-related health effects. Carcinogenic toxicity (HTPc) is lower at 120.02 kg 1,4-DCB-Eq. The fossil fuel potential (FFP) is 10.98 kg oil-Eq, showing a moderate level of non-renewable energy resource consumption.

Other environmental concerns include terrestrial acidification potential (TAP) at 0.19 kg SO_2-Eq, indicating a modest impact on soil acidification. Particulate matter formation potential (PMFP) is 0.08 kg $PM_{2.5}$-Eq, contributing to air quality concerns. Ozone depletion potential (ODP) is minimal at 0.00002371 kg CFC-11-Eq. Water consumption (WCP) is 0.19 m^3, suggesting a moderate impact on water resources.

Overall, Layer 5 shows moderate impacts in terms of global warming potential, terrestrial acidification, and water use, with significant concerns in marine and terrestrial ecotoxicity, as well as human health risks.

Impact category	Reference unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	0.189969
climate change - global warming potential (GWP1000)	kg CO2-Eq	47.21028
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	0.885897
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	7429.13
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	432.2445
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	10.98148
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	0.005692
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	0.001031
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	120.0195
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	5952.86
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	0.890308
land use - agricultural land occupation (LOP)	m2*a crop-Eq	3.774503
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	284.9994
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	2.37E-05
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	0.076643
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	0.211208
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	0.218178
water use - water consumption potential (WCP)	m3	0.188807

4.6.2.6 Overall Impacts

This table sums up the impacts from each layer to provide an overall view of the environmental impact across all layers.

In comparing the environmental impacts across the five layers, it is evident that the Wear Layer (Layer 1) has the highest overall contribution to climate change across most categories. This layer produces the most CO2-equivalent emissions, particularly in terms of GWP20, with a value of 231.6952 kg CO2-Eq, indicating a significant short-term impact on climate change.

The Binder Layer (Layer 2) follows closely, with moderately high emissions, especially in GWP20, reflecting its substantial contribution to near-term warming. While its total emissions are lower than Layer 1, it still plays a significant role in climate impacts.

The Base Layer (Layer 3) shows a further reduction in emissions in all categories, signifying a lower climate impact compared to the Wear and Binder layers. Its emissions are particularly reduced in long-term categories such as GTP100 and GWP500, indicating a lesser contribution to long-term warming.

Both the Graded Stabilized Layer (Layer 4) and the Cemented Mix Layer (Layer 5) have considerably lower emissions. Layer 4 contributes the least to overall emissions, making it the least impactful in terms of CO2-equivalents. Layer 5 has slightly higher emissions than Layer 4 but remains much lower than the Wear, Binder, and Base layers.

In summary, the Wear Layer (Layer 1) stands out as the most impactful, especially in short-term climate measures like GWP20, while the Graded Stabilized Layer (Layer 4) is the least environmentally impactful. The deeper layers, particularly Layer 4 and Layer 5, have a much lower contribution to global temperature change and warming potential.

Impact category	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Total
climate change - global temperature change potential (GTP100)	167.6566	152.3823	130.1722	24.654	47.6821	522.5472
climate change - global temperature change potential (GTP50)	**172.8567**	**157.0589**	**134.29**	**25.2001**	**48.3445**	**537.7502**
climate change - global warming potential (GWP100)	186.872	169.6361	145.3769	26.5624	50.0395	578.4869
climate change - global warming potential (GWP20)	**231.6952**	**209.8685**	**180.838**	**30.9543**	**55.4898**	**708.8459**
climate change - global warming potential (GWP500)	169.0974	153.6559	131.3001	24.7307	47.8049	526.589
climate change: fossil - global temperature change potential (GTP100)	**167.604**	**152.336**	**130.1294**	**24.6311**	**47.6087**	**522.3092**
climate change: fossil - global temperature change potential (GTP50)	172.7923	157.0011	134.2363	25.1701	48.2638	537.4636
climate change: fossil - global warming potential (GWP100)	**186.7731**	**169.5448**	**145.2914**	**26.5118**	**49.9375**	**578.0586**
climate change: fossil - global warming potential (GWP20)	231.487	209.6708	180.6515	30.8385	55.3203	707.9681
climate change: fossil - global warming potential (GWP500)	**169.0396**	**153.6046**	**131.2525**	**24.7047**	**47.7283**	**526.3297**

Based on ReCiPe Midpoint method In terms of acidification, Layer 1 exhibits the highest total impact, with Layers 2 and 3 following, while Layer 4 shows the lowest impact, highlighting notable differences in terrestrial acidification across the layers. For climate change, Layer 1 has the greatest contribution to global warming, whereas Layer 4 records the lowest impact, suggesting considerable variation in climate change impacts among the layers.

Marine ecotoxicity is most significant in Layer 1, indicating a substantial environmental impact, while freshwater and terrestrial ecotoxicity are highest in Layers 1 and 2. In terms of energy resources, Layer 1 demonstrates the highest fossil fuel potential, with a noticeable decrease in Layer 4.

Eutrophication impacts are the lowest in Layer 4 for both freshwater and marine categories, reflecting a reduced environmental impact in these areas. Human toxicity is notably high in Layer 1, particularly for non-carcinogenic toxicity, with significant levels across all layers. Carcinogenic toxicity is also considerable in Layers 1 and 2.

Ionising radiation impacts are relatively uniform across all layers, totaling 7.0643 kBq Co-60-Eq. Land use impacts are fairly consistent, with slightly higher values in Layers 1 and 2. The highest impact on material resources is observed in Layer 4, suggesting greater resource consumption or waste in this layer.

Ozone depletion remains minimal across all layers. Particulate matter formation is highest in Layer 1, and the impacts of photochemical oxidant formation are moderate, with Layer 1 leading in both human health and ecosystem categories. Finally, Layer 4 shows the lowest water consumption potential, indicating reduced water use compared to the other layers.

Overall, the data illustrates substantial variability in environmental impacts across different layers, with Layer 1 typically showing higher impacts across many categories compared to the other layers.

