Co-funded by the European Union

ERASMUS MUNDUS JOINT MASTER DEGREE

MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION AND MANAGEMENT OF THE BUILT ENVIRONMENT

MBUILD

LIFE CYCLE ASSESSMENT (LCA) APPLIED TO PAVEMENT MATERIALS ON LOW TRAFFIC ROADS IN GUINEA-BISSAU

JAQUILINA DA COSTA

Supervision: Prof. Pablo Pascual Muñoz (UC)

Co-supervision: Irune Indacoechea (UC)

Santander, July 2025

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✉ mbuild@fe.up.pt

🌍 www.mbuild.eu

Edited by

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Rua Dr. Roberto Frias
4200-465 Porto
PORTUGAL
☎ +351-22-508-1400
✉ feup@fe.up.pt
🌍 www.fe.up.pt

TECHNISCHE HOCHSCHULE MITTELHESSEN

Wiesenstraβe 14
D – 35390 Gieβen
DEUTCSHLAND
☎ +49-641-309-0
✉ info@thm.de
🌍 www.thm.de

UNIVERSIDAD DE CANTABRIA

Avda. De los Castros, s/n
39005 Santander
ESPAÑA
☎ +34-942-20-10-18
✉ informacion.general@unican.es
🌍 https://web.unican.es

This work is dedicated to the people of Guinea-Bissau, with the hope that sustainable solutions will contribute to a better future for our communities.

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ABSTRACT

Lack of infrastructure is one of the most significant barriers to socio-economic development in Guinea-Bissau. With only 10% of its road network paved and limited connectivity hinders access to essential services such as healthcare and education, particularly in rural areas. Simultaneously, climate change poses a growing threat, as a low-lying coastal country is highly vulnerable to extreme weather events, sea-level rise, flooding, and changes in rainfall patterns, which disproportionately affect its agriculture-dependent economy and fragile infrastructure. These climatic pressures not only threaten livelihoods in rural communities but also accelerate the deterioration of already limited road networks, further isolating vulnerable populations. Considering these challenges, it is imperative to design and construct resource-efficient and eco-friendly infrastructures for Guinea-Bissau.

This study uses a Life Cycle Assessment (LCA) method to compare the environmental performance of alternative materials in low-traffic road construction in Guinea-Bissau. Four pavement design scenarios were created: a standard one with virgin aggregates and bitumen, and three alternatives using industrial and agricultural waste materials, specifically steel slag, crumb rubber, palm kernel shells (PKS), and recycled glass powder. The analysis followed EN 15804 and ISO 14040/44 standards and covered life cycle stages A1 to A5 (cradle to practical completion), utilizing Simapro with Ecoinvent datasets.

Results show that long-distance transportation significantly adds to environmental burdens, especially regarding global warming potential, fossil resource scarcity, and particulate matter formation. Scenario 4, which uses locally available PKS, consistently shows the lowest environmental impacts because of reduced material density, shorter transport distances, and lower emissions during extraction. Conversely, Scenario 3, although the materials used were recycled crumb rubber and steel slag, suffers from high emissions due to long-haul logistics.

The results highlight the need to integrate local sourcing, lightweight materials, and circular design principles to improve sustainability in infrastructure projects. This research provides valuable guidance for policymakers, engineers, and development practitioners aiming to promote sustainable road construction in resource-limited areas like Guinea-Bissau. It supports material-efficient, locally tailored design approaches that consider environmental, economic, and logistical factors. Additionally, this study adds to the emerging but limited literature on sustainable road construction in West Africa, offering region-specific data and insights that can shape national development strategies in infrastructure and sustainability.

Keywords: Life Cycle Assessment (LCA), Sustainable Road construction, Guinea-Bissau, Alternative materials.

RESUMO

A falta de infraestrutura é um dos obstáculos mais significativos ao desenvolvimento socioeconômico da Guiné-Bissau. Com apenas 10% de sua rede rodoviária pavimentada e a limitação de conectividade com serviços essenciais, como saúde e educação, principalmente nas áreas rurais. Ao mesmo tempo, as mudanças climáticas representam uma ameaça crescente, uma vez que o país por estar situada na costa é vulnerável a fenómenos meteorológicos extremos, como à subida do nível do mar, a inundações e a alterações nos padrões de precipitação, que afetam desproporcionadamente a sua economia que depende da agricultura e infraestruturas frágeis. Estas pressões climáticas não só ameaçam os meios de subsistência nas comunidades rurais, mas também aceleram a deterioração das redes rodoviárias já limitadas, isolando ainda mais as populações vulneráveis. Considerando esses desafios, é imperativo projetar e construir infraestruturas sustentáveis e eficientes em termos de recursos para a Guiné-Bissau.

Este estudo utiliza o método de Avaliação do Ciclo de Vida (ACV) para comparar o desempenho ambiental de materiais alternativos na construção de estradas de baixo tráfego na Guiné-Bissau. Quatro cenários foram criados: Primeiro cenário com matérias convencionais (agregados virgens e betume), e três outros cenários com materiais sustentáveis como resíduos industriais e agrícolas, especificamente escória de aço, borracha granulada, cascas de palmiste e vidro reciclado. A análise seguiu as normas EN 15804 e ISO 14040/44 e abrangeu os estágios de ciclo de vida A1 a A5, utilizando o programa Simapro com base de datos da Ecoinvent.

Os resultados mostram que o transporte de longa distância aumenta significativamente os impactos ambientais, especialmente em relação ao potencial de aquecimento global, à escassez de recursos fósseis e à formação de material particulado. O cenário 4, que utiliza cascas de palmiste que é disponível localmente, apresenta consistentemente os menores impactos ambientais devido à menor densidade do material, às distâncias de transporte mais curtas e às menores emissões durante a extração. Por outro lado, o Cenário 3, embora os materiais utilizados sejam borrachos reciclada e escória de aço, tem altas emissões devido à logística de longa distância da fonte desses matérias com o lugar da construção.

Os resultados destacam a necessidade de integrar fontes locais, materiais leves e princípios de design circular para melhorar a sustentabilidade em projetos de infraestrutura. Esta pesquisa fornece orientações valiosas para formuladores de políticas, engenheiros e profissionais de desenvolvimento que buscam promover a construção sustentável de estradas em áreas com recursos limitados, como a Guiné-Bissau. Ela apoia abordagens de projeto com eficiência de materiais e adaptadas localmente, que consideram fatores ambientais, econômicos e logísticos. Além disso, este estudo contribui para a literatura emergente, porém limitada, sobre construção sustentável de estradas na África Ocidental, oferecendo dados e insights específicos para cada região que podem moldar estratégias nacionais de desenvolvimento em infraestrutura e sustentabilidade.

Palavras-chave: Avaliação do Ciclo de Vida (ACV); Construção Sustentável de Estradas; Guiné-Bissau; Materiais Alternativos.

GENERAL INDEX

INDEX OF FIGURES

INDEX OF TABLES

SYMBOLS, ACRONYMS AND ABBREVIATIONS

BREEAM – Building Research establishment Environmental Assessment Methodology

EEA – European Environment Agency

EN – European Norm

EU – European Union

ISO – International Organization for Standardization

LEED – Leadership in Energy and Environmental Design

OCED – Organization for Economic Co-operation and Development

SDG(s) – Sustainable Development Goals

UNEP – United Nations Environment Programme

WCED – World Commission on Environment Development

WGBC – World Green Building Council

AM – Asphalt Mix

AP – Terrestrial acidification

BFS – Blast Furnace Slag

BOFS – Basic Oxygen Furnace Steel Slags / Basic Oxygen Furnace

CBR – California Bearing Ratio

CDW – Construction Demolition Waste

CR – Crumb Rubber

CRG – Coarse Recycled Glass

CRMA – Crumb Rubber Mix Asphalt

EAFS – Electric Arc Furnace Slag

EPD – Environmental Product Declaration

FETP – Freshwater ecotoxicity

FEuP – Freshwater eutrophication

FRG – Fine Recycled Glass

FRS – Fossil resource scarcity

GBFS – Granulated Blast Furnace Slag

GL – Laterite Gravel

GLc – Treated Laterite Gravel

GLli – Litho-stabilized

Gla – Improved Laterite Gravel

GWP – Global warming

HCTP – Human carcinogenic toxicity

HMA – Hot Mix Asphalt

HnCTP – Human non-carcinogenic toxicity

IR – Ionizing radiation

LCA – Life Cycle Assessment

LCC – Life Cycle Cost

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

LFS – Ladle Furnace Slag

LU – Land use

LVRs – Low Volume Roads

LVSR – Low Volume Sealed Roads

MEuP – Marine eutrophication

METP – Marine ecotoxicity

MO – Marshall Quotient

MRG – Medium Recycled Glass

MRS – Mineral resource scarcity

NA – Natural Aggregate

OBC – Optimal Bitumen Content

ODP – Stratospheric ozone depletion

OFHH – Ozone formation, Human health

OFTE – Ozone formation, Terrestrial ecosystems

PKS – Palm Kernel Shells

PMF – Fine particulate matter formation

RAMs – Rubberized Asphalt Mixtures

RAP – Recycled Asphalt Pavement

RHA – Rice Husk Ash

SMA – Stone Mastic Asphalt

SS – Steel Slag

WC – Water consumption

WMA – Warm Mix Asphalt

cm – Centimetres

kg – Kilograms

Gt - Gigatons

m - Meters

m^2 - Square Meters

MJ - Megajoule

un – Unity

1
INTRODUCTION

1.1. PROBLEM STATEMENT

The construction industry is one of the most concerned industries nowadays in terms of environmental impact. It is responsible for around 35% of the world's total energy use and carbon dioxide emissions. These emissions constitute 38% of the world's cumulative emissions [1]. A large amount of energy is consumed during raw material extraction and transportation. According to [2], the construction industry accounts for 23% of air pollution, 40% of drinking water contamination, and 50% of landfill waste. By using recycled materials for construction, we can reduce raw material extraction and, at the same time, decrease landfill waste, not only from construction industries but also from other industries. Consequently, this helps reduce environmental impact. The selection of materials is essential for sustainable and thoughtfully designed construction. Therefore, this dissertation aims to analyse different sustainable materials that can replace conventional road construction materials by conducting a life cycle assessment on a low traffic road in Guinea-Bissau.

In addition to these global concerns, lack of infrastructure is one of the biggest gaps that significantly impede Guinea-Bissau socio-economic development. Only 10% of its road network is tarred, and there's no railway system [2]. This factor gives negative impact socially and economically. The physical accesses to social services like to healthcare and education is very difficult without a proper road especially in the rural area. Agriculture is major component of Guinea-Bissau economy, and most of the population depend on it. The poor road condition and limited connectivity directly hampers the agricultural sector, by restricting the efficient movement of goods from rural areas to urban commercial centres. On the other hand, climate change poses a severe threat, already impacting vulnerable communities, those dependent on agriculture and fisheries [3] and the already limited infrastructure system. Without adaptation, climate change could further increase poverty.

Considering these two main challenges together, to mitigate them it is essential to devise and adopt more efficient, inventive, and green plans. This is why it is important to focus research efforts on developing sustainable road infrastructure in Guinea-Bissau. By conducting a life cycle assessment of sustainable road materials, will provide a critical insight, like identifying innovative and cost-effective solutions that can enhance road performance and many other. In this sense, improved road infrastructure would facilitate better access to social services and increase the efficiency of agricultural supply chains and utilizing sustainable road materials has the potential to reduce the environmental footprint of infrastructure projects. Developing Sustainable Road infrastructure in Guinea-Bissau will impact positively in social and economic development while simultaneously contributing to environmental conservation.

This dissertation can also offer evidence-based recommendations for policymakers and infrastructure stakeholders. By providing an analysis of the life cycle performance of sustainable road materials, the study will help guide future investments in infrastructure that are both economically viable and environmentally friendly. Moreover, these insights also can serve as a model for other regions facing similar challenges.

1.2. OBJECTIVES

1.2.1. GENERAL OBJECTIVE

The general objective of this research is to evaluate the environmental performance of alternative and potential sustainable materials that can be used in the construction of low-traffic roads in Guinea-Bissau, using a Life Cycle Assessment (LCA) approach to assess the full life cycle of selected pavement designs from raw material extraction to road construction, in order to identify more sustainable solutions that are not only technically feasible but also contextually appropriate for Guinea-Bissau's geographic, economic, and environmental conditions. The study will explore how alternative design strategies and material choices, guided by sustainability principles, can be leveraged to improve road infrastructure with lower environmental costs. The research applies Life Cycle Assessment (LCA) as a systematic methodology for quantifying environmental impacts at each stage of a road's life cycle (material extraction, manufacturing, transport, and construction), thereby enabling a comprehensive and evidence-based comparison between different design approaches. Through this method, the study aims to identify which combinations of design decisions and material types offer the greatest potential for reducing environmental burdens while maintaining or enhancing functional performance.

Also, other objective is to provide a scientific basis for the adoption of environmentally sound materials, particularly those that are local, waste-derived, or recycled, as alternatives to conventional road-building resources. This includes exploring the potential of such strategies to deliver not only ecological benefits but also socio-economic value, such as improved access to rural areas through more cost-efficient road infrastructure. By generating context-specific knowledge that reflects both environmental metrics and infrastructural realities, the study aims to provide practical insights for policymakers, engineers, planners, and other stakeholders involved in infrastructure development. These insights can support the formulation of strategies that are not only ecologically responsible but also economically feasible and socially equitable.

Ultimately, the general objective of this research is to contribute to the advancement of sustainable road infrastructure in Guinea-Bissau by demonstrating how integrated, life cycle-based decision-making can inform better planning and design. This includes offering alternatives that reduce environmental harm, improve resource use efficiency, and ensure that infrastructure development plays a positive role in addressing the interlinked challenges of poverty, climate vulnerability, and underdevelopment. In doing so, the research aligns with global sustainability goals and provides a model that may be adapted to other regions facing similar constraints and opportunities.

1.2.2. SPECIFIC OBJECTIVES

To achieve this general objective, some specific objectives have to be met. These specific objectives include:

- To identify and characterize the most commonly used conventional materials in low-traffic road construction in Guinea-Bissau, including their environmental, economic, and logistical implications.
- To select and evaluate alternative sustainable materials (e.g., recycled, waste-based, or locally available materials) that have potential to replace traditional road construction inputs.
- To conduct a comprehensive Life Cycle Inventory (LCI) for selected materials and road design scenarios, mapping all inputs and outputs from raw material extraction to construction stages (A1–A5).
- To assess the environmental impacts of different road construction scenarios using Life Cycle Impact Assessment (LCIA) methods.
- To compare the life cycle performance of traditional and alternative road designs, identifying which achieve the lowest environmental impact while maintaining technical feasibility.
- To propose context-specific recommendations for material selection and road design, considering both environmental benefits and practical feasibility in Guinea-Bissau's socio-economic and infrastructural context.