Impact Category	Reference Unit	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Total
Acidification: Terrestrial (TAP)	kg SO_2-Eq	0.8939	0.8157	0.6984	0.0896	0.1900	2.6876
Climate Change: Global Warming Potential (GWP1000)	kg CO_2-Eq	164.38	149.41	127.56	24.24	47.21	512.80
Ecotoxicity: Freshwater (FETP)	kg 1,4-DCB-Eq	2.0000	1.8666	1.7073	0.6381	0.8859	7.0979
Ecotoxicity: Marine (METP)	kg 1,4-DCB-Eq	14924.12	13946.48	12802.35	5536.79	7429.13	61,638.87
Ecotoxicity: Terrestrial (TETP)	kg 1,4-DCB-Eq	908.70	874.37	821.76	387.62	432.24	2,424.69
Energy Resources: Non-Renewable, Fossil (FFP)	kg oil-Eq	101.26	90.78	80.02	8.23	10.98	291.27
Eutrophication: Freshwater (FEP)	kg P-Eq	0.0071	0.0065	0.0058	0.0025	0.0057	0.0276
Eutrophication: Marine (MEP)	kg N-Eq	0.0090	0.0082	0.0074	0.0008	0.0010	0.0264
Human Toxicity: Carcinogenic (HTPc)	kg 1,4-DCB-Eq	356.68	312.54	256.65	91.18	120.02	1136.07
Human Toxicity: Non-Carcinogenic (HTPnc)	kg 1,4-DCB-Eq	11010.26	10300.31	9494.30	4358.80	5952.86	46,116.53
Ionising Radiation (IRP)	kBq Co-60-Eq	1.9573	1.8080	1.6209	0.7878	0.8903	7.0643
Land Use: Agricultural Land Occupation (LOP)	m^2*a crop-Eq	4.0323	4.0751	4.0053	3.6889	3.7745	19.5761
Material Resources: Metals/Minerals- Surplus Ore Potential (SOP)	kg Cu-Eq	176.05	212.56	234.00	381.64	285.00	1,289.25
Ozone Depletion (ODPinfinite)	kg CFC-11-Eq	0.00013	0.00012	0.00010	0.00002	0.00002	0.00039
Particulate Matter Formation (PMFP)	kg $PM_{2.5}$-Eq	0.3327	0.2986	0.2463	0.0481	0.0766	1.0023
Photochemical Oxidant Formation: Human Health (HOFP)	kg NOx-Eq	0.9246	0.7886	0.5823	0.1541	0.2112	2.6608
Photochemical Oxidant Formation: Terrestrial Ecosystems (EOFP)	kg NOx-Eq	0.9873	0.8439	0.6296	0.1603	0.2182	2.8393
Water Use: Water Consumption Potential (WCP)	m^3	0.3604	0.3176	0.2861	0.0659	0.1888	1.2188

4.6.3 Evaluation of the Impact of New Equipment on Pavement Construction

In this section, we examine the environmental benefits of incorporating advanced equipment into pavement construction activities. The integration of new technologies and equipment is a crucial factor in enhancing the efficiency and sustainability of construction processes. By replacing older, less efficient equipment with newer, more sophisticated alternatives, significant reductions in environmental impacts can be achieved.

New equipment often brings improvements in energy efficiency, reduced emissions, and better resource utilization. For example, modern machinery may utilize cleaner energy sources, implement advanced emission control systems, or incorporate more precise technologies that minimize material waste. These advancements not only contribute to lower greenhouse gas emissions and reduced ecological disturbances but also promote overall cost savings and operational efficiency. This analysis will quantify the improvements in environmental performance associated with the use of new equipment across various pavement construction activities. By comparing the impacts of traditional versus enhanced equipment, we aim to highlight the potential reductions in overall environmental footprint and identify opportunities for further optimization in the construction process. Here is a table summarizing the performance of the new equipment introduced for the Zero-Pavement construction:

Equipment	Role	Fuel Consumption	Performance Metrics	Reference
Volvo FH Electric Truck	Long-distance material transport	Zero tailpipe emissions	Range of up to 300 km per charge	Volvo Trucks (2024)
Volvo L25 Electric Wheel Loader	Material loading	Zero tailpipe emissions	Operating weight: ~5 tons; Full day's work per charge	Volvo Construction Equipment (2024)
Caterpillar AP555F Mobil-Trac Paver	Laying and compacting asphalt layers	Reduced by up to 20%	Lays up to 160 tons of asphalt per hour	Caterpillar Inc. (2024)
Wirtgen W 210i Milling Machine	Surface preparation and milling	Reduced by ~20%	Processes up to 220 tons per hour	Wirtgen Group (2024)
Caterpillar CB10 Roller	Compaction of asphalt layers	Improved fuel efficiency	Compacts up to 50 cubic meters per hour	Caterpillar Inc. (2024)
Cimline M-Series M4 Melter	Application of bituminous emulsion	7 liters/hour	Covers up to 0.03 square kilometers per hour	Cimline (2024)
Bucher CityCat 2020 Sweeper	Urban and site cleaning	12 liters/hour	Covers up to 0.04 square kilometers per hour	Bucher Municipal (2024)

The updated equipment table reflects a shift towards more sustainable and efficient machinery in road construction and maintenance. Notably, the introduction of electric vehicles, such as the **Volvo FH Electric Truck** and **Volvo L25 Electric Wheel Loader**, demonstrates a commitment to reducing emissions with zero tailpipe emissions and improved energy efficiency. Additionally, advancements in fuel efficiency are evident with the **Caterpillar AP555F Mobil-Trac Paver** and **Wirtgen W 210i Milling Machine**, which have reduced fuel consumption by approximately 20% compared to their older counterparts while maintaining or enhancing their operational performance. This transition to electric and more fuel-efficient equipment not only minimizes environmental impact but also aligns with industry trends towards sustainability and reduced operational costs. The data highlights significant improvements in fuel consumption and performance metrics, underscoring the benefits of adopting new technologies in construction and maintenance operations.

Equipment	**Fuel Consumption (liters/hour)**	**Performance Metrics (tons/hour)**
Old Equipment		
30t Truck	0.6 liters/km	N/A
Wheel Loader	23 liters/hour	220 tons/hour
Paver	21 liters/hour	140 tons/hour
Miller	100 liters/hour	200 tons/hour
Roller	13 liters/hour	40 cubic meters/hour
Emulsifier	8.5 liters/hour	0.025 square kilometers/hour
Sweeper	15 liters/hour	0.038 square kilometers/hour
New Equipment		
Volvo FH Electric Truck	0 liters (electric ~1.2 kWh/km)	N/A
Volvo L25 Electric Wheel Loader	0 liters (electric ~20-30 kWh/hour)	~2.5 tons/hour
Caterpillar AP555F Mobil-Trac Paver	Reduced by 20% vs. old	160 tons/hour
Wirtgen W 210i Milling Machine	Reduced by 20% vs. old	220 tons/hour
Caterpillar CB10 Roller	Improved fuel efficiency	50 cubic meters/hour
Cimline M-Series - M4 Melter	7.5 liters/hour	~0.030 square kilometers/hour
Bucher CityCat 2020 Sweeper	12 liters/hour	~0.040 square kilometers/hour

The updated table outlines the fuel consumption and performance metrics for both old and new construction equipment. We will utilize these new, more efficient machines to recalculate the fuel consumption for each layer in the pavement structure. This will provide a more accurate assessment of resource use and environmental impact for the installation phase.

Table for Layer 1(New Equipment)

Equipment	Fuel Consumption Rate (liters/hour)	performance	Operational Hours	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Sprayer (Emulsifier)	7	0.03 (km²/hour)	0.378	2.65	35,800	94,470
Sweeper	12	0.04 (km²/hour)	0.284	3.41	35,800	122,658
Paver	16.8	160 tons/hour	0.0077	0.12	35,800	4,296
Roller	11	50 m³/hour	0.011	0.12	35,800	4,296
Total				6.30		225,720

Table for Layer 2 (New Equipment)

Equipment	Fuel Consumption Rate (liters/hour)	Performance	Operational Hours	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Sprayer (Emulsifier)	7	0.03 km²/hour	0.253	1.77	35,800	63,606
Sweeper	12	0.04 km²/hour	0.190	2.28	35,800	81,624
Paver	16.8	160 tons/hour	0.00285	0.048	35,800	1,719
Roller	11	50 m³/hour	0.00912	0.10	35,800	3,580
Total				4.15		150,529

Table for Layer 3 (New Equipment)

Equipment	Fuel Consumption Rate (liters/hour)	Performance	Operational Hours	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Paver	16.8	160 tons/hour	0.0065	0.11	35,800	3,938
Roller	11	50 m³/hour	0.0089	0.10	35,800	3,580
Emulsifier (Sprayer)	7	0.03 km²/hour	0.123	0.86	35,800	30,772
Total				1.07		38,290

Layer 4 (New Equipment)

Equipment	Fuel Consumption Rate (liters/hour)	Performance	Operational Hours	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Wirtgen W 210i	80	220 tons/hour	0.0045	0.36	35,800	12,888
Roller	11	50 m³/hour	0.0105	0.1155	35,800	4,134
Total				0.4755		17,022

Table for Layer 5 (New Equipment)

Equipment	Fuel Consumption Rate (liters/hour)	Performance	Operational Hours	Total Fuel Consumption (liters)	Energy Content (kJ/liter)	Total Energy Consumption (kJ)
Paver	16.8	160 tons/hour	0.0066	0.11	35,800	3,948
Roller	11	50 m³/hour	0.0101	0.11	35,800	3,948
Total				0.22		7,896

This table consolidates the environmental impacts from each layer, offering a comprehensive overview of the effects across the entire pavement structure. The data reflects the use of new, more efficient equipment, which plays a significant role in recalculating fuel consumption and minimizing the environmental footprint. These impacts are based on IPCC 2021 guidelines, ensuring standardized and accurate assessment of climate-related effects. By incorporating the performance of these advanced machines, the table highlights how improvements in equipment efficiency directly influence the total environmental impact across all construction layers, leading to a more sustainable approach to road construction.

Impact Category	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Total Impact**
Climate Change - Global Temperature Change Potential (GTP100)	**159.86**	**146.75**	**128.57**	**24.00**	**47.35**	**506.53**
Climate Change - Global Temperature Change Potential (GTP50)	164.92	151.32	132.66	24.54	48.01	521.45
Climate Change - Global Warming Potential (GWP100)	**178.58**	**163.64**	**143.67**	**25.87**	**49.69**	**561.45**
Climate Change - Global Warming Potential (GWP20)	222.25	203.04	178.89	30.17	55.09	689.45
Climate Change - Global Warming Potential (GWP500)	**161.28**	**148.00**	**129.69**	**24.08**	**47.47**	**510.52**
Climate Change: Fossil - Global Temperature Change Potential (GTP100)	159.81	146.70	128.52	23.98	47.28	506.29
Climate Change: Fossil - Global Temperature Change Potential (GTP50)	**164.86**	**151.27**	**132.60**	**24.51**	**48.01**	**521.24**
Climate Change: Fossil - Global Warming Potential (GWP100)	178.48	163.55	143.58	25.82	49.58	561.02
Climate Change: Fossil - Global Warming Potential (GWP20)	**222.05**	**202.85**	**178.71**	**30.05**	**54.92**	**688.58**
Climate Change: Fossil - Global Warming Potential (GWP500)	161.22	147.95	129.64	24.05	47.40	510.26

This table presents a consolidated view of the environmental impacts across five layers, using the ReCiPe Midpoint methodology. The data reflects the use of advanced, more efficient equipment, significantly reducing fuel consumption and environmental burden. The impacts are calculated based on standardized indicators such as global warming potential (GWP) and human toxicity, among others. Incorporating more efficient machinery leads to an overall reduction in impacts across key categories like climate change, resource depletion, and toxicity potential, contributing to a more sustainable approach to road construction.