1.3. DISSERTATION STRUCTURE

This dissertation is structured into chapters, where chapter 1 the introduction outlines the background and motivation for the study, focusing on Guinea-Bissau's infrastructural challenges and the environmental impact of conventional road construction. It presents the aims and objectives (both general and specific), and the significance of the study. Chapter 2 the general background provides an overview of road infrastructure in Guinea-Bissau, it explores the types of pavement structures used locally and details the materials typically applied in each layer. Also, in this chapter it can be found the general background of LCA. Chapter 3 presents the literature review on sustainable materials for road, it explores global practices of potential sustainable materials (steel slag, crumb rubber, PKS, glass waste and RAP), for low traffic road construction in Guinea-Bissau. The following chapter 4, it is the chapter where the scenarios are defined and described, including the design detail. Chapter 5, Life Cycle assessment of selected scenario, provides detailed inventory data for each road scenario and material used. It includes quantities of materials, transport distances, and energy consumption for all life cycle stages. In Chapter 6 results and discussion, the environmental impact results of the LCA are presented and analysed. Graphs and tables are used to compare the performance of each scenario across the different impact categories. It identifies the most sustainable solutions and explains trade-offs among scenarios. The Chapter 7 conclusions, synthesize the key findings, as well as provides suggestions for future work to further improve this study.

2
GENERAL BACKGROUND

2.1. ROADS DESIGN IN GUINEA-BISSAU

2.1.1. ROAD STATISTICS IN GUINEA-BISSAU

The International Road Federation's World Road Statistics (WRS) indicate that globally, approximately 39% of roads are paved, leaving around 61% of the network unpaved or classified as low-level infrastructure [4], [5]. This imbalance is even more pronounced in many African nations, where data from the African Development Bank shows that, in Sub-Saharan Africa, paved roads typically account for only 10–15% of the total road network [5]. Consequently, an overwhelming 85–90% of roads remain unpaved, often limiting accessibility and reducing transport efficiency. As illustrated in Figure 1, the disparity is stark across the continent. Countries such as Guinea-Bissau, Chad, and the Central African Republic exhibit particularly low proportions of paved roads relative to their total networks. By contrast, a few countries, including South Africa and Morocco, show a higher share of paved roads, though unpaved routes still dominate. This infrastructural gap has far-reaching implications for economic development, trade, and access to essential services, particularly in rural regions where poor road conditions exacerbate isolation and hinder socio-economic growth.

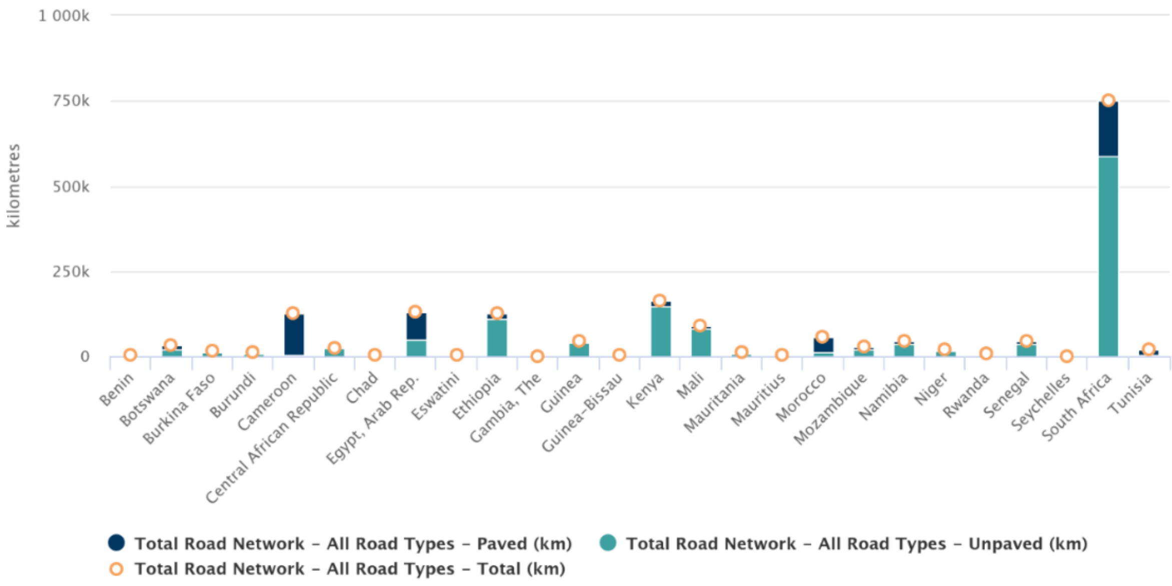


Figure 1. Total road network (paved and unpaved) – 2018 [4]

West Africa reflects many of the broader infrastructural deficiencies observed across the African continent. Research by [6] indicates that in several West African nations, the proportion of paved roads can be as low as 15–20%, leaving approximately 80–85% of the road network unpaved or classed as low-level infrastructure. As illustrated in Figure 2, the disparity between paved and unpaved roads is pronounced across the region, with countries such as Mali, Niger, and Guinea-Bissau showing particularly low levels of paved infrastructure. Guinea-Bissau presents an even more critical case, with only about 10% of its road network surfaced with bitumen, meaning that nearly 90% remains unpaved and often in poor condition. Official statistics from Boletim Oficial Nº 31 classify the country's roads into three categories, which are national roads, regional roads and local roads [7], totalling approximately 4,400 km. Of this, only 453 km are paved, leaving around 3,947 km unpaved and largely degraded [4]. This limited network significantly restricts mobility, impedes access to markets and services, and exacerbates rural isolation, thereby constraining socio-economic development.

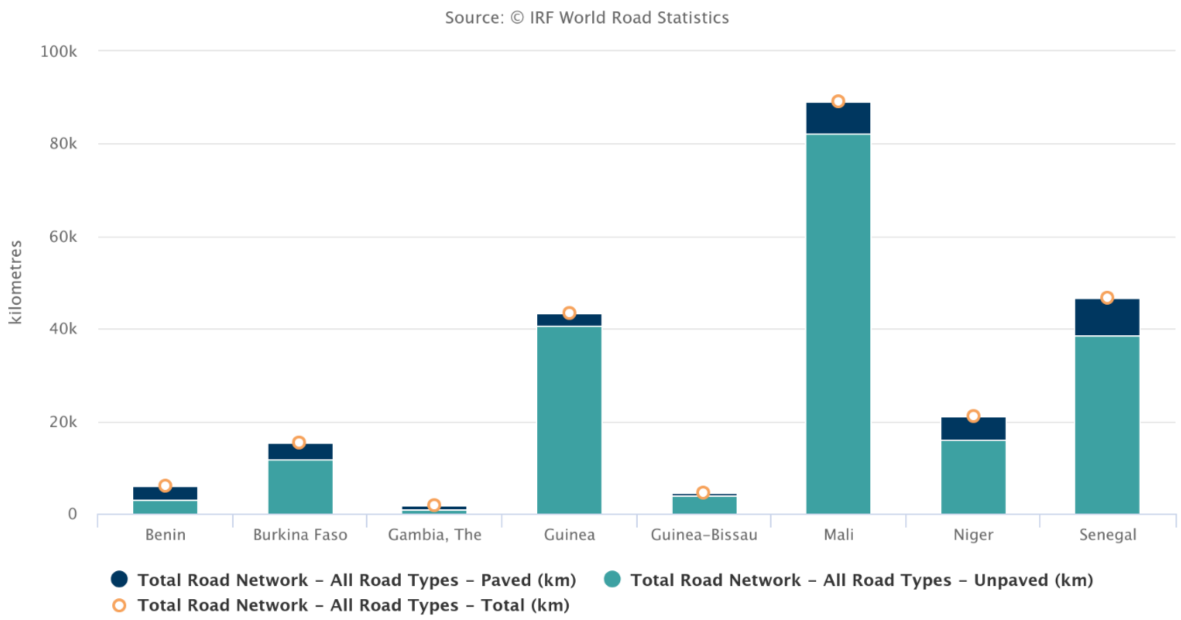


Figure 2. West Africa Road Network (by paved and unpaved) 2018 [4]

2.1.2. ROAD TYPE IN GUINEA-BISSAU

The choice between the different type of structures usually is based on a technical, economic and environmental study. In Guinea-Bissau the commonly used road types are flexible pavement structure, semi-rigid and rigid pavement structure. There are two different type of flexible pavements that are used in Guinea-Bissau, the thin bituminous pavement and the thick bituminous pavement. The thin bituminous pavement is the most common structure in Guinea-Bissau.

Typical Asphalt Mix Design for flexible pavement contains bitumen content of approximately 5.0% by mass of the total mix, with a variation of ±0.5%, layer Thickness usually ranges from 50 mm to 140 mm and the target air voids content is between 4–8% to ensure durability and strength. In flexible pavements, the base layer is typically composed of untreated granular aggregates, such as natural gravel, crushed stone, or lateritic gravel, selected and compacted to provide structural support and load distribution.[8]

The semi-rigid roadway comprises a bituminous surface layer on a base of materials treated with hydraulic binders: Treated laterite gravel (GLc1 or GLc2), adobe-shell cement (BQc). Note that cement is the only hydraulic binder used in Guinea-Bissau. For the highest traffic classes, the surface layer of asphalt is thicker than for other types of structures to delay the growth of cracks.

In rigid pavements, commonly used materials for the aggregates in concrete mix comprise cement, fine aggregates (sand), coarse aggregates (gravel or crushed stone), and water. Rigid structure is used in the areas that has risk of immersion and in the swamp areas. The most common concrete structure is that used for rafts: sand + 10 cm clean concrete + 20 cm reinforced concrete slab with reinforcement 10mm.

Typical Concrete Mix Design, while specific mix proportions can vary, a general guideline for rigid pavement concrete in Guinea-Bissau the cement content ranges from 300 to 400 kg/m^3, water-cement ratio is between 0.4 to 0.5, while for aggregates the coarse aggregates typically constituting 60–70% of the total aggregate content [8].

2.1.3. MATERIAL AND LAYERING

Material used in the typical structures of road in Guinea-Bissau are the following constituents: aggregates and binders

The mineral resources available in Guinea-Bissau that are used in the road construction industry are basalt, sandstone, limestone and gravel. Cement is the only hydraulic binders that is used and currently there is only one cement plant in the in Guinea-Bissau. The bitumen used in Guinea-Bissau are imported from other countries, as Guinea-Bissau doesn't have domestic production facilities for bitumen. Penetration grade bitumen 60/70 or 80/100 is commonly used as a binder.

Raw laterite gravel (GL), litho-stabilized (GLli), improved (GLa) or treated with cement (GLc), are used in the base or foundation (sub-grade) layer of the road. Thicknesses of 10 to 30 cm for untreated and 15 to 30 cm for treated. Numerous projects involving untreated laterite (GL), improved laterite (GLa) or laterite treated with a hydraulic binder (GLc) have been carried out in Guinea-Bissau. This material is abundant in Guinea-Bissau and offers favourable properties for supporting pavement structures. It can also be used in other layers. Improved laterites contain only a small percentage of cement (2 to 3%) so the pavement retains its flexible behaviour. However, cement-treated laterites contain a higher percentage of cement (generally 4 to 6%) and the road surface has a semi-rigid behaviour.

The following Table 1 is the value for the pavement sub-grade thickness, these values are based on the soil strength classification (California Bearing Ratio).

Table 1. Value for the pavement sub-grave thickness [8]

Bearing Ratio	Thickness
CBR < 5	25 cm
CBR 5 – 7	35 cm
CBR 8 – 14	45 cm
CBR 15 – 29	55 cm
CBR > 30	65 cm

2.1.4. TYPICAL ROAD DESIGN IN GUINEA-BISSAU

Because the climate and soil conditions in tropical countries differ greatly from those in temperate zones, road design in these countries requires a unique strategy. To maintain durability and usage, effective road design must address issues including high temperatures, excessive rainfall, and certain soil types. For designers, creating pavement for LVR is a unique task. This is mostly due to the fact that these roads were not expressly designed for until recently, and the transition from a gravel road to a paved road was a significant one. But thanks to extensive international research, simplified pavement design techniques have been developed that allow unpaved roads to be economically upgraded to paved standards by utilizing local materials that don't meet the standard specifications found in most design manuals. The "catalogue" approaches, which are the most widely utilized design techniques for LVR in Guinea-Bissau, will be employed for this study's rural road design. This approach enables the construction of suitable pavement structures for a variety of subgrade strengths and traffic loading classes based on empirical and experimental data. A thin, flexible bituminous coating intended to create a long-lasting and waterproof seal is the most used LVR surfacing material. Since these seals don't significantly increase the pavement's structural strength, they have no effect on the pavement's design. Figure 3 illustrate the typical pavement structure of low traffic road in Guinea-Bissau.

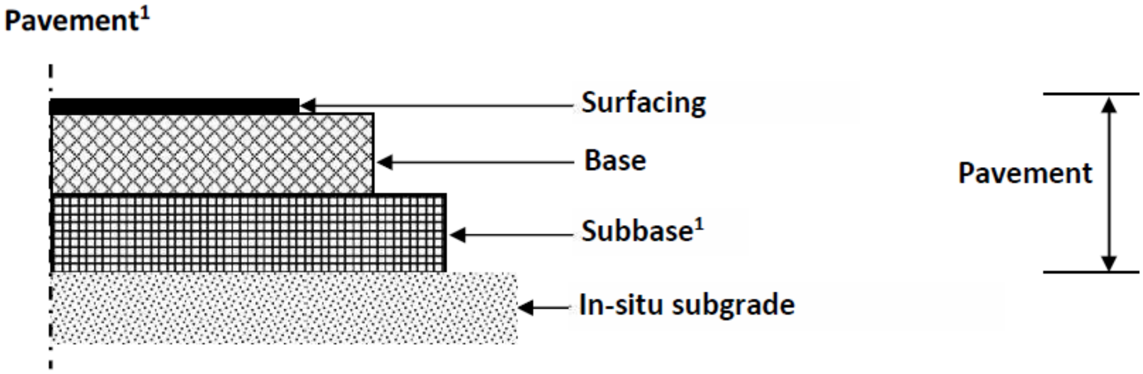


Figure 3. Main components of a low-traffic road pavement [9]

Design standards and specifications vary from project to project because there are no fixed standards for road construction in Guinea-Bissau. This creates challenges for the designer, who must adapt to the standards of other countries or base their plans on already completed projects. For the purpose of conducting the LCA in the LVR in Guinea-Bissau, the current design is based on the Malawi low-volume road standard and the Senegal standard, as these countries share similar climate and soil conditions with Guinea-Bissau. Additionally, some information was sourced from various West Africa Road construction standards and documents from roads already built in Guinea-Bissau.

The pavement structure proposed, consisting of a 50 mm hot mix asphalt (HMA) surface, a 200 mm crushed gravel a 300 mm natural West Africa Road sub-base, and an in-situ subgrade layer with a California Bearing Ratio (CBR) of approximately 5%, is a carefully balanced solution that responds to both engineering demands and contextual realities in tropical, low-traffic environments such as those found in Guinea-Bissau. This configuration reflects a considered application of both the Low Volume Roads Manual (Malawi Roads Authority, 2020) and the Catalogue of New and Existing Roadway Structures (Senegal, 2015), which together form a robust foundation for pavement design in regions characterized by climate variability, material constraints, and evolving transport needs.

The use of a 50 mm hot mix asphalt layer as the surface course is well-supported in both documents. Asphalt concrete is selected not only for its riding surface properties but also for its structural value and the protection it offers. It restricts moisture entry and protects the layers below from oxidation and weather-related distress. According to [8], this thickness is standard for roads with moderate loading and environmental exposure. Likewise, [9] confirms that 50 mm is a suitable thickness for the bituminous surface on low-volume roads where dust control, waterproofing, and surface resilience are essential Furthermore, the selected bituminous mixture (granular in this case) is defined in the Senegalese guide [8]. The bituminous mixture was chosen in appropriate proportions of coarse and fine aggregates with a 4–6% bitumen rate to ensure satisfactory flexibility and rutting resistance for the usual thermal cycles and heavy axle loads to be experienced occasionally.