Impact Category	Reference Unit	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Total
Acidification: terrestrial (TAP)	kg SO2-Eq	0.8538	0.7868	0.6901	0.0862	0.1883	2.6052
Climate Change (GWP1000)	kg CO2-Eq	156.6855	143.8484	125.9762	23.5989	46.8823	496.9914
Ecotoxicity: freshwater (FETP)	kg 1,4-DCB-Eq	1.9598	1.8375	1.6990	0.6347	0.8842	7.0152
Ecotoxicity: marine (METP)	kg 1,4-DCB-Eq	14632.8004	13735.9001	12742.3731	5512.5066	7416.7167	54040.2970
Ecotoxicity: terrestrial (TETP)	kg 1,4-DCB-Eq	898.5252	867.0208	819.6700	386.7738	431.8110	3403.8008
Energy Resources: non-renewable (FFP)	kg oil-Eq	98.7554	88.9667	79.5026	8.0216	10.8747	286.1209
Eutrophication: freshwater (FEP)	kg P-Eq	0.0069	0.0063	0.0058	0.0025	0.0057	0.0271
Eutrophication: marine (MEP)	kg N-Eq	0.0088	0.0081	0.0073	0.0007	0.0010	0.0259
Human Toxicity: carcinogenic (HTPc)	kg 1,4-DCB-Eq	333.9780	296.1302	251.9757	89.2846	119.0520	1090.4206
Human Toxicity: non-carcinogenic (HTPnc)	kg 1,4-DCB-Eq	10810.1023	10155.6317	9453.0993	4342.1214	5944.3316	40605.2863
Ionising Radiation (IRP)	kBq Co-60-Eq	1.8911	1.7602	1.6072	0.7823	0.8875	6.9284
Land Use (LOP)	m2*a crop-Eq	4.0089	4.0582	4.0005	3.6869	3.7735	19.5281
Material Resources: metals/minerals (SOP)	kg Cu-Eq	175.9363	212.4781	233.9772	381.6258	284.9946	1288.0119
Ozone Depletion (ODP infinite)	kg CFC-11-Eq	0.0001	0.0001	0.0001	0.0000	0.0000	0.0004
Particulate Matter Formation (PMFP)	kg PM2.5-Eq	0.3120	0.2836	0.2420	0.0464	0.0758	0.9598
Photochemical Oxidant Formation: humans (HOFP)	kg NOx-Eq	0.8300	0.7202	0.5628	0.1462	0.2072	2.4665
Photochemical Oxidant Formation: ecosystems (EOFP)	kg NOx-Eq	0.8902	0.7738	0.6097	0.1522	0.2140	2.6399
Water Use (WCP)	m3	0.3541	0.3131	0.2848	0.0654	0.1885	1.2059

5. Results and Discussion

5.1 Evaluation of Fuel Consumption and CO2 Emissions

An assessment of fuel consumption and CO2 emissions highlights the advancements achieved with new road construction equipment. The new equipment demonstrates a slight reduction in overall fuel consumption by approximately 0.24%. More notably, fuel consumption during the installation phase has decreased by 24.2%, indicating improved operational efficiency. Additionally, a corresponding reduction in total CO2 emissions is observed, with the new equipment showing a decrease of about 0.24% compared to the reference equipment.

Table 1: Fuel Consumption and CO2 Emissions by Equipment

Equipment	Overall Fuel Consumption (liters)	Installation Fuel Consumption (liters)	CO2 Emissions per Liter of Diesel (kg CO2/liter)	Total CO2 Emissions (kg)
Reference Equipment	1,619.04	16.08	2.68	4,336.43
New Equipment	1,615.16	12.2	2.68	4,326.43

Note: The CO2 emissions per liter of diesel fuel are assumed to be 2.68 kg CO2/liter, a typical value for diesel fuel.

Overall Fuel Consumption:

The new equipment exhibits a marginal reduction in overall fuel consumption by 0.24%. This improvement signifies enhanced fuel efficiency, contributing to a lower environmental footprint for construction activities.

Installation Fuel Consumption:

The new equipment shows a significant reduction of 24.2% in fuel consumption during the installation phase compared to the reference equipment. This substantial decrease reflects advancements in equipment design and operational performance, resulting in more efficient fuel use.

Total CO2 Emissions:

The new equipment results in a reduction of total CO2 emissions by approximately 0.24% relative to the reference equipment. This reduction aligns with the observed improvements in fuel consumption and highlights incremental advancements in emissions management.

Interpretation and Implications

The new equipment demonstrates incremental improvements in fuel consumption and CO2 emissions. The significant reduction in installation fuel consumption indicates effective technological advancements in enhancing operational efficiency. While the overall reduction in CO2 emissions is modest, the improvements during installation contribute positively to sustainability in construction practices.

Broader Implications:

- Environmental Benefits: The observed reductions in fuel consumption and CO2 emissions, although modest, contribute to more sustainable construction practices. The improvements during installation phases offer potential environmental benefits that could be scaled across various projects.
- Future Considerations: Achieving more substantial environmental improvements requires continued advancements in fuel efficiency and emissions control technologies. Comprehensive lifecycle assessments should incorporate detailed operational data to fully capture the benefits of new equipment.
- Policy and Practice: These findings underscore the importance of continued innovation in construction equipment technology. Supporting advancements focused on reducing fuel consumption and emissions will be essential for promoting sustainable construction practices and minimizing environmental impacts.

In summary, the new equipment reflects incremental improvements in fuel consumption and CO2 emissions. While the reductions are modest, they signify progress towards more sustainable construction practices. Ongoing advancements and research will be crucial for achieving more significant environmental benefits.

5.2 CO2 Emissions by Layer

An analysis of CO2 emissions by pavement layer was conducted for both reference and new equipment. This assessment provides insight into the environmental impact of each layer's construction process and highlights the improvements achieved with the new equipment. The revised emissions data for each layer is summarized in Table 2 below.

Table 2: Comparison of CO2 Emissions by Layer

Layer	Reference Equipment (kg CO2)	New Equipment (kg CO2)	Emissions Reduction (kg CO2)
1	440.643	438.693	1.95
2	438.533	437.393	1.14
3	434.793	434.293	0.50
4	235.973	235.873	0.10
Total	1,549.942	1,546.252	3.69

The analysis of CO2 emissions across different pavement layers, comparing reference and new equipment, provides critical insights into the environmental efficiency of modern road construction machinery. The data, summarized in Table 2, shows a modest reduction in CO2 emissions with the adoption of new equipment. This evaluation aims to assess the significance of these reductions and their implications for sustainability in construction practices.

Detailed Emission Analysis

Layer 1:

The reduction of 1.95 kg CO2 in Layer 1 represents a 0.44% decrease compared to the reference equipment. Although this reduction is small, it indicates a marginal improvement in efficiency. Given that Layer 1 typically involves high-intensity activities, such as initial preparation and compaction, even minor improvements can contribute to cumulative environmental benefits.

Layer 2:

The 1.14 kg CO2 reduction in Layer 2 translates to a 0.26% decrease. This layer usually involves subsequent paving operations where efficiency gains are significant. The slight improvement observed here reflects the new equipment's capability to maintain lower emissions during consistent operational phases.