The lower base layers are made of a crushed gravel base course mixed with lateritic sand and is 200 mm thick. This thickness is to ensure a load spreading function and to protect the overall structure in case the subgrade is not sufficient. The role of the moisture resistance, volumetric stability, and shear strength of this layer is at the heart of the overall performance. The selected 200 mm thickness aligns with recommended values for roads built over subgrades with CBRs ranging between 3–5%, as shown in the structural design tables and pavement configurations in both references [8], [9]. The use of crushed stone ensures the mechanical interlock and bearing capacity required for roads that may occasionally carry medium-weight commercial vehicles.

The sub-base layer is 300 mm thick and is made up of compacted natural lateritic gravel. It serves several purposes, including: The distribution of stresses to limit excessive stresses to the subgrade, provide a working platform during construction, and to act as a buffer layer for the base against long term moisture changes. The lateritic material is selected for its ubiquity, workability, and adequate CBR performance when properly processed often exceeding 10%, which satisfies the design expectations for such layer. The Senegalese guide details the sizing characteristics of untreated lateritic gravel, supporting its use in this application. Moreover, the use of locally available materials such as laterites fosters both environmental and economic sustainability, as sourcing materials locally not only reduces transport costs but also minimizes environmental impacts associated with long-distance logistics.

Finally, the subgrade, at a CBR of 5% approximately, is the natural subsoil on which the road is built. This is considered to be very weak structurally, however, it is not an unusual subgrade strength in tropical climates, particularly where clayey or silty soils are present. In these cases, the total pavement thickness is simply increased to reduce strain and protect the subgrade from deformation and damage by moisture. Both design manuals agree that when the subgrade exhibits low bearing capacity, the solution lies not in deep chemical stabilization but in structural compensation using quality granular layers [8], [9]. The compacted in-situ layer thus serves as a practical measure to ensure uniformity and continuity in load support. This pavement design is grounded in context-specific design logic and regional experience. The material choices and thicknesses are to fulfil the structural requirements, climate resilience and cost-effectiveness.

2.2. LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) represents a standardized framework for the evaluation and comparison of the environmental repercussions associated with products, processes, or services throughout their entire life cycle, encompassing stages from the extraction of raw materials to the ultimate disposal or recycling at end-of-life. This methodology comprehensively accounts for all resource utilization and pollutant emissions pertinent to each phase, which includes material processing, manufacturing, transportation, construction, and final treatment. The approach incorporates an impact assessment phase, during which the environmental ramifications are quantified across pertinent categories[10], [11].

Within the construction sector, LCA has emerged as an efficient instrument for evaluating the environmental efficacy of materials, components, and systems utilized in buildings and infrastructure. Its systematic methodology empowers stakeholders to assess the ramifications of various design and material selections, thereby fostering more sustainable decision-making processes[12]. In this investigation, LCA is employed to examine the environmental impacts of alternative materials for the pavement on low-traffic roads in Guinea-Bissau, thereby offering a thorough foundation for the comparison of design scenarios and the identification of more resource-efficient and low-impact alternatives.

2.2.1. DEFINITIONS OF LIFE CYCLE ANALYSIS AND APPLICATION IN CONSTRUCTION

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental implications of a product, process, or service across all stages of its life from the extraction of raw materials through manufacturing, transportation, use, maintenance, and ultimately, disposal or recycling, often referred to as a "cradle-to-grave". Figure *4* illustrates the general life cycle considered for the typical LCA. Also, it examines both resource inputs (such as energy, water, and raw materials) and environmental outputs (such as emissions, waste, and by-products) in order to provide a holistic picture of environmental performance [13], [14]. This makes LCA a valuable tool for understanding the trade-offs between different design or production choices and identifying opportunities to reduce environmental burdens.

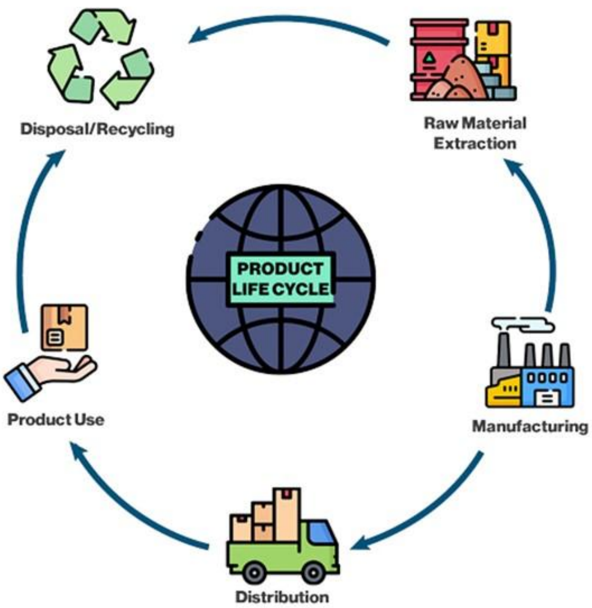


Figure 4. Life cycle assessment phases [15]

In construction, LCA has become increasingly relevant as the industry seeks to address the significant environmental challenges associated with resource consumption and emissions. Buildings and infrastructure are long-lived systems that demand large quantities of materials and energy throughout their life cycles. By applying LCA, decision-makers can evaluate the environmental impacts of materials and construction techniques before projects are implemented, enabling them to select options that minimize negative impacts while maintaining functionality and safety[16].

LCA is an instrument that offers varying levels of detail, ranging from a comprehensive assessment of the overall life cycle to the quantification of impacts associated with a specific material or component. It encompasses a wide array of impacts; although greenhouse gas emissions represent a critical category, they constitute merely one dimension that an LCA can evaluate. Other impact categories, such as ozone depletion, eutrophication, and effects on human health, can also be assessed through LCA. Furthermore, LCA is underpinned by international standards to guarantee uniformity and dependability. The

International Organization for Standardization (ISO) has published the principles, framework, requirements, and guidelines pertaining to LCA in the ISO14040 and ISO 14044 documents [13], [14].

The strength of LCA in construction lies in its ability to break down the life cycle into discrete stages including material extraction (A1), transportation (A2), manufacturing or processing (A3), delivery to the construction site (A4), and installation (A5), as defined in EN 15804. This stage-by-stage analysis allows stakeholders to pinpoint “hotspots” of environmental impact, such as high emissions from energy-intensive material production or the significant carbon footprint from long-distance transportation. Once identified, these hotspots can be addressed by selecting alternative materials, optimizing transport logistics, or improving construction efficiency [17].

Beyond material selection, LCA in construction can inform broader sustainability strategies. For example, it can compare the environmental performance of renovation versus demolition and new construction, assess the benefits of integrating recycled or locally sourced materials, or quantify the long-term environmental benefits of low-maintenance infrastructure. It can also contribute to achieving compliance with environmental regulations and earning credits in green building certification systems like BREEAM and LEED [18].

2.2.2. LIFE CYCLE ANALYSIS PHASES

According to the ISO 14040 and 14044, LCA studies consist of four phases:

1. Goal and Scope
2. Inventory Analysis (LCI)
3. Impact Assessment (LCIA)
4. Interpretation

Each phase is linked to the others, with outputs from one stage feeding into the next, forming a continuous feedback loop throughout the process. This cyclical interaction strengthens both the depth and reliability of an LCA study, ensuring that the conclusions are well-founded[19]. Figure *5* presents a visual representation of how these phases interact.

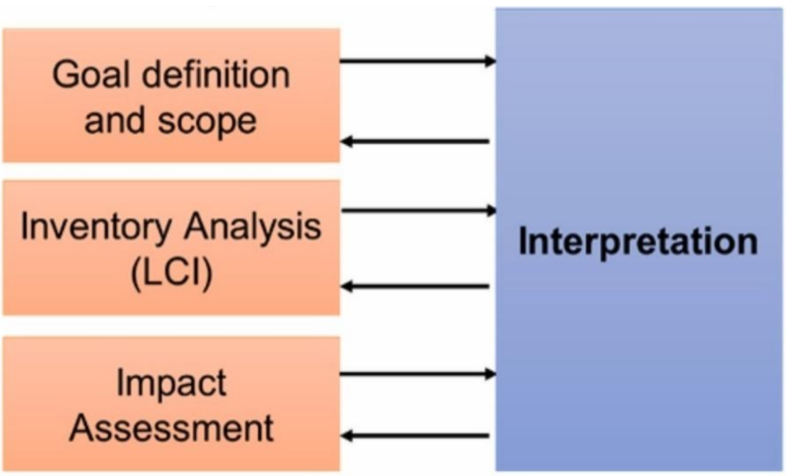


Figure 5. Relationships between phases of the LCA [20]

2.2.3. GOAL AND SCOPE

The initial stage of an LCA focuses on establishing both the goal and the scope of the study. The scope outlines the system boundaries and the level of detail to be applied, which are determined according to the subject matter and the intended use of the assessment. The goal, on the other hand, defines the overall breadth and depth of the analysis. For the results to be meaningful and applicable, the goal and scope must be stated clearly and remain consistent with the intended application of the study. While these definitions are set at the start, they may be refined as the LCA progresses, reflecting the iterative nature of the process.

When setting the goal, it is important to specify the intended application, the reasons for undertaking the study, the target audience, and the ways in which the results will be applied. The scope should also describe key elements such as the functional unit, system boundaries, chosen LCIA methodology, underlying assumptions, study limitations, and required data types. Although a system may serve several potential functions, one must be selected as the basis for the assessment. The functional unit expresses this chosen function in measurable terms, providing a reference point for quantifying inputs and outputs.

Equally important is defining the system boundary. In the LCA model, boundaries identify which elements of the physical system are included and determine which unit processes are to be assessed. A product system generally consists of several unit processes, each representing the smallest segment for which input and output data are gathered. Figure *6* provides an example of how multiple unit processes can form a complete product system. The chosen system boundary must correspond with the study's purpose and underlying assumptions, and any decisions to include or exclude processes should be fully documented.

In comparative analyses, such as the one in this dissertation, it is essential to define the study's scope in a way that ensures the results can be directly compared. For a fair and meaningful comparison, all scenarios must be based on the same functional unit and adhere to equivalent methodological parameters. These include performance criteria, system boundaries, allocation methods, rules for selecting and evaluating inputs and outputs, and the chosen impact assessment approach. Maintaining this consistency across scenarios not only safeguards the reliability of the comparison but also enhances the validity of the study's conclusions.

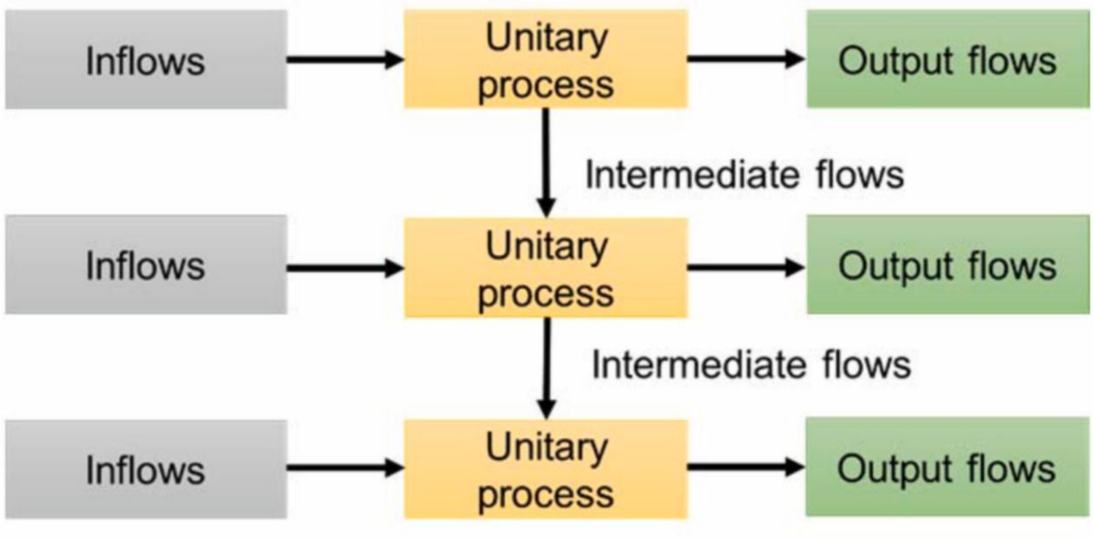


Figure 6.Set of unit processes [20]

2.2.4. INVENTORY ANALYSIS (LCI)

The Life Cycle Inventory (LCI) phase involves the systematic collection and quantification of data on all relevant inputs and outputs within the system boundaries established in the scope definition. This includes gathering information on the resources consumed, such as raw materials, energy, and water, as well as the emissions released to air, water, and soil, and any waste generated. Data may be obtained directly from primary sources, such as on-site measurements and process records, or from secondary sources, including scientific literature, industry reports, and LCA databases. Ensuring data quality is essential at this stage, with particular attention given to its representativeness in terms of time, location, and technology.

The data collected is organized into unit processes, which are modelled to reflect the flows of materials and energy between them and the environment. Where processes generate multiple outputs, allocation procedures or system expansion methods are applied in accordance with ISO 14044 guidelines. All assumptions, exclusions, and data sources must be documented to maintain transparency and enable reproducibility of the study. The outcome of this phase is a detailed inventory that quantifies all input and output flows per functional unit, forming the basis for the Life Cycle Impact Assessment phase. Figure 7 illustrate a simplified procedure for inventory analysis (process of data collection)

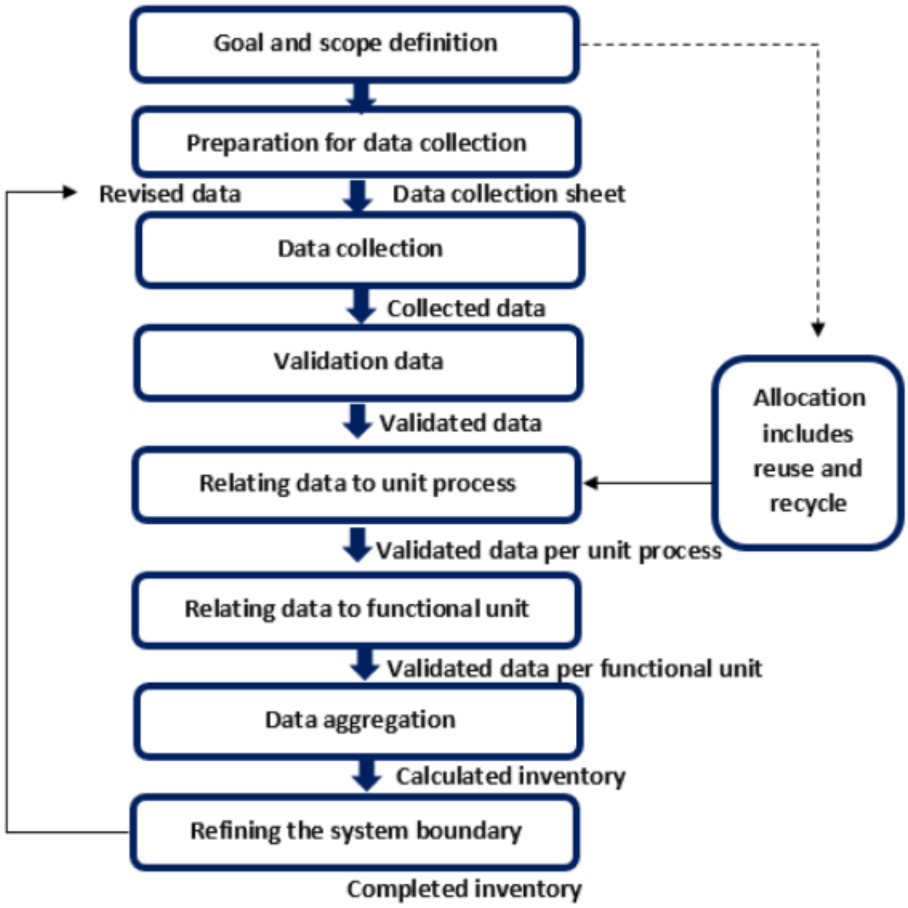


Figure 7. Process of data collection according to ISO 14040:2006 [21]

2.2.5. IMPACT ASSESSMENT (LCIA)

The Life Cycle Impact Assessment (LCIA) phase builds on the results of the Life Cycle Inventory by translating the quantified input and output flows into potential environmental impacts. This step involves classifying each flow according to the impact categories it contributes to, such as global warming potential, fossil resource scarcity, eutrophication, acidification, particulate matter formation and more. The flows are then characterised using scientifically derived factors that convert physical quantities into a common unit for each category, enabling the aggregation of contributions from different processes. In essence, LCIA links inventory data with selected environmental categories and indicators to provide a deeper understanding of potential impacts, forming the necessary basis for the subsequent interpretation phase.

The LCIA method applied in this study follows the guidelines set out in ISO 14044 and utilises the method ReCiPe 2016 Midpoint framework, which provides characterisation factors for a comprehensive range of impact categories. According to ISO 14040 and ISO 14044, several elements should be included in LCIA. The mandatory elements are the selection of impact categories, category indicators, and characterisation models, as well as classification (assigning LCI results to the chosen impact categories) and characterisation (calculating category indicator results). Optional elements such as normalisation, grouping, weighting, and data quality analysis may also be applied, depending on the goal and scope of the study, but must be clearly justified and reported.

Numerous LCIA methods have been developed, each varying in how environmental impacts are quantified and calculated. These methods group and categorise environmental effects such as climate change, water use, or toxicity, and the selection of a method depends on the focus of the study and the categories it intends to evaluate. In practice, the choice of method is often linked to the options available in the LCA software being used. Commonly applied LCIA methods include ReCiPe, TRACI, EN15804+A2 (EU construction sector), EF v3.1, CML, Eco-Indicator 99, CST 99, and Environmental Prices. While no universally accepted method exists for consistently associating inventory data with environmental impacts—representing a limitation of LCA—these models are continually being refined and improved [19]. The results of this phase provide a clear link between the system's life cycle flows and their associated environmental consequences, forming the basis for interpretation and decision-making in the final stage of the LCA. Figure 8 illustrates mandatory and optional elements for LCIA.

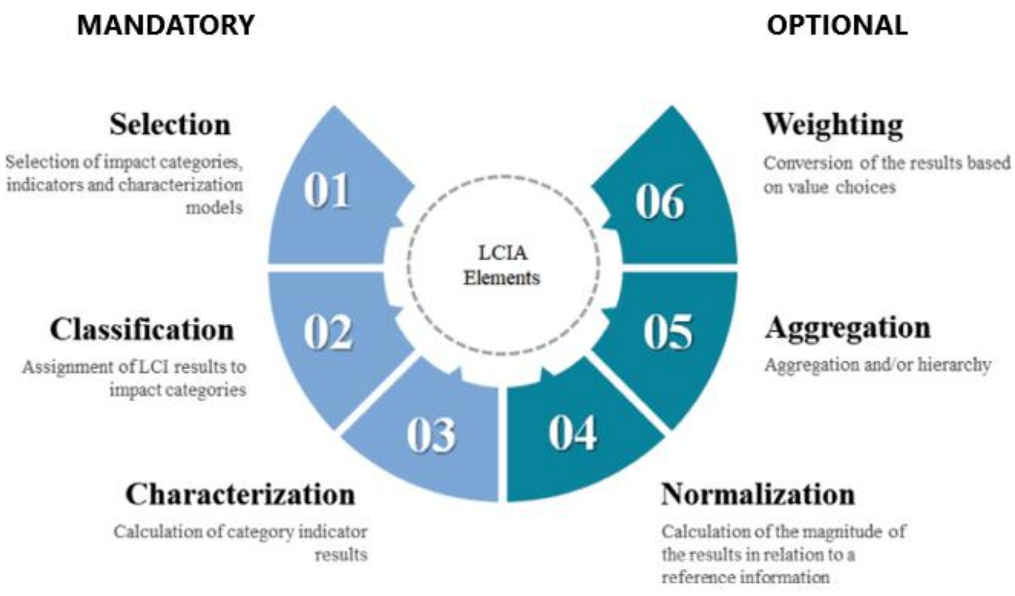


Figure 8. Structure of the life cycle impact assessment (LCIA) elements[22].

2.2.6. INTERPRETATION

The Life Cycle Interpretation is the final phase of the LCA process. It involves analyzing previous stages—specifically, the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA)—to draw conclusions, interpret findings, and suggest future actions aligned with the study's goals and scope. During this stage, results are carefully reviewed to ensure completeness, consistency, and reliability. This includes identifying key issues, assessing how sensitive results are to assumptions and data, and verifying that conclusions are supported by the data and methods used. According to ISO 14044, the interpretation should encompass three main components: identifying significant issues, evaluating them, and forming conclusions or recommendations. Significant issues may relate to particular life cycle stages, processes, materials, or environmental impacts that heavily influence the results. The evaluation step confirms robustness through completeness checks, consistency assessments, and sensitivity analyses, determining if variations in data, system boundaries, or methods could significantly change outcomes. The interpretation process is iterative; findings might lead to re-examining earlier phases to refine data or assumptions. Recommendations should be directly linked to the results and the intended use of the study, covering areas such as product or process improvements, sustainable material choices, or supply chain optimization. For comparative analyses, it's important that all scenarios are evaluated under consistent conditions so differences are due to the systems themselves, not methodology or data discrepancies. Well-documented assumptions, limitations, and uncertainties help stakeholders understand the scope and relevance of the results. Ultimately, this phase transforms the quantitative outcomes of the LCA into practical insights, guiding decision-makers toward strategies that minimize environmental impacts while meeting economic and functional needs. Figure *9* illustrates these interpretation steps in relation to the earlier phases, highlighting the iterative nature of LCA studies.

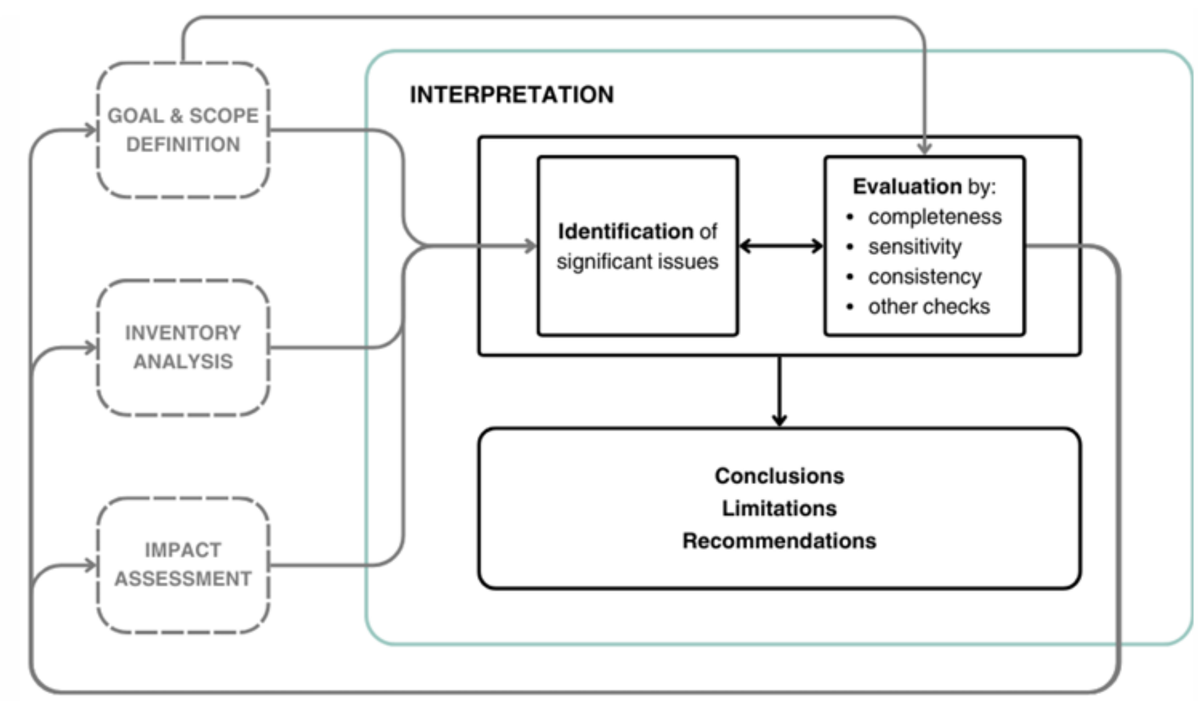


Figure 9. Relationships between elements within the interpretation phase with other LCA phases [19]

2.2.7. LIFE CYCLE AND STAGES OF THE BUILT ENVIRONMENT

The built environment encompasses all human-made structures and infrastructure, including buildings, roads, bridges, and public spaces. Understanding its life cycle is essential for evaluating environmental performance, as each stage involves specific material, energy, and resource flows, as well as associated environmental impacts. The life cycle approach enables a holistic assessment of these impacts, supporting the development of sustainable construction strategies and the selection of resource-efficient materials.

The concept of the "life cycle" refers to the entire span of service life of a material, assembly, or component, which can be particularly long in the context of the built environment. It begins with the extraction of raw materials, followed by their manufacturing and processing into finished goods. These goods are then transported to the construction site, where they are installed and assembled. Over its lifespan, the infrastructure may undergo repairs, refurbishments, and maintenance to extend usability. Eventually, at the end of its service life, it may be demolished, offering opportunities for material recovery and circular economy practices although in many cases, materials still end up in landfills, underscoring the need for improved waste management [19]. Figure *10* display these stages, illustrating the source of the embodied carbon emissions for each stage.

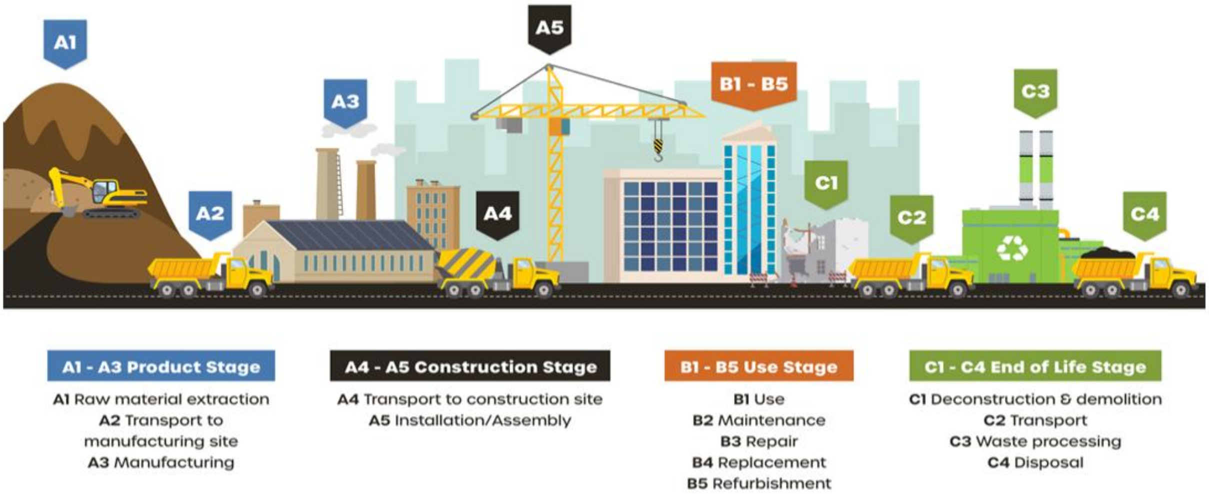


Figure 10. Construction life cycle stages [23].

The life cycle of the built environment can generally be divided into five key stages: product stage (A1–A3), construction process stage (A4–A5), use stage (B1–B7), end-of-life stage (C1–C4), and benefits and loads beyond the system boundary (D), as defined in standards such as EN 15978 and EN 15804 [24].

1. Product Stage (A1–A3): Covers raw material extraction and processing (A1), transportation to the manufacturer (A2), and manufacturing (A3). This is often referred to as "cradle to gate" and includes all material provision, energy requirements, and waste generated during initial processing. This stage is typically highly resource- and energy-intensive, contributing significantly to emissions and environmental burdens.
2. Construction Process Stage (A4–A5): Includes transportation of products to the construction site (A4) and on-site construction or installation activities (A5). A4 considers the impacts from transport distance, fuel type, and vehicle efficiency, while A5 encompasses all site activities, including installation processes, temporary works and any material losses or waste generated

during construction. This stage is termed "cradle to practical completion" or "cradle to handover"

3. Use Stage (B1–B7): Represents the operational life of the built asset. It includes use/application (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7). For roads, this stage covers periodic resurfacing, patch repairs, and material replacements required to maintain performance.
4. End-of-Life Stage (C1–C4): Covers deconstruction or demolition (C1), transportation of waste materials (C2), waste processing for reuse, recovery, or recycling (C3), and disposal (C4). This stage accounts for all energy, water, and transport associated with dismantling and processing materials. Studies that include this stage adopt a "cradle to grave" perspective.
5. Beyond the System Boundary (D): Captures potential benefits from reuse, recovery, and recycling after the life cycle ends. When included, this is referred to as a "cradle to cradle" approach, which considers net environmental benefits from material recovery, such as recycled steel slag or reclaimed asphalt pavement substituting virgin materials. Although this stage is challenging due to limited data on the fate of construction products after demolition, it promotes design strategies that enhance material circularity and reduce waste.