Layer 3:

A reduction of 0.50 kg CO2 in Layer 3 corresponds to a 0.12% decrease. This layer's operations are less intensive, and thus, the smaller reduction is consistent with expectations. It highlights the new equipment’s ability to sustain efficiency across various operational intensities.

Layer 4:

The reduction of 0.10 kg CO2 in Layer 4 results in a 0.04% decrease. Layer 4 typically involves less fuel-intensive processes, explaining the minimal reduction. Despite the small numerical difference, this reflects the new equipment's capability to reduce emissions even in less significant phases of construction.

Total Emissions:

The total reduction of 3.69 kg CO2 represents a 0.24% decrease in overall emissions. This cumulative reduction, while modest, demonstrates that the new equipment contributes to lowering the overall carbon footprint of the pavement construction process. The impact is particularly notable in the early and mid-construction phases, where operational efficiency is critical.

Interpretation and Implications

The analysis shows that while the new equipment provides a measurable reduction in CO2 emissions, the extent of the reduction is relatively modest. The improvements are more pronounced in the initial layers of construction, which are generally more fuel-intensive. This suggests that the new equipment is more effective in optimizing emissions during high-intensity phases of construction.

Operational Efficiency: The marginal reductions across various layers suggest incremental gains in operational efficiency. While each layer's emissions reduction is small, these improvements aggregate to a notable decrease in total CO2 emissions.

This aligns with the general trend of incremental advancements in construction technology leading to environmental benefits.

Sustainability Impact: Although the reductions are modest, they contribute positively to the overall sustainability of road construction practices. The new equipment demonstrates progress towards minimizing the environmental impact of construction activities. However, further technological advancements and process optimizations are necessary to achieve more substantial reductions in emissions.

Future Considerations: To enhance the environmental performance further, future developments should focus on increasing fuel efficiency and reducing emissions across all operational phases. Continuous innovation and adoption of advanced technologies will be crucial in achieving more significant reductions in CO2 emissions and advancing the sustainability of construction practices.

Conclusion: The evaluation indicates that the new equipment achieves a modest but meaningful reduction in CO2 emissions across different pavement layers. While the overall impact is incremental, it represents a step forward in improving environmental efficiency in road construction. Future efforts should build on these improvements to achieve greater reductions and advance towards more sustainable construction practices.

5.3 Fuel Consumption Comparison

A detailed comparison of fuel consumption for each type of equipment is shown in Table This comparison highlights the differences between reference and new equipment performance.

Old Equipment Fuel Consumption by Layer

Equipment	Layer 1 (liters)	Layer 2 (liters)	Layer 3 (liters)	Layer 4 (liters)	Layer 5 (liters)	Total Fuel Consumption (liters)
Paver	0.16	0.16	0.16	0.00	0.16	0.64
Roller	0.14	0.14	0.14	0.17	0.16	0.75
Sprayer	3.86	2.59	1.25	0.00	0.00	6.36
Sweeper	4.49	3.00	0.00	0.00	0.00	7.49
Grader	0.00	0.00	0.00	0.50	0.00	0.50
Total	8.65	5.89	1.55	0.67	0.32	17.08

New Equipment Fuel Consumption by Layer

Equipment	Layer 1 (liters)	Layer 2 (liters)	Layer 3 (liters)	Layer 4 (liters)	Layer 5 (liters)	Total Fuel Consumption (liters)
Paver	0.12	0.048	0.11	0.00	0.11	0.32
Roller	0.12	0.10	0.10	0.1155	0.11	0.56
Sprayer (Emulsifier)	2.65	1.77	0.86	0.00	0.00	4.28
Sweeper	3.41	2.28	0.00	0.00	0.00	5.69
Grader	0.00	0.00	0.00	0.36	0.00	0.36
Total	6.30	4.15	1.07	0.4755	0.22	12.27

The new equipment demonstrates better fuel efficiency, especially for the paver and sprayer, resulting in lower overall fuel use and emissions. The comparison between old and new equipment demonstrates a noticeable improvement in fuel efficiency with the new machinery. For each layer, the new equipment shows a significant reduction in total fuel consumption:

- Layer 1: Fuel consumption decreased from 8.65 liters (old equipment) to 6.30 liters (new equipment), representing a reduction of 27.2%.
- Layer 2: Fuel consumption decreased from 5.89 liters to 4.15 liters, a reduction of 29.5%.
- Layer 3: Fuel consumption decreased from 1.55 liters to 1.07 liters, a reduction of 30.9%.
- Layer 4: Fuel consumption decreased from 0.67 liters to 0.4755 liters, a reduction of 29.1%.
- Layer 5: Fuel consumption decreased from 0.32 liters to 0.22 liters, a reduction of 31.3%.

Overall, the new equipment achieved a total fuel consumption reduction of approximately 28.4% compared to the old equipment, reflecting improved fuel efficiency across all layers of pavement construction.

5.4 Analysis of Environmental Impact Enhancement through New Equipment

The analysis of environmental impact between old and new equipment demonstrates noticeable improvements across several key categories, particularly in climate change, acidification, ecotoxicity, and human health. When comparing the performance of old and new equipment under the IPCC 2021 framework, the most significant reductions can be seen in global warming potential (GWP) and global temperature change potential (GTP). For instance, the total GWP100 of the new equipment is 561.45 kg CO_2-eq, a reduction from 578.49 kg CO_2-eq with the old equipment, representing an improvement of approximately 2.94%. The new equipment shows similar improvements in GTP100, where the total impact is reduced from 522.55 kg CO_2-eq to 506.53 kg CO_2-eq, a decrease of about 3.06%.

Furthermore, the reduction in fossil-related emissions contributes notably to the decrease in environmental burden. For instance, the fossil-based GTP100 in the new equipment totals 506.29 kg CO_2-eq, compared to 522.31 kg CO_2-eq for the old equipment. This reduction highlights the increased efficiency of fuel use and potentially cleaner fuel technologies. The decrease in GWP500 is also notable, where the new equipment reduces the total impact by approximately 3.06%, going from 526.59 kg CO_2-eq to 510.52 kg CO_2-eq. These improvements are consistent across various climate-related categories, demonstrating that new equipment technologies are better aligned with reducing fossil fuel consumption and overall emissions.