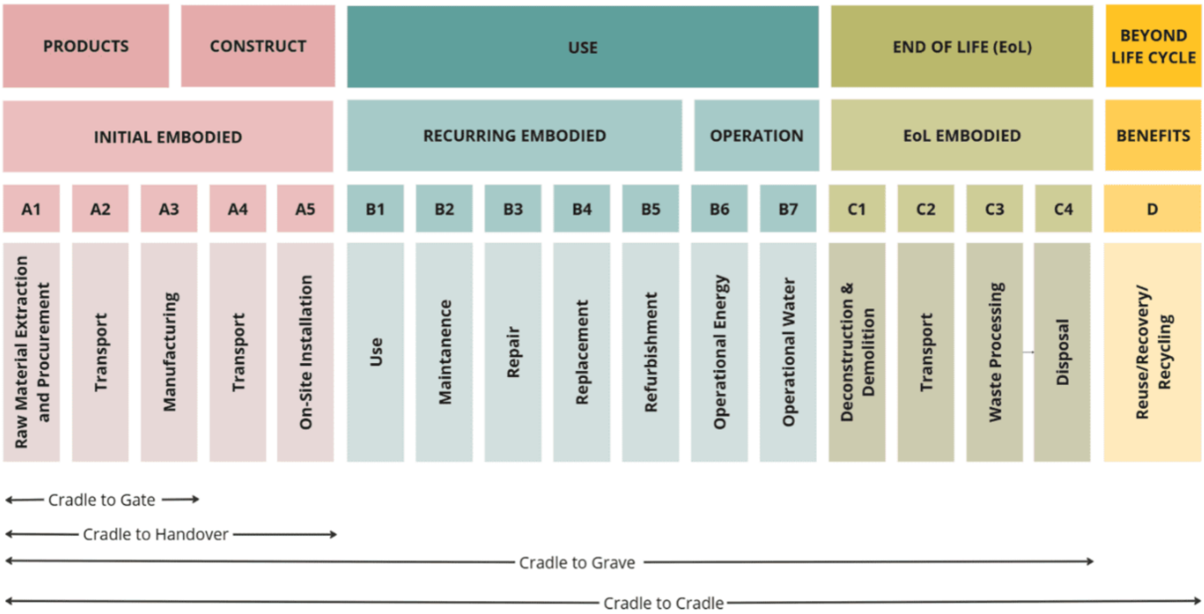


Figure 11. System boundary definition as per EN 15978 [25]

2.3. SUSTAINABLE MATERIAL FOR ROAD CONSTRUCTION

The search for sustainable alternatives in road construction requires materials that not only reduce environmental burdens but also meet the stringent mechanical and durability demands of pavements. In this study ten (10) possible sustainable material for road construction are considered, recycled asphalt pavement (RAP), construction and demolition waste (CDW), steel slag (SS), palm kernel shells (PKS), crumb rubber (CR), glass waste, shell waste, plastic waste, fly ash, and rice husk ash (RHA). These materials were selected because of their demonstrated potential to enhance pavement performance while promoting circular economy practices.

RAP, for example, has been widely recognized for its ability to reduce the demand for virgin aggregates and bitumen while lowering greenhouse gas emissions [26]. This makes it not only environmentally beneficial but also cost-effective in road rehabilitation and new pavement design. Similarly, CDW is considered a sustainable substitute for natural aggregates in sub-base applications, with studies showing that recycled concrete aggregates can provide comparable mechanical strength while significantly reducing landfill pressure [27].

Industrial by-products such as steel slag have gained attention for their durability and high load-bearing capacity in road layers, offering superior performance compared to natural aggregates [28]. In parallel, organic agricultural wastes like PKS have emerged as promising lightweight aggregates. Research demonstrates that PKS can reduce pavement density while maintaining structural integrity, thus lowering overall material and transport emissions, an important advantage for low-volume roads in rural West Africa [29]. Crumb rubber derived from waste tires has also been widely used in asphalt mixtures to improve elasticity, fatigue resistance, and service life, while at the same time diverting a difficult-to-dispose waste stream from landfills [30]. Other wastes, including glass and shell materials, also offer unique benefits. Recycled glass has been successfully incorporated into asphalt and base layers, contributing to resource conservation and reducing landfill waste, though with careful attention to gradation and durability [31]. Shell waste, abundant in coastal regions, has been shown to improve compressive strength in concrete and sub-base applications, thus providing a low-cost alternative for tropical regions [32]. Plastic waste, another pressing environmental challenge, has demonstrated strong potential as a modifier in asphalt mixes, improving rutting resistance and flexibility while contributing to waste reduction [33]. Materials such as fly ash and rice husk ash (RHA) provide pozzolanic properties that improve the strength and durability of pavement layers. Fly ash is widely used for reducing cement content and mitigating CO_2 emissions, while RHA has been found to enhance soil stabilization and increase the bearing capacity of weak subgrades [34], [35]. These materials address both environmental and contextual priorities: they reduce dependency on virgin resources, minimize waste disposal challenges, improve structural performance.

However, despite these promising characteristics, the sustainability of these materials cannot be fully insured without considering contextual factors such as local availability, economic viability, and technical adaptability. To account for these practical realities in Guinea-Bissau, a secondary selection was made, prioritizing materials that not only demonstrate technical performance or environmental benefits but, more importantly, for their availability in the local or regional context, their feasibility of implementation with the country’s limited industrial capacity, and their straightforward integration into existing road design practices. Among the various alternatives sustainable materials that have been listed below, four materials stand out as more feasible for practical implementation in Guinea-Bissau: steel slag, palm kernel shells, crumb rubber, and glass waste. These materials are available, do not need very advanced technologies to be used and can easily replace the conventional material.

Steel slag, an industrial by-product, is one of the most technically reliable substitutes for natural aggregates in road construction. While Guinea-Bissau itself does not have a major steel industry, the material is produced in significant volumes in neighbouring West African countries such as Nigeria, Ghana, and Senegal creating a regional supply opportunity. Moreover, it is already widely used worldwide due to its exceptional mechanical properties, making it a durable and strong replacement for natural aggregates. Although Guinea-Bissau lacks local steel production, the proximity of industrial centres in Senegal or Ghana makes regional sourcing feasible. Senegal is Guinea-Bissau’s neighbour country, they produce steel slag which can be used as potential replacement material for the conventional. So, the price is going to be analysed and the transportation as well, in order to know if this material is worthy use in Guinea-Bissau LVRs. Senegal produces approximately 4 million tonnes of steel annually, primarily through the Falémé project in the southeast of the country [20]. Steelmaking processes typically generate slag at a rate of about 10% to 15% of crude steel production, applying this ratio, Senegal's steel slag production would be estimated between 400,000 and 600,000 tonnes per year

[21]. The main steel factory is in Dakar which is 432 Km away from Guinea-Bissau. **Error! Reference source not found.** illustrate the route for steel slag transportation, from Senegal to Guinea-Bissau

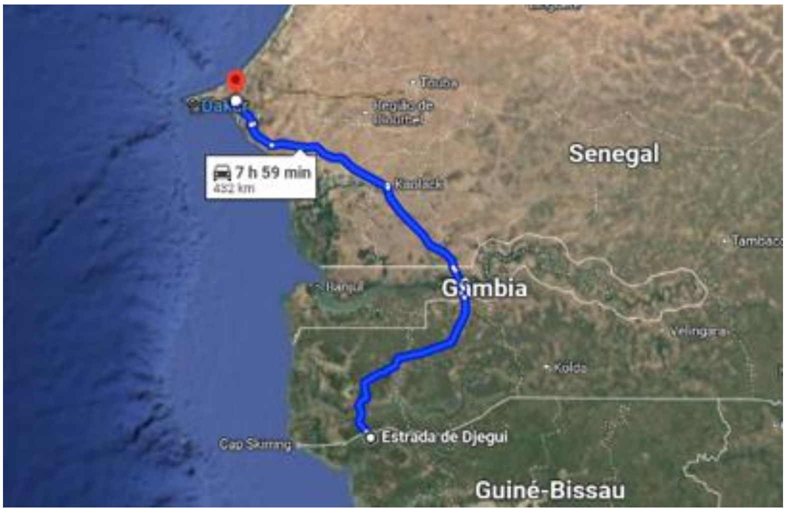


Figure 12.Possible route for Steel Slag transportation from Senegal to Guinea-Bissau [36]

Palm kernel shells (PKS), in contrast, represent a resource that is locally abundant and closely tied to Guinea-Bissau's agricultural economy. As a palm oil producer, the country generates large volumes of PKS as a waste by-product. This local availability eliminates the need for long-distance transport and makes PKS one of the most context-appropriate options. Their lightweight nature also means that pavements constructed with PKS aggregates require less material by volume, reducing both costs and embodied emissions. In terms of design, PKS can partially substitute natural aggregates in asphalt mixtures or be used in base layers, with existing literature suggesting replacement rates that maintain mechanical stability [37]. This makes PKS a highly feasible material for integration, particularly in low-volume rural roads.

Crumb rubber, derived from discarded tires, offers both an environmental and an engineering solution. Waste tires are an increasing challenge in many African contexts, including Guinea-Bissau, where disposal options are limited, and open burning is still practiced. Local availability of tires, combined with simple shredding or grinding facilities, makes the material feasible without requiring highly advanced processing plants. In road design, crumb rubber has been widely incorporated into asphalt mixes as a modifier, enhancing elasticity and durability. For Guinea-Bissau, integrating crumb rubber into asphalt pavements could extend road service life and reduce maintenance costs an important advantage where resources for frequent rehabilitation are scarce.

Glass waste also presents an opportunity closely tied to Guinea-Bissau's urban centers, where post-consumer bottles and glass containers form a persistent fraction of municipal solid waste. Although available in smaller volumes compared to PKS or tires, glass waste is locally accessible and typically underutilized. With relatively simple crushing and grading, it can be integrated into asphalt or granular layers. In design terms, glass can be blended into asphalt mixtures in controlled proportions without compromising performance, provided gradation and durability are carefully managed.

Together, these four materials reflect a pragmatic balance of availability, feasibility, and design adaptability. Unlike other alternatives such as RAP, CDW, plastics, or industrial ashes, which require established recycling infrastructure, advanced processing technologies, or large-scale sources not present in Guinea-Bissau, steel slag, PKS, crumb rubber, and glass waste can be realistically mobilized within the country's current economic and technical constraints.

3

LITERATURE REVIEW ON SUSTAINABLE MATERIALS FOR ROAD

3.1. STEEL SLAG

The use of steel slag in road construction has gained significant attention in recent years due to its potential to reduce environmental impacts that traditional construction materials usually cause. The use of steel slag, a by-product of the steelmaking process, offers several advantages, including reduced greenhouse gas emissions, conservation of natural resources, and the diversion of waste materials from landfills. The replacement of natural aggregates by steel slags in road construction significantly reduces the carbon footprint of the construction process. Studies have shown that the production of steel slag aggregates generates lower embodied CO_2 emissions compared to the production of natural granite aggregates. This is primarily due to the avoidance of energy-intensive quarrying and transportation processes associated with natural aggregates[38].

Steel slag exhibits excellent engineering properties, such as high durability, resistance to abrasion, and good interlocking capabilities, making it a suitable material for road construction. Its high calcium oxide content also contributes to improved binding properties, which can enhance the stability and longevity of road pavements [39]. These properties are particularly beneficial in tropical regions where roads are often subjected to heavy rainfall and high humidity. Also, his high density and low water absorption properties reduce the risk of moisture-induced damage, which is a common issue in tropical climates[40]. The performance of steel slag in high-temperature and high-humidity conditions has been evaluated in several studies. Results indicate that steel slag retains its engineering properties under these conditions, making it a reliable choice for road construction in tropical regions [41], [42][43].

Pasetto and Baldo [44] investigated replacing 40% of natural coarse aggregates with coarse steel slag aggregates in a warm-mix asphalt. The researchers confirmed that adding steel slag improved the stiffness and permanent deformation, though it decreased the fatigue resistance of the warm-mix asphalt. In another study by Pasetto and Baldo [45], conventional coarse aggregates in stone-mix asphalt were substituted with 59% steel slag aggregates. The research results indicated that asphalt mixes with steel slag aggregates performed well in terms of tensile strength, fatigue resistance, resilient modulus, and rutting resistance. The researchers observed an increase in the creep modulus by 53%, the stiffness modulus by 22%, and the tensile strength ratio by 10%.

A case study in Bangladesh demonstrated the successful use of steel slag as a subbase material in road construction. The study found that steel slag exhibited superior mechanical properties compared to conventional materials, including higher unconfined compressive strength and California Bearing Ratio (CBR) values [46], [47].

3.1.1. STEEL SLAG PRODUCTION

The diverse types of steel slag produced during steel manufacturing vary significantly in origin, formation, quality, and application, making them widely useful in civil construction. Naturally, the production process influences the differences observed in iron and steel wastes. The following are some of types of steel slag production process.
Blast Furnace Iron Slags (BFS), a byproduct of iron or steel production, varies depending on the cooling method applied to molten slag from iron ore reduction to molten iron used in iron products or mainly as steel feedstock. A coke-fueled blast furnace, containing iron ore, iron scrap, and fluxing agents like dolomite or limestone, operates at temperatures up to 1650°C to generate the carbon monoxide needed for the reduction process.

Basic oxygen furnace steel slag (BOFS) is generated as a byproduct when molten iron is blown in a basic oxygen furnace during steel manufacturing. The furnace process involves mixing limestone (used as flux), steel waste, and ferroalloys. Steel scraps are crucial in this process to cool the furnace and maintain the temperature around 1600 °C, which is vital for the chemical reactions between iron ore and coke. Usually, the furnace charge consists of 80–90% molten iron and 10–20% steel scraps, with a small addition of ferroalloys and fluxes.

Electric Arc Furnace Steel Slags is employed in furnaces to melt steel wastes and produce high-quality steel. An electric arc allows current to pass between graphite electrodes, generating intense heat once different types of steel scraps varying in size, density, and chemistry are loaded into the furnace to ensure uniformity. By gradually lowering the electrodes as the scrap layer melts, the entire charge can be fully fused. Additionally, oxygen injection reduces scrap sizes and facilitates reactions between fluxes (initially charged) and impurities in the scrap, promoting the formation of CaO (lime or dolomite) and aiding the oxidation of elements like aluminum, silicon, manganese, phosphorus, and carbon. This method is similar to steelmaking in a basic oxygen furnace.

To achieve specific chemical compositions, secondary steel-making operations, or refining procedures applied to basic steel produced via electric arc or basic oxygen furnace methods, generate ladle furnace slag (LFS). These secondary refining processes, which include desulfurization, decarburization, and impurity removal of oxygen, hydrogen, and nitrogen, significantly influence the morphological properties of the refined steel. Ladle furnaces are also characterized by graphite electrodes attached to the arc for heating. To stir and homogenize the molten steel, controlled argon gas can be introduced from the bottom of the ladle. During refining, alloy additions are made to achieve the desired chemical composition.

3.1.2. APPLICATION IN ROAD CONSTRUCTION

The road's surface, base layer, sub-base, and road base are arranged in layers from top to bottom, following typical road construction principles. The materials required for each layer differ, and Figure 13 shows an example of how these layers are structured in road construction.

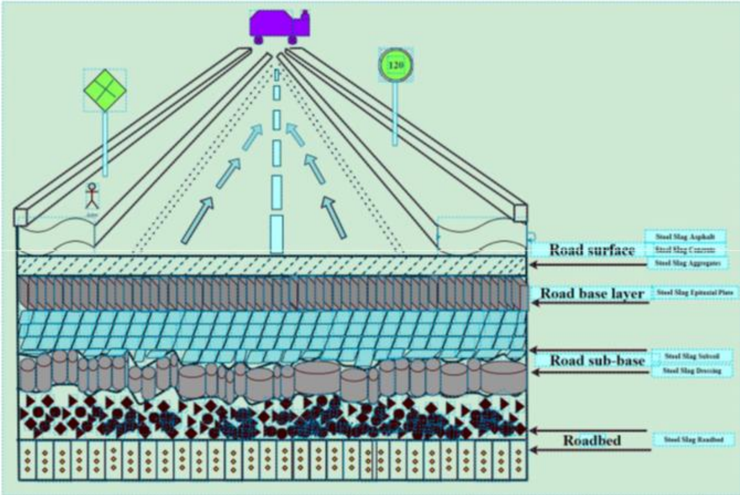


Figure 13. Steel slag layering in road pavement [48]

In road construction, aggregates are essential materials that make up the road structure, classified according to their position and role as surface aggregates and base and sub-base aggregates [49], [50]. Steel slag's thermal expansion properties are similar to those of common road construction materials, boosting deformation resistance and reducing pavement cracking caused by temperature changes. Furthermore, steel slag's low water absorption improved frost resistance and minimized freeze-thaw damage, vital for pavement in cold climates [48]. By promoting the recycling of industrial waste and reducing the exploitation of natural resources, using steel slag as an aggregate embodies principles of sustainability and environmental responsibility. Steel slag, a byproduct of industry, often provides significant economic advantages due to lower costs compared to traditional aggregates. Its sharp-edged particles (see Figure 14) enhance asphalt adhesion, thereby improving driving safety and preventing skidding issues.[51]

The mechanical properties of fillers are directly related to the deformation and stability of the subgrade. The chemical composition and mechanical properties are conducive to the enhancement of subgrade strength and bearing capacity, thus it is increasingly used in the stabilization of soil [39] steel slag as a filler used in subgrade has many advantages. When used to strengthen a soft foundation, the most evident benefit for engineering is to improve bearing capacity, thereby reducing uneven settlement [52]. InTable 2. Comparison of steel slag and the traditional material properties [48] Table 2 can be found the comparison of steel slag and the traditional material properties.

Figure 14. SS (left) and NA (right) aggregate

Table 2. Comparison of steel slag and the traditional material properties [48]

Performances	Steel Slag	Basalt (Geology)	Limestone	Granite	Regulatory Requirement
Relative density	3.1–3.5	2.9–3.0	2.6–2.7	2.8–3.0	>=2.5
Water absorption/%	1.5–2.2	0.3–0.5	0.5–1.0	0.3–1.2	<=3.0
Grinding value/%	54–70	50–56	35–45	45–55	>=36
Attrition rate/%	9–15	12–18	18–22	15–20	<=28
Crushing value/%	12–16	12–18	15–20	12–27	<=26
Adhesion grade	5	4	4–5	4	4–5

Steel slag is commonly utilized in the base or sub-base layer of road construction[53]. According to [54], [55] increasing the electric arc furnace steel slag aggregate in the subgrade layer enhances dry density, CBR value, and resilient modulus of the layer. The optimal balance of steel slag aggregate percentage and minimal construction costs was achieved at 70% steel slag and 30% limestone aggregates.[55] used basic oxygen furnace steel slag and obtain almost the same result. with 70% BOFS and 30% soil the results shows high CBR, maximum dry density, low-plasticity and no expansion. In [56], their results showed that mixing fuming furnace steel slag with local soil up to 75% can enhance the properties of the subgrade layer. Additionally, they suggest that SS can partially replace conventional aggregates by 45-50% in the granular sub-base layer. [57] The study explored the use of industrial waste in low-volume roads. It assessed the potential of utilizing steel slag. The findings clearly show that blast furnace steel slag is suitable for use in the base and sub-base layers of pavements. However, SS proper treatment is necessary to reduce volumetric expansion instability. [58] The study examined the mechanical properties of ferrochromium slag in granular layers and found that its CBR, resilient modulus, and Poisson's ratio were higher than those of limestone aggregates. Therefore, it can be concluded that slag has potential for use in pavement construction and is unlikely to contaminate groundwater. Figure 15 shows the graphs of variation of CBR with the percentage change of slag

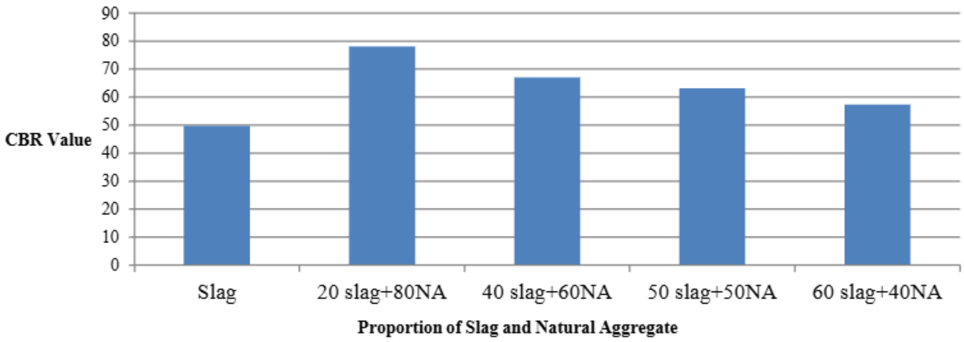


Figure 15. Variation of CBR with percentage change of slag [57]

The well-known Marshall method is the most widely utilized mix design process for asphalt mixtures including steel slag. Steel slag experiments are typically conducted by comparing with other materials to assess the impact of aggregate substitution. Conventional asphalt compositions made entirely of natural materials, like basalt, granite, or limestone are normally used as control mixtures for comparison. Rapid cooling during steel manufacturing causes the porous structure of steel slag, which raises the optimal bitumen content (OBC). This is a consistent conclusion across various research. Micropores between 0.5 and 5 μm have been found in SEM examinations, and these micropores enhance the binder absorption capacity, especially in slags from Electric Arc Furnace (EAFS) and Basic Oxygen Furnace (BOFS) operations[59]. While some studies demonstrate little to no change (usually when lesser volumes or finer fractions of slag are employed), others claim significant increases in OBC, particularly when steel slag substitutes a large portion of the mix. Despite these differences, more slag substitution often results in an improvement in the Marshall Quotient (MQ). Higher Marshall stability, lower flow values, and the angularity and abrasive texture of slag which improves interlock and friction in the mix are all responsible for this. Applications in stone mastic asphalt (SMA) also show these patterns [60], [61], [62].

The behaviour of voids in Mineral Aggregate and total voids (V) varies depending on bitumen content and gradation. In order to take into consideration, the greater density and porosity of slag, some research have proposed modified Marshall approaches and other mix design methodologies [63]. Although Superpave and Bailey method approaches have been utilized in less studies, the results indicate that bitumen absorption from slag has led to an increase in OBC. The Bailey technique emphasizes how crucial it is to account for variations in aggregate fraction specific gravities[64], [65], [66].

Table 3. Investigation summary on road performance of SS mixture[39]

Properties	**Incorporation Method**	**Test and Evaluation Index**	**Observations**
Permanent deformation resistance	0%, 25%, 50%, 75%, and 100% substitution of natural aggregate	Static creep test, dynamic creep test; total strain; recovered strain accumulated strain	Substitution of EAFS is up to 75%
Moisture resistance	0%, 25%, 50%, 75%, and 100% substitution of natural aggregate	Hamburg wheel-tracking test	Substitution of EAFS is up to 75%
Freeze–thaw stability	0%, 30%, 50%, 70%, and 100% weight of overall coarse aggregate	5, 10, 15, 20, and 25 times of freeze–thaw cycles	Higher strength mixture with 100% EAFS; increased moisture and freeze–thaw susceptibility
Fatigue behavior	0%, 25%, 50%, 75%, and 100% substitution of natural aggregate	Indirect tensile fatigue test	Substitution of EAFS is up to 75%
Mechanical performance	0%, 25%, 50%, 75%, and 100% substitution of natural aggregate.	Indirect tensile stiffness modulus test; indirect tensile modulus; dynamic modulus;	Substitution of EAFS is up to 75%;
Crack resistance	25%, 50%, 75%, and 100% replacement of coarse basalt aggregate	ITS and AE tests: ITS, failure strain, and fracture energy	Optimum crack resistance with 100% EAFS; more uniform release of AE energy in SS

3.2. CRUMB RUBBER

According to global tyre market reports, approximately 1.6 billion tyres are sold worldwide each year, yet only about 10% are recycled. The remaining majority often accumulates as end-of-life tyres, contributing to significant environmental challenges. In Africa, where the tyre market is expanding rapidly, millions of tyres are sold annually, and as these reach the end of their service life, inadequate waste management practices such as direct landfilling and open burning are commonly employed. These practices not only waste a potentially valuable resource but also generate severe soil contamination and air pollution, exacerbating existing environmental and public health concerns [67]. To address these challenges, the use of crumb rubber (CR) as a bitumen modifier has recently gained popularity, because it also contributed to reducing the inappropriate disposal of end-of life tyres in nature [68][69]. There are many technical advantages beside the environmental impact. CR can improve the road performance while reducing the thickness of the asphalt layer, road noise, and maintenance expenses [70].

In the United States, states such as California and Arizona have been pioneers in the use of rubber asphalt. In California, for example, the city of Los Angeles has implemented paving projects with this material on several road, resulting in a significant improvement in durability and noise reduction. In Brazil, some cities have also adopted rubber asphalt as a sustainable solution. Curitiba, known for its innovative urban practices, has carried out pilot projects using rubber asphalt, obtaining positive results in terms of resistance and road maintenance. Figure 16 illustrates the materials extracted from waste tyres, including the crumb rubber.

Figure 16. Various recycled materials extracted from waste tyres [71]

3.2.1. APPLICATION IN ROAD CONSTRUCTION

Since the 1960s, the use of crumb rubber (CR) in asphalt pavements through the dry process has been studied as an alternative to traditional hot mix asphalt (HMA). Originating in Sweden, this method involved substituting a small percentage of aggregates with rubber granules, resulting in rubber-modified asphalt concrete (RUMAC). These mixes usually contained 1% to 3% rubber by weight of the aggregate, aiming for an air void content of 2–4% [72]. By the 1980s, technological improvements led to the commercial launch of PlusRide, a gap-graded bituminous mixture designed to include coarse crumb rubber [73]. At the same time, the U.S. Army Corps of Engineers at Cold Regions Research and Engineering Laboratory (CRREL) also developed variations like chunk-rubber asphalt concrete with larger particles and increased rubber content [74].

Unlike traditional asphalt mix design, there is no standard method for dry-process rubberized asphalt. Most reported procedures are mainly empirical, focusing on optimizing mechanical and physical properties like maximum dry density, California Bearing Ratio (CBR), resilient modulus, and direct shear strength [75], [76]. Nonetheless, few studies have explored the vibratory or dynamic behaviors of rubberized materials, even though these properties could greatly affect pavement performance. In practice, crumb rubber is used as a partial substitute for fine aggregates, with rubber and natural aggregates mixed before adding the binder [77]. This straightforward method is a key advantage of the dry process, as it can be performed at any standard asphalt plant without significant modifications or special equipment [78]. Generally, the concentration of granulated CR used for dry processing varies from 1 to 4 % by weight of the aggregates in the rubber-modified HMA, as reported by various researchers [79], [80], [81]. Some experts recommend optimal ratios between 5–8%, although others warn that benefits diminish beyond 6% [77]. Recent advances in hybrid dry technologies have broadened design options. For example, [82] developed a dry-hybrid approach where fine CR replaced lime filler in stone mastic asphalt (SMA) mixes with SBS-modified binder, achieving performance similar to cellulose fiber mixes. Likewise, [83] studied dense-graded dry mixes with CR, RAP, and rejuvenating agents, showing that CR can stiffen these mixtures and enhance fracture resistance, though it may reduce workability.

Dry process provides notable performance benefits, a key advantage is its capacity to include coarser rubber particles, allowing for higher recycling rates, sometimes two to four times greater than wet methods, making it especially appealing from a waste management standpoint [84]. Moreover, because it does not demand specialized equipment, the dry process is more cost-effective for asphalt plants in resource-limited environments. Functionally, the dry process shows promise for creating low-noise pavements, with experimental sections indicating strong acoustic absorption. This effect is stronger when devulcanized rubber is included, as the increased chain flexibility of rubber molecules improves sound absorption [85], [86], [87]. Mechanistically, dry mixes' benefits are generally linked to two factors: (i) larger rubber particles serving as flexible inclusions that absorb stress, and (ii) finer rubber particles altering the binder matrix [88].

Several practical limitations still hinder the use of the dry process. Initially, poor bonding between crumb rubber and bitumen often leads to increased moisture sensitivity and aggregate detachment, which decreases pavement lifespan [89]. Another issue is compaction: during paving, dry-process mixes cool faster than traditional asphalt, shrinking the workable compaction window and often resulting in lower densities. While rapid compaction is necessary, early compaction can cause a "sticky wheel" issue, where rollers stick to the surface. To address this, researchers suggest increasing mixing temperatures by 5–10

°C, slowing rolling speeds, and sometimes storing the mixture for at least 30 minutes before paving to improve binder–rubber bonding [90], [91].

3.3. PALM KERNEL SHELLS

The use of palm kernel shells (PKS) as a sustainable alternative in road construction presents several environmental benefits. PKS, a by-product of the palm oil industry, offers a viable solution to waste management issues while reducing reliance on conventional aggregates. By replacing conventional aggregates, PKS reduces the demand for natural resources, thus conserving them and minimizing environmental degradation associated with aggregate extraction[92]. The material's availability and low cost make it a sustainable choice for regions with abundant palm oil production[93]. Its mechanical properties, such as reduced compressive strength compared to conventional aggregates, may limit its application to specific types of road construction, [93]

The investigation for of partially replacing conventional aggregate with PKS based on the flow values and the Marshal Stability shows that a replacement of about 30 % NA with PKS is possible before an extreme reduction in Marshall Stability is noticed. Thus, a replacement of up to 100 % is recommended for light traffic roads in rural communities [94].

Specific gravity of the palm kernel shells does not place it in the category of common rock groups whose gravities range from 2.62-3.00. However, it showed same porosity as granite, and quartzite, far above limestone. The arrangement of the shells as they touched each other would have accounted for this. Dry density values place the palm kernel shells in the same category as lightweight aggregate.

Figure 17. Palm kernel shells [96]

Table 4. Physical properties of the palm kernel shells [95]

Property	Value
Bulk density Mg/m3	0.74
Dry density Mg/m3	0.65
Void ratio	0.40
Porosity (%)	28
Water content (%)	9
Water absorption (%)	14
Specific gravity	1.62
Impact Value (%)	4.5

3.3.1. APPLICATION IN ROAD CONSTRUCTION

Research has shown that palm kernel shells (PKS) can serve as a viable partial replacement for aggregates in both asphalt and concrete mixtures, offering potential cost savings and promoting the use of agricultural waste. In asphalt concrete, PKS can replace up to 30% of coarse aggregates without significantly compromising strength, though more conservative limits such as 10–20% are recommended for heavily trafficked roads [95], [97]. For medium-traffic roads, replacement levels between 10–30% are feasible, while lightly trafficked or rural roads may tolerate even higher percentages, with some studies supporting up to 100% replacement [98]. In concrete applications, a 25% substitution of granite with PKS yields optimal compressive and tensile strength, while 50% still qualifies as lightweight concrete.

Crushed PKS (CPKS) has also been used to replace up to 20% of fine aggregates in asphalt mixes for high-traffic roads [93]. Additionally, PKS-laterite mixtures have shown promising in sub-base and base layers, particularly for low-cost pavement structures in low-traffic areas [99]. Overall, PKS improves properties such as stability, flow, and structural performance, making it a sustainable material option for diverse traffic conditions in road construction.