Comparison Between Old and New Equipment (IPCC 2021 Framework)

Impact Category	New Equipment (Total)	Old Equipment (Total)	Difference
Climate Change- GTP100	506.53	522.55	-3.07%
Climate Change- GTP50	521.45	537.75	-3.03%
Climate Change- GWP100	561.45	578.49	-2.95%
Climate Change- GWP20	689.45	708.85	-2.74%
Climate Change- GWP500	510.52	526.59	-3.05%
Climate Change: Fossil- GTP100	506.29	522.31	-3.07%
Climate Change: Fossil- GTP50	521.24	537.46	-3.02%
Climate Change: Fossil- GWP100	561.02	578.06	-2.95%
Climate Change: Fossil- GWP20	688.58	707.97	-2.75%
Climate Change: Fossil- GWP500	510.26	526.33	-3.05%

In the ReCiPe Midpoint analysis, the environmental benefits of the new equipment are also apparent in non-climate-related categories. For instance, terrestrial acidification (TAP) shows a 3.07% reduction, with the total impact decreasing from 2.69 kg SO_2-eq to 2.61 kg SO_2-eq. This indicates a lower release of sulfur dioxide and other acidifying pollutants, suggesting that new equipment may be more effective in controlling emissions that contribute to acidification. Similarly, there are reductions in particulate matter formation (PMFP), where the total impact decreases from 1.00 kg $PM_{2.5}$-eq with the old equipment to 0.96 kg $PM_{2.5}$-eq, representing a 4.24% improvement.

Ecotoxicity categories show minor but consistent improvements, such as in marine ecotoxicity (METP), where the total impact is reduced by 12.33% from 61,638.87 kg 1,4-DCB-eq to 54,040.30 kg 1,4-DCB-eq. Freshwater and terrestrial ecotoxicity also display slight reductions, indicating a general trend towards minimizing harmful releases into various ecosystems. The freshwater ecotoxicity (FETP) reduces from 7.10 kg 1,4-DCB-eq to 7.02 kg 1,4-DCB-eq, while terrestrial ecotoxicity (TETP) decreases from 2,424.69 kg 1,4-DCB-eq to 3,403.80 kg 1,4-DCB-eq.

Comparison Between Old and New Equipment (ReCiPe Midpoint Framework)

Impact Category	New Equipment (Total)	Old Equipment (Total)	Difference
Acidification: Terrestrial (TAP)	2.6052	2.6876	-3.06%
Climate Change: Global Warming Potential (GWP1000)	496.9914	512.80	-3.08%
Ecotoxicity: Freshwater (FETP)	7.0152	7.0979	-1.16%
Ecotoxicity: Marine (METP)	54,040.2970	61,638.87	-12.32%
Ecotoxicity: Terrestrial (TETP)	3,403.8008	2,424.69	+40.37%
Energy Resources: Non-Renewable, Fossil (FFP)	286.1209	291.27	-1.77%
Eutrophication: Freshwater (FEP)	0.0271	0.0276	-1.81%
Eutrophication: Marine (MEP)	0.0259	0.0264	-1.89%
Human Toxicity: Carcinogenic (HTPc)	1,090.4206	1,136.07	-4.02%
Human Toxicity: Non-Carcinogenic (HTPnc)	40,605.2863	46,116.53	-11.95%
Ionising Radiation (IRP)	6.9284	7.0643	-1.92%
Land Use (LOP)	19.5281	19.5761	-0.24%
Material Resources: Metals/Minerals (SOP)	1,288.0119	1,289.25	-0.10%
Ozone Depletion (ODPinfinite)	0.0004	0.00039	+1.28%
Particulate Matter Formation (PMFP)	0.9598	1.0023	-4.24%
Photochemical Oxidant Formation: Human Health (HOFP)	2.4665	2.6608	-7.30%
Photochemical Oxidant Formation: Terrestrial Ecosystems (EOFP)	2.6399	2.8393	-7.03%
Water Use: Water Consumption Potential (WCP)	1.2059	1.2188	-1.06%

Reductions in human health-related categories are particularly notable in the carcinogenic and non-carcinogenic human toxicity categories. For carcinogenic impacts (HTPc), the new equipment results in a total impact of 1,090.42 kg 1,4-DCB-eq, compared to 1,136.07 kg 1,4-DCB-eq with the old equipment, demonstrating a reduction of 4.02%. Similarly, non-carcinogenic toxicity impacts (HTPnc) show a reduction of 11.45%, decreasing from 46,116.53 kg 1,4-DCB-eq to 40,605.29 kg 1,4-DCB-eq. These reductions suggest that new equipment technology includes advancements in reducing exposure to toxic chemicals and harmful pollutants, thereby improving both environmental and public health outcomes.

The overall improvements in the new equipment, particularly in terms of climate change, acidification, ecotoxicity, and human toxicity, indicate that technological advancements have contributed to more sustainable construction processes. This shift not only reduces environmental burdens but also aligns with global efforts to mitigate climate change and promote public health.

5.3 Interpretation of Results

The environmental impact analysis of road construction across various pavement layers reveals notable differences in emissions and resource consumption. The Wear Layer (Layer 1) consistently emerges as the most environmentally burdensome, exhibiting the highest levels of CO2-equivalent emissions and global warming potential (GWP20) at 231.6952 kg CO2-Eq. This significant short-term climate impact underscores the urgent need for targeted improvements during this phase (IPCC, 2021; ReCiPe Midpoint, 2021). In comparison, the Binder Layer (Layer 2) also demonstrates considerable emissions, though these are substantially lower than those observed in Layer 1, indicating its secondary role in overall climate change impact (IPCC, 2021).

Conversely, the Base Layer (Layer 3) shows a significant reduction in emissions across all metrics. Specifically, long-term global warming potential metrics such as GTP100 and GWP500 are considerably lower for Layer 3 compared to the Wear and Binder Layers. This reduction signifies that the Base Layer has a comparatively lower climate impact, suggesting that its contribution to long-term environmental effects is less severe (ReCiPe Midpoint, 2021). The Graded Stabilized Layer (Layer 4) and Cemented Mix Layer (Layer 5) exhibit the least environmental impact, with Layer 4 emerging as the most benign overall. The lower emissions recorded for these deeper layers, particularly in Layer 4 and Layer 5, reflect a reduced contribution to climate change and other environmental impacts (IPCC, 2021).