3.4. GLASS WASTE

The use of glass waste in road construction has emerged as a promising solution to address environmental challenges, and reduce the demand for virgin materials, thereby preserving natural resources for future generations [31], [100]. Glass waste, which is non-biodegradable, often ends up in landfills, contributing to environmental pollution. Utilizing glass waste in road construction provides an effective way to manage this waste stream, reducing the volume of glass sent to landfills and promoting a circular economy [101], [102]. The incorporation of glass waste in road construction materials, such as concrete and asphalt, has shown to significantly reduce greenhouse gas emissions and energy consumption. Studies have indicated that replacing cement or fine aggregate with recycled glass can lead to an average reduction of up to 19% in greenhouse gas emissions and 17% in energy consumption [103], [104]

Research in Australia explored the use of waste glass in asphalt pavements, with a focus on improving the mechanical properties of the asphalt mixtures. The study found that the incorporation of glass waste enhanced the tensile strength and resistance to permanent deformation of the asphalt mixtures. Furthermore, the use of glass waste was found to reduce the water absorption rate, making the pavements more durable and resistant to degradation[105], [106].

In worldwide contest, with almost 23 mt of waste glass produced yearly, China leads the world in glass trash production; nevertheless, its recycling rate is just about 40%, underscoring the urgent need for better waste management techniques. India (21 mt), the USA (11.4 mt), the UK (2.4 mt), Australia (1.1 mt), and Canada (0.75 mt) are the countries that contribute the most to the generation of waste glass after China. As Figure 18 illustrates, recycling rates in these countries range from 27% in the USA to 57% in Australia. On the other hand, European nations have attained an astounding 80% recycling rate through the use of effective waste collection systems, strict regulations, and active citizen participation [107]

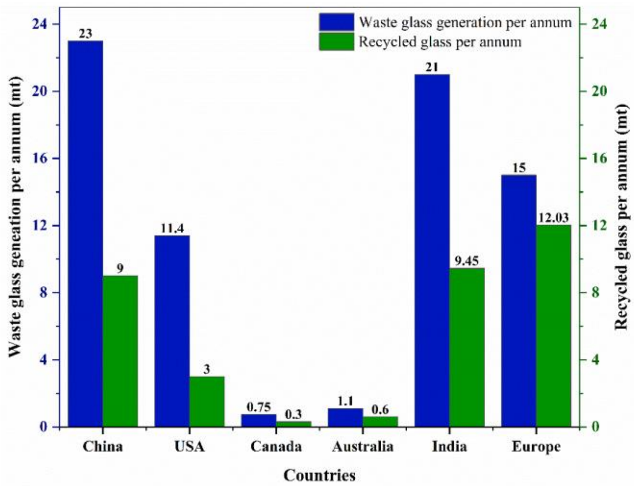


Figure 18. Worldwide waste glass generation [107]

Particles smaller than 10 mm, particularly fine recycled glass (FRG) under 4.75 mm, were the main focus of earlier research on recycled crushed glass (RCG). Based on particle size, RCG is often divided into three groups (see Figure *19*): coarse recycled glass (CRG, up to 19 mm), medium recycled glass (MRG, up to 9.5 mm), and FRG, up to 4.75 mm. Whereas MRG contains both sand- and gravel-sized particles, FRG is primarily composed of sand-sized particles. According to research by Kazmi et al., FRG particles, which range in size from 0.425 mm to 2.36 mm, have a lower roundness index (0.32 vs. 0.55) and are more angular than natural sand, suggesting a higher possibility for interlocking. In building applications, this angularity helps to improve frictional resistance, especially in coarser and well-graded mixes [107].
For its application in road construction, several studies have shown that asphalt mixtures containing, 10% and 20% levels of glass content exhibit satisfactory performance. Glass contents higher than 30% significantly reduce the moisture resistance of asphalt mixtures [108], [109], [110].

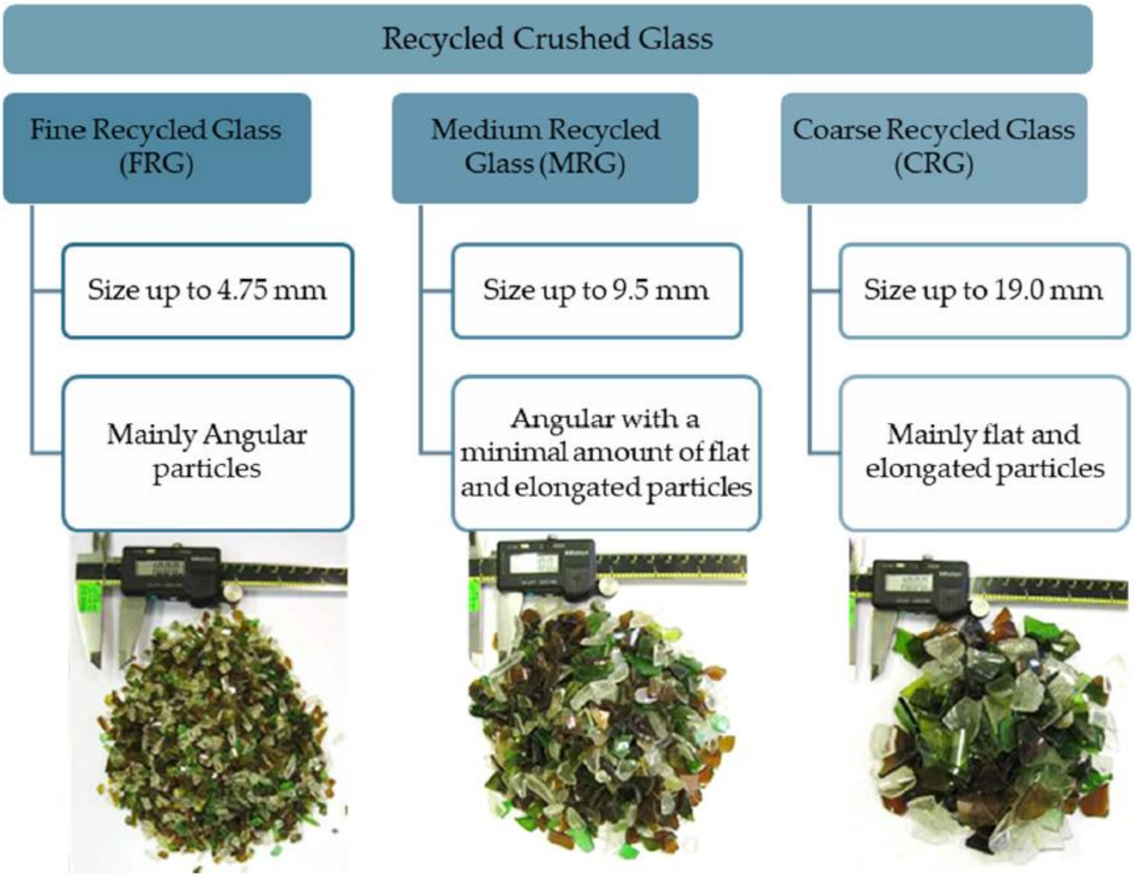


Figure 19. Classification base on the shape [107]

3.4.1. APPLICATION IN ROAD CONSTRUCTION

Glass waste has been studied as a sustainable alternative material in road construction, particularly as a partial replacement for natural aggregates in asphalt mixtures. The incorporation of waste glass addresses two critical issues: reducing the demand for virgin aggregates and diverting significant volumes of glass from landfills. Early research demonstrated that replacing fine aggregates with crushed glass could be technically feasible, although challenges such as stripping and reduced durability were noted [111]. Over the years, advancements in mix design and processing have improved the performance of glass–asphalt mixtures, making their application more viable in practice.

One of the most common applications of glass waste in pavements is in the form of glassphalt, a hot mix asphalt where 10–30% of the fine aggregate fraction is substituted with crushed glass [112]. Several studies have shown that asphalt mixtures containing 10% and 20% of glass content exhibit satisfactory performance. Glass contents higher than 30% significantly reduce the moisture resistance of asphalt mixtures [108], [109], [110]. Studies in Australia, the United States, and Europe have shown that the inclusion of finely ground glass (generally <4.75 mm) improves certain mechanical properties such as tensile strength, stiffness modulus, and rutting resistance, provided that the gradation is well-controlled [113]. Mills-Beale and You (2010)[114] found that asphalt mixtures containing recycled glass exhibited improved tensile strength and deformation resistance, while simultaneously reducing water absorption, which enhanced pavement durability. Similarly, [115] reported that recycled crushed glass provided comparable performance to conventional aggregates in base and sub-base applications, highlighting its suitability for low-volume roads and non-structural pavement layers.

The particle size and content of glass waste play a decisive role in determining the performance of mixtures. [116] demonstrated that finer glass particles, used at replacement levels of up to 15%, enhanced the strength properties of asphalt mixtures, whereas higher proportions or coarser particles could reduce resistance to stripping and moisture damage. For this reason, most researchers recommend limiting the glass content to 10–20% of the aggregate weight in surface and binder courses, while higher contents may be permissible in base layers [117].

Recent innovations have sought to overcome the drawbacks associated with moisture susceptibility and stripping. For example, the addition of anti-stripping agents, hydrated lime, or polymer modifiers has been shown to improve the bonding between glass and bitumen, reducing the risk of premature pavement failure [118]. Furthermore, glass waste has also been studied in combination with other recycled materials. [119] explored its use in asphalt concrete along with crumb rubber and found that the composite mix provided balanced mechanical and environmental benefits, improving both rutting resistance and sustainability outcomes.

4

DEFINITION AND DESCRIPTION OF SELECTED SCENARIOS OF LCA

4.1. LOCATION CHOSEN FOR THE STUDY

The road that is selected is located in the Northern province of Guinea-Bissau, near the Senegal border. This road segment connects rural farming communities with the town of São Domingos, the chosen road is classified as earth road in poor state of conservation[89]. This selection was made based on a combination of geographic, technical, socio-economic, and environmental criteria that align with the objectives of evaluating sustainable road construction practices under realistic conditions. This road is a suitable choice because it has relatively low traffic flow, which makes it a good candidate for the application of alternative materials that may not yet be optimized for high-load or high-speed conditions.

The climate conditions in this area, is a typical tropical savannah climate (Aw) with a wet season from June to October and a dry season from November to May. Annual rainfall goes beyond 1,500 mm, with peak precipitation in August. These conditions subject roads to extreme wet–dry cycles, leading to rapid deterioration if materials are not well adapted. This makes the area pertinent for testing the moisture resistance and durability of innovative materials. Chosen area embodies the structural, climatic, and logistical challenges typical of Guinea-Bissau's rural infrastructure, making it an ideal candidate for demonstrating how sustainable material choices can improve road performance, cost-efficiency, and long-term environmental outcomes.

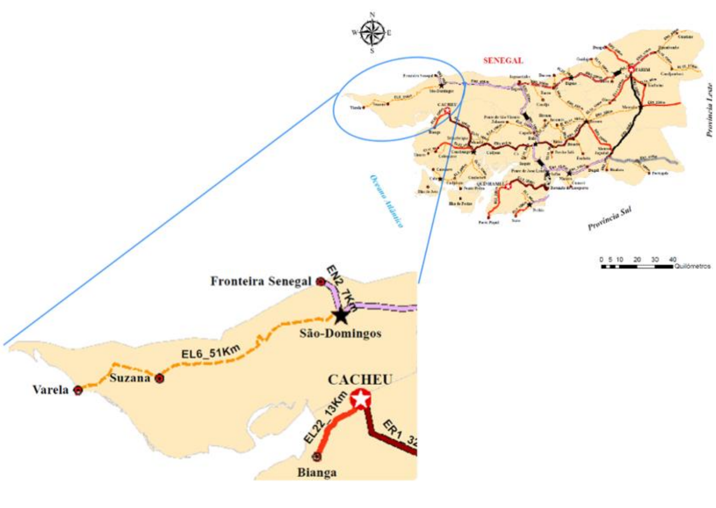
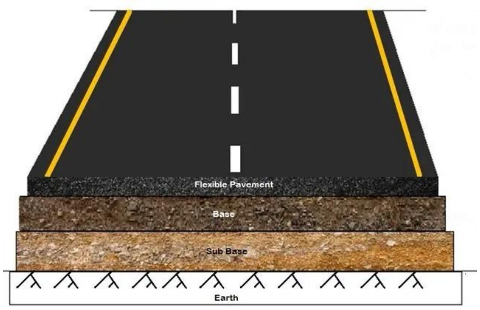


Figure 20. Map of the chosen location for the study [89]

4.2. SCENARIO 1 (REFERENCE SCENARIO)

Scenario 1 serves as the reference design for this study and reflects a conventional approach to flexible pavement construction, particularly suitable for low-volume roads in tropical regions such as Guinea-Bissau. The pavement structure and composition of the wearing course is shown in Figure 21. The structure consists of a 50 mm asphalt surface course, a 200 mm base layer of crushed gravel, a 300 mm sub-base of natural lateritic gravel, and a subgrade composed of in-situ soil with a California Bearing Ratio (CBR) of approximately 5%. This combination of layers represents a balanced strategy in terms of technical performance, material availability, and constructability within the regional context. The overview of this design and detailed information was given in the chapter 2 in the section detailed design.



Layer	Material	Typical Thickness (mm)
Surface course	Hot Mix Asphalt (HMA)	50 mm
Base course	Crushed gravel 85% Lateritic sand 15%	200 mm
Sub-base Course	Lateritic gravel	300 mm
Subgrade	In-situ soil (CBR ~5%)	300 mm

Hot Mix Asphalt

Component	Description	Typical Proportion (by weight of total mix)
Coarse Aggregates	Gravel	50%
Fine Aggregates	Lateritic Sand	35%
Filler	Mineral fines (dust)	10%
Bitumen (Binder)	Asphalt binder (typically 60/70 or 80/100 penetration grade)	5% (of total mix weight)

Figure 21. Scenario 1 design

4.3. SCENARIO 2

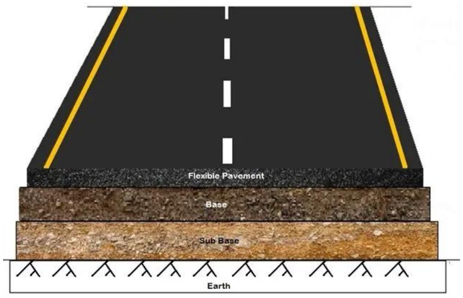
In Scenario 2, in the design (see the Figure 22) the sustainable and alternative materials are implemented particularly in both the sub-base and base layers. The sub-base layer consists of a blend of 75% steel slag and 25% natural lateritic gravel, while the base layer partially replaces conventional crushed gravel with 45% of steel slag and lateritic sand was replaced with 10% of glass waste. In addition, sustainable materials were applied to the asphalt mix as well. These were done to not only enhance mechanical properties and durability of the products but also, to reduce carbon footprint and allow for circularity of materials that are geo-sourced or waste-sourced from the area. For the sub-base, up to 75% steel slag added further enhances load bearing capacities and reduces the need for virgin lateritic gravel. Steel slag has a high CBR value often over 120% in its weathered state while the Los Angeles abrasion value is about 20-25%, which is much lower than many natural aggregates meaning less disintegration under traffic loading [61], [120]. For instance, a country with a tropical climate like Guinea-Bissau will have roads subjected to wetting and drying seasonal stresses, so its low-water absorption value and high angularity of the particles will help them interlock and remain stable over time. The addition of 25% lateritic gravel allows for ease of compaction and local availability, thus providing the best of structural improvement and practical construction efficacy.

The base layer introduces an innovative substitution of 10% crushed glass into the aggregate structure. Glass waste can be crushed to fine or medium aggregate size and used in bound or unbound layers. Its inclusion here aims to reduce the use of natural aggregates, mitigate landfill pressures, and valorise an otherwise non-biodegradable waste stream. [121], [122], [123] show that crushed glass exhibits acceptable particle hardness, contributing positively to load distribution in base layers when used in proportions of up to 30%. However, due to its potential brittleness and lower frictional properties compared to traditional material, it is not recommended as a full replacement. In this scenario, the 10% inclusion ensures that structural strength is maintained while promoting resource efficiency. Glass aggregates, when combined with natural crushed rock have demonstrated resilient modulus values similar to those of 100% natural sand base layers, especially when moisture control is applied [123]

For the asphalt mix, the inclusion of 50% steel slag as a substitute for natural coarse aggregates is supported by extensive research demonstrating its excellent performance characteristics in asphalt mixtures. Steel slag is highly angular, hard, and possesses a rough surface texture, which improves interlocking and adhesion with the bituminous binder. These properties translate to enhanced rutting resistance, skid resistance, and Marshall stability in surface layers. According to [61], dense-graded asphalt mixtures with 40–60% steel slag demonstrated increased stiffness modulus (up to 22%) and deformation resistance (53% improvement in creep modulus) compared to traditional granite or basalt-based mixes. The high density and surface roughness of steel slag particles also contribute to a more durable pavement structure, particularly under warm-climate conditions like those in Guinea-Bissau

Ultimately, incorporating steel slag into the asphalt mixture fosters environmental and economic sustainability. Using a steel-industry by-product to substitute for 50% of the natural aggregates means the design greatly lessens the demand for quarrying, a construction activity often requiring extensive energy expenditure and land disruption. Furthermore, the researchers can source steel slag locally from industrial areas in neighbouring Senegal. In addition, the use of 20% glass powder as a supplementary material creates an even more sustainable and efficient asphalt. Glass powder typically comes from post-consumer or post-industrial glass waste, ground to a powdered form which serves as a mineral filler for improved binder bonding and matrix densification.

Studies have shown that glass powder has latent pozzolanic activity, and when used in asphalt, it can improve void filling, reduce binder aging, and enhance thermal stability. According to [122], [124], asphalt mixes incorporating 10 to 25% glass powder exhibit increased Marshall stability and improved resistance to moisture damage compared to conventional materials.



Layer	Material	Typical Thickness (mm)
Surface course	Hot Mix Asphalt (HMA)	50 mm
Base course	Steel slag 45% Crushed gravel 40% Sand (5% LS, glass powder 10%)	200 mm
Sub-base Course	Steel slag 75% Lateritic gravel 25%	300 mm
Subgrade	In-situ soil (CBR ~5%)	300 mm

Hot Mix Asphalt

Component	Description	Typical Proportion (by weight of total mix)
Coarse Aggregates	Steel slag	50%
Fine Aggregates	Lateritic Sand 15% Glass powder 20%	35%
Filler	Mineral fines (dust)	10%
Bitumen (Binder)	Asphalt binder (typically 60/70 or 80/100 penetration grade)	5% (of total mix weight)

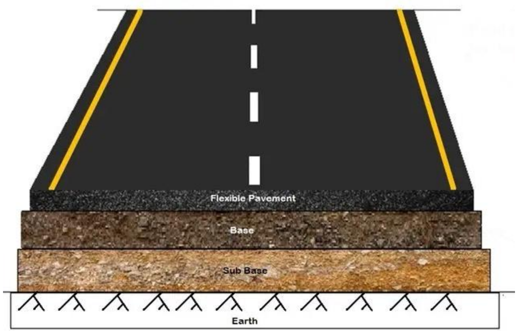
Figure 22. Scenario 2 design

4.4. SCENARIO 3

In this scenario, the aim is to maximize the use of steel slag across both unbound and bound layers, reflecting a full commitment to industrial waste valorisation in pavement construction. The sub-base is made of 75% steel slag and 25% lateritic gravel, the base layer is composed of 75% steel slag, 10% lateritic gravel and 15% lateritic sand, and the asphalt consists of steel slag and gravel for coarse aggregates while lateritic sand and crumb rubber (CR) are utilized for fine aggregates (see the Figure 23). This means an highly engineered solution specifically intended for increased durability, strength, and sustainability such a low-volume road network in Guinea-Bissau would require. Continuing with 100% steel slag for the sub-base layer is based upon the material's superior geotechnical properties. Steel slag typically exhibits CBR values above 120%, a low Los Angeles abrasion loss (20–25%), and high specific gravity (around 3.2), all of which contribute to a highly stable and durable layer. According to [61] slag used in granular layers resists freeze-thaw and wet-dry cycles effectively and requires lower maintenance over time due to its inherent stiffness. In this scenario, the slag is assumed to be pre-aged to mitigate volumetric instability associated with free lime (CaO) and periclase (MgO) reactions known issues that are resolved by stockpiling slag in open-air environments for several months, as recommended by [125].

The percentage of materials in the base course is 75% steel slag, 10% lateritic gravel and 15% lateritic sand due to optimal grading, compaction and workability. Lateritic sand serves to occupy interparticle voids occupied by the maximum particle size distribution of the coarse slag and facilitates compaction characteristics as a result of its smaller particle size and corresponding plasticity. This combination enhances particle interlock and mitigates segregation, improving both shear resistance and load distribution. Literature by [126] supports this hybrid use, showing that partial substitution of slag with fine mineral sands improves the modulus of resilience and tensile strength, particularly under repeated loading.

The asphalt mix in this scenario consist in blending steel slag (20%) and natural gravel (30%) as coarse aggregates, crumb rubber (4%) and lateritic sand (31%) as fine aggregates, along with 10% mineral filler and 5% binder. The use of steel slag as a coarse aggregate in asphalt has been proven effective in enhancing skid resistance and stiffness, and other property as listed before in the previous scenario. With studies showing improved Marshall stability and rutting resistance compared to granite or basalt-based mixes [127]. The rubber would be blended with the asphalt mixture to ensure high structural integrity and flexibility. For instance, crumb rubber increases fatigue life, thermal resilience, and sound absorption. The latter is particularly important in Guinea-Bissau, where high temperatures exist, and pavement needs to be quite flexible. Thus, 4 % rubber (rubber as part of the fine fraction) by total mixture weight. In addition, rubber serves to absorb bitumen and expand during mixing, which reduces binder bleed and promotes bonding. This allows for a higher binder content without bleeding. When used alongside lateritic sand a naturally available, low-cost aggregate, the mix becomes both functionally robust and economically viable.



Layer	Material	Typical Thickness (mm)
Surface course	Hot Mix Asphalt (HMA)	50 mm
Base course	Steel Slag 75% Lateriic gravel 10% Lateritic sand 15%	200 mm
Sub-base Course	Steel Slag 75% Lateritic gravel 25%	300 mm
Sub-grade	In-situ soil (CBR ~5%)	300 mm

Hot Mix Asphalt

Component	Description	Typical Proportion (by weight of total mix)
Coarse Aggregates	SS 20% gravel 30%	50%
Fine Aggregates	CR 4% of total mix weight Lateritic Sand 31%	35%
Filler	Mineral fines (dust)	10%
Bitumen (Binder)	Asphalt binder (typically 60/70 or 80/100 penetration grade)	5% (of total mix weight)

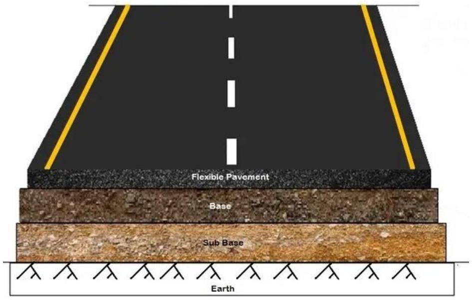
Figure 23. Scenario 3 design

4.5. SCENARIO 4

In scenario 4 some of the sustainable materials chosen in Chapter 3 were brought into the mix. For the sub-base layer, it was 100% Palm Kernel Shells (PKS) which is a lightweight, locally sourced sustainable additive. For the base layer, PKS and lateritic sand were similarly applied to create structural stability with a lower carbon footprint. For the surface course, however, the initial design and material percentages changed. The composite was PKS (30%) coarse aggregate, gravel (20%), lateritic sand (35%) fine aggregates. Bitumen (5%) and filler (10%) were equivalent to scenario 1 (see Figure 24) in order to ensure proper bonding and composite integrity. The hot mix asphalt was consistent with this design. This design is the least typical for aggregate use as Palm Kernel Shells (PKS) is the predominant ingredient for the base and sub-base layers as well as a component in the asphalt composite. For the base layer, it is 85% PKS and 15% lateritic sand; for the sub-base, it is 100% PKS. In addition, PKS is accounted for as the coarse aggregate (30%) in hot mix asphalt with 20% gravel. This design reflects a movement towards fully renewable, locally sourced materials from Guinea-Bissau. The country has a significant amount of agricultural biomass waste, and after palm oil processing, the Palm Kernel Shells are often disposed of; therefore, using it as a lightweight, angular, carbon-reducing material is in full contrast to typical stone aggregates. The reasoning for integrating PKS into the sub-base and base layers comes from increasingly published studies on its viability for low-volume roads [93], [128], [129]. PKS is hard and durable; its rough characteristics provide solid geometrically angular edges that render good interlocking and load transfer if sufficiently compacted. While it does possess a lower specific gravity than natural aggregates, findings on its California Bearing Ratio (CBR) varies between 25-35% depending on compaction and gradation[129], [130]. This supports its structural viability most effectively for low-volume roads in tropical climates where axle loads are on the low side and environmental conditions necessitate flexibility, moisture-resistance properties. Furthermore, to ensure better workability and proper gradation, the base layer contains PKS with 15% lateritic sand which is a known filler material across West Africa. This aids in packing density and reduction of internal voids which leads to improved stiffness and reduced permanent deformation under vehicular loading for better service life. Lateritic sand masks the lightweight quality of PKS, while simultaneously aiding achieving proper compaction to avoid floatation or movement due to saturation during the wet season. Composite test sections in Nigeria and Ghana showed that the modulus of subgrade reaction value of PKS-laterite composites was comparable to that of crushed stone-laterite composites [131]. Economically, this was valuable: PKS is often seen as agricultural waste, normally used for fuel or burning and can be found throughout Guinea-Bissau, especially within Bafatá, Quinara, and Tombali areas where Palm Oil is harvested; thus, it is abundantly available for minimally priced or logistics savings purposes as communities adhere to circular economies. In the asphalt mixture, the percentage of aggregate content of PKS equals 30% with additional gravel accounting for 20% coarse aggregate, while lateritic sand (fine) equals 35% with 10% mineral filler and 5% bitumen retained for consistency.

The adoption of PKS in asphalt paving is relatively new but gaining traction. PKS aggregates, when properly graded and pretreated, provide sufficient hardness for surface course applications. Though lighter than stone, their high silica and lignin content contributes to mechanical durability. Studies by [128], [132] demonstrated that HMA mixes incorporating up to 40% PKS as coarse aggregate can achieve Marshall stability values above 8.0 kN, which meets the requirements for light to medium traffic loads. These mixes also showed improved skid resistance and acceptable flow values, while reducing unit weight and material cost.

While PKS does not yet appear in commercial LCA databases like Ecoinvent, emerging life cycle studies indicate that replacing even 30–40% of conventional aggregates with PKS can cut GHG emissions by up to 40% for the aggregate component, depending on transport distances and binder use [133]



Layer	Material	Typical Thickness (mm)
Surface course	Hot Mix Asphalt (HMA)	50 mm
Base course	PKS 85% Lateritic sand 15%	200 mm
Sub-base Course	PKS	300 mm
Subgrade	In-situ soil (CBR ~5%)	300 mm

Hot Mix Asphalt

Component	Description	Typical Proportion (by weight of total mix)
Coarse Aggregates	Gravel 20% PKS 30%	50%
Fine Aggregates	Lateritic Sand 35%	35%
Filler	Mineral fines (dust)	10%
Bitumen (Binder)	Asphalt binder (typically 60/70 or 80/100 penetration grade)	5% (of total mix weight)

Figure 24. Scenario 4 design

5

LIFE CYCLE ASSESSMENT OF SELECTED SCENARIOS

5.1. INTRODUCTION

Life cycle assessment is a standard method which takes into account all environmental aspects of the product life cycle (emissions into air, water and soil, waste, use of raw material and exploitation of nature) [134]. It is considered as the most recognized and globally accepted method for evaluating and comparing the environmental impacts of processes and assessing their sustainability from 'cradle to grave'. All resource consumptions and pollutant emissions related to the life cycle of process phases are included in the life cycle assessment, such as raw materials extraction and processing, chemical manufacturing, and transport, in addition to final disposal and recycling[135]. This comprehensive approach avoids the misallocation of environmental effects and provides an overview for possible impact reductions. The LCA method is described in the international standards ISO 14040 (ISO14040, 2006) and 14044 (ISO 14044, 2006).

In the context of this study, LCA is used to compare conventional and sustainable pavement materials. Common tools used in LCA include OpenLCA, SimaPro, and GaBi, supported by databases such as Ecoinvent or the African LCA Database. These platforms facilitate the integration of global and regional data for modelling. Despite its comprehensiveness, LCA is not without challenges. In countries like Guinea-Bissau, limitations include the lack of local data, the need for assumptions in inventory modelling, and the variability in construction practices. However, when applied carefully, LCA becomes a powerful tool for advancing sustainable infrastructure development by promoting informed and context-relevant material choices.

5.2. GOAL AND SCOPE

The goal is to compare the life cycle environmental impact of using sustainable versus conventional materials in a road pavement, for the construction of a 1 km stretch of low volume road flexible pavement in the rural area of the city of Sao-Domingos, in Guinea-Bissau.

5.2.1. FUNCTIONAL UNIT

The functional unit will be 1 km of a two-lane (8 m) rural road with pavement thickness of 85 cm. The pavement structure was calculated based on the type of soil in Guinea-Bissau and the traffic volume in the area, for which a maximum of 100 vehicles per day has been considered. The study will consider 10-15-year of design life. On this study it will be considered 4 different scenarios, each one will be designed in a different way, one with conventional materials and the three others with more sustainable materials. As it is shown in chapter 4 in section scenario 1 (reference scenario), in Figure 21, the asphalt layer thickness is 50 mm, base course 200 mm sub-base course 300 mm and subgrade soil 300 mm. In this study, all the layers will be considered except the subgrade soil, as no especial work has to be done with it. Finally, all the energy consumption, material and emissions will be measured based on this functional unit. The system boundary will follow a "cradle-to-gate" approach, including raw material extraction, transport, and construction.

5.2.2. SYSTEM BOUNDARIES

The system boundary defines the processes and life cycle stages considered in this Life Cycle Assessment (LCA). For this study, a "cradle-to-practical completion" approach is adopted, which includes all activities from raw material extraction to on-site road construction (A1 to A5), as seen in Figure 11 in chapter 2 in section life cycle assessment. It excludes the use phase (e.g., vehicle operation, road maintenance) and