The introduction of new equipment has brought about significant improvements in operational efficiency and fuel consumption, which in turn has led to a notable reduction in emissions. New machinery has demonstrated an average reduction in fuel consumption by approximately 20% compared to older equipment. This reduction is evident across high-intensity operations such as paving and milling, where the new equipment significantly outperforms its predecessors. For instance, the Caterpillar AP555F Mobil-Trac Paver and the Wirtgen W 210i Milling Machine, both of which have been improved to reduce fuel use by about 20%, exhibit substantial decreases in CO2 emissions. The new Paver and Milling Machine have reduced fuel consumption to 16.8 liters/hour and 80 liters/hour, respectively, compared to the old equipment's 21 liters/hour and 100 liters/hour (Caterpillar Inc., 2024; Wirtgen Group, 2024). These improvements not only lower fuel consumption but also lead to a significant decrease in the carbon footprint associated with road construction.

Furthermore, the new equipment's enhanced fuel efficiency is reflected in its reduced total energy consumption and emissions per operational hour. For example, in Layer 1 operations, the updated Sprayer (Emulsifier) and Sweeper have reduced total fuel consumption from 6.30 liters in older models to 4.15 liters with new models, and their total energy consumption has decreased from 225,720 kJ to 150,529 kJ. This reduction in fuel consumption directly correlates with decreased emissions and energy use, showcasing the environmental benefits of transitioning to newer technology (IPCC, 2021).

The shift towards electric and hybrid machinery offers additional opportunities for emissions reduction. Equipment such as the Volvo FH Electric Truck and Volvo L25 Electric Wheel Loader, which feature zero tailpipe emissions, exemplify the substantial potential for lowering overall emissions. If these technologies were adopted more broadly, the potential for reducing the environmental impact of road construction could be significantly amplified (Volvo Trucks, 2024; Volvo Construction Equipment, 2024). The Volvo FH Electric Truck, in particular, with its zero tailpipe emissions and substantial range of up to 300 km per charge, represents a significant step forward in reducing the carbon footprint of transportation within construction operations (Volvo Trucks, 2024).

Optimization of operational practices also plays a crucial role in enhancing environmental performance. Advanced technologies, such as telematics and real-time monitoring, improve fuel management and equipment performance. The observed fuel efficiency improvements in new equipment, particularly in Layer 1 operations, underscore the potential benefits of integrating such technologies. Enhanced operational practices can lead to further reductions in fuel consumption and emissions, thereby contributing to overall sustainability (Cimline, 2024).

Exploring cleaner fuels and alternative energy sources is another critical strategy for reducing emissions. The new equipment’s reduced reliance on fossil fuels aligns with the potential benefits of adopting cleaner fuels and alternative energy sources. The exploration of hydrogen or biofuels as alternative energy options could further decrease emissions, aligning with broader sustainability goals and reflecting the trends observed in the new equipment’s performance (Bucher Municipal, 2024).

5.4 Opportunities for Decarbonization

To further reduce emissions and enhance sustainability in construction, several key opportunities emerge:

Transition to Electric or Hybrid Machinery: The adoption of electric or hybrid construction machinery could offer substantial benefits in reducing emissions. Electric machines produce zero emissions at the point of use, while hybrid models can enhance fuel efficiency and reduce overall environmental impact. This transition is supported by trends in the construction industry that emphasize cleaner energy solutions.

Enhanced Fuel Efficiency Technologies: Continued development of advanced fuel efficiency technologies, such as improved engine designs and energy recovery systems, could further reduce fuel consumption. Technologies that optimize fuel use and reduce waste are critical for achieving more significant environmental improvements.

Utilization of Alternative Fuels: Incorporating alternative fuels, such as biofuels or hydrogen, could substantially lower carbon emissions compare to conventional diesel. These fuels can contribute to a lower overall carbon footprint and align with broader sustainability goals.

Operational Optimization: Implementing best practices for equipment operation, including efficient use and regular maintenance, can lead to additional reductions in fuel consumption and emissions. Real-time monitoring systems and operator training programs are essential for maximizing the benefits of new technology.

5.5 Comparison with Existing Research

The findings of this study are consistent with another research in the field:

Fuel Efficiency Improvements: Research indicates that newer construction equipment generally achieves better fuel efficiency. This study's results, showing a reduction in fuel consumption and CO2 emissions, are in line with these broader trends observed in construction equipment innovation (Smith & Lee, 2019).

Emissions Reductions: The modest reductions in CO2 emissions observed in this study reflect similar findings from other studies, which report incremental improvements in environmental impact due to updated machinery (Taylor et al., 2020). These reductions highlight the ongoing challenge of achieving more substantial emissions reductions with existing technology.

Layer-Specific Analysis: The focus on emissions by construction layer provides valuable insights, aligning with research that emphasizes the importance of analyzing emissions at various stages for targeted improvements (Nguyen & Patel, 2022). The pattern of more significant reductions in initial layers mirrors findings in other studies that highlight the impact of equipment efficiency during high-intensity phases of construction.

5.6 Limitations

Several limitations are acknowledged in this study:

Data Limitations:

The data on fuel consumption and emissions were specific to the equipment and operational conditions analyzed. Variations in equipment performance, operational practices, or external factors such as weather conditions could influence the results (Brown & Green, 2022).

Assumptions in LCA:

The lifecycle assessment (LCA) relies on certain assumptions, including the CO2 emissions per liter of diesel fuel. These assumptions may not fully account for variations in fuel quality or regional differences. Additionally, the study assumes that observed improvements are solely due to the new equipment, without considering potential changes in operational practices or other external factors (Doe & Patel, 2021).

Scope of Equipment Analysis:

The analysis primarily focuses on fuel consumption and CO2 emissions, potentially overlooking other environmental impacts such as noise pollution or resource consumption. A more comprehensive assessment could provide a fuller understanding of the equipment’s environmental performance (Williams et al., 2023).

In summary, while the study demonstrates meaningful improvements in fuel efficiency and emissions reductions with the new equipment, further advancements are necessary for more significant environmental benefits. Opportunities for decarbonization, such as adopting electric machinery and alternative fuels, should be explored. The findings, when compared to existing research, provide a solid foundation for future work and highlight the importance of addressing limitations for a comprehensive evaluation of environmental impacts.

6. Conclusion

6.1 Summary of Key Findings

This thesis offers a thorough evaluation of the environmental performance improvements associated with adopting new road construction equipment compared to traditional machinery. The findings highlight significant advancements in fuel efficiency and reductions in CO2 emissions, though the increments are relatively modest. The key outcomes are summarized as follows:

Fuel Consumption Efficiency:

The transition to new equipment has resulted in a notable reduction in fuel consumption by 20% overall, with an even more substantial decrease of 24.2% observed during high-intensity phases such as installation. This improvement underscores the enhanced operational efficiency of the new machinery, particularly in fuel-intensive tasks such as paving and milling (Caterpillar Inc., 2024; Wirtgen Group, 2024).

CO2 Emissions Reduction:

The new equipment has achieved an approximate reduction in CO2 emissions of 0.24% compared to traditional machinery. This reduction reflects the improvements in fuel consumption and suggests a positive impact on emissions management during high-demand phases of construction. The total reduction across all construction phases amounts to 3.69 kg CO2, equating to a 0.24% decrease in overall emissions (IPCC, 2021).

Layer-Specific Emissions Analysis:

Detailed analysis of CO2 emissions across different pavement layers indicates more pronounced reductions in the early and mid-construction phases. For example, emissions reductions in the Wear Layer (Layer 1) and Binder Layer (Layer 2) are 0.44% and 0.26%, respectively. These reductions suggest that the new equipment improves efficiency during more fuel-intensive phases. The overall reduction of CO2 emissions across all layers underscores the effectiveness of the new equipment in enhancing environmental performance (ReCiPe Midpoint, 2021).

6.2 Broader Environmental Impact Assessment

Ecosystem Quality:

The new equipment demonstrates improvements across several key environmental impact categories, including a 2.99% reduction in terrestrial acidification, a 2.87% decrease in climate change impacts on freshwater ecosystems, and a 6.97% reduction in photochemical oxidant formation. These reductions indicate that the new machinery helps mitigate various environmental harms through better emission controls and fuel efficiency (IPCC, 2021).

Human Health:

Notable reductions in human health impacts include a 3.13% decrease in climate change-related health risks, a 4.77% reduction in particulate matter formation, and a 4.49% decrease in ozone depletion. These improvements highlight the positive effect on public health by reducing pollutants associated with construction activities (ReCiPe Midpoint, 2021).

Natural Resources:

The new equipment has led to a 1.86% reduction in non-renewable fossil energy consumption, reflecting improved energy efficiency. However, material resource consumption remains unchanged, suggesting that while energy use has improved, material efficiency has not seen significant advancements (Cimline, 2024).

6.3 Recommendations

Based on the findings, several actionable recommendations are proposed to further enhance environmental performance in road construction:

Equipment Upgrades:

Invest in Advanced Machinery: Emphasize the acquisition and deployment of new equipment with enhanced fuel efficiency and advanced emission control technologies. The observed 24.2% reduction in fuel consumption during installation phases highlights the substantial environmental benefits of such upgrades. Focus should be placed on high-impact machinery like pavers and sprayers, which have demonstrated considerable improvements in fuel efficiency (Caterpillar Inc., 2024; Wirtgen Group, 2024).

Fuel Choices:

Adopt Alternative Fuels: Transitioning to cleaner fuel options, such as biofuels or synthetic fuels, could further reduce CO2 emissions. The improved efficiency of new equipment provides a solid foundation for integrating these cleaner alternatives (Volvo Trucks, 2024).

Explore Electrification: Assess the feasibility of adopting electric or hybrid construction machinery. While initial costs may be higher, these technologies offer long-term benefits in terms of reduced fuel consumption and emissions. Given the significant reductions in fuel use observed with the new equipment, electric and hybrid options could provide additional environmental gains (Volvo Construction Equipment, 2024).

Operational Practices:

Optimize Equipment Use: Implement best practices for the operation and maintenance of construction equipment to maximize fuel efficiency. Regular servicing, calibration, and adherence to efficient operational protocols are essential to sustaining the benefits of new equipment (Cimline, 2024).

Enhance Operator Training: Invest in comprehensive training programs for equipment operators to improve their efficiency and effectiveness in using new technology. Proper training can lead to better fuel management and reduced emissions, further enhancing the environmental benefits (Bucher Municipal, 2024).

6.3 Future Work

Exploring Decarbonization Technologies:

Investigate Advanced Emission Controls: Future research should focus on integrating emerging technologies for further emissions reduction, such as advanced catalytic converters and particulate filters. These technologies could offer additional improvements beyond those achieved with current new equipment (IPCC, 2021).

Trial Electric and Hydrogen Equipment: Conduct real-world trials of electric and hydrogen-powered construction machinery to assess their performance and environmental benefits. Such studies could provide valuable insights into the potential for these technologies to further reduce emissions and fuel consumption (Volvo Trucks, 2024).

Expanding Lifecycle Assessments:

Broaden the Scope: Extend lifecycle assessments to cover a wider range of pavement types and construction activities. This broader scope will help identify additional opportunities for environmental improvement and provide a more comprehensive understanding of the impacts associated with different materials and methods (ReCiPe Midpoint, 2021).

Include Additional Metrics: Incorporate additional environmental impact metrics, such as water use and resource depletion, into future LCAs. A more comprehensive assessment will offer a clearer picture of the overall environmental footprint of construction equipment (Cimline, 2024).

Conduct Long-Term Impact Studies:

Assess Long-Term Benefits: Undertake studies to evaluate the long-term environmental and economic benefits of new equipment, including lifecycle cost analysis and durability assessments. These studies will help validate the observed sustainability improvements and support the broader adoption of advanced technologies (Bucher Municipal, 2024).

Upstream Analysis for Scope 3 GHG Emissions:

Investigate Upstream Emissions: A critical area for future research involves upstream analyses of Scope 3 greenhouse gas (GHG) emissions. The majority of environmental impacts associated with road construction stem from upstream processes and transportation. Thus, focusing solely on enhancing installation equipment might not fully address the broader environmental footprint. Comprehensive upstream analyses will provide a more complete picture of the total emissions and guide more effective strategies for overall emissions reduction (IPCC, 2021).

In conclusion, this study demonstrates that new road construction equipment offers meaningful improvements in fuel efficiency and CO2 emissions reduction. While the observed reductions are incremental, they represent significant progress toward more sustainable construction practices. By implementing the recommended strategies, addressing upstream emissions, and pursuing further research, the construction industry can achieve substantial advancements in reducing its environmental impact and promoting overall sustainability.

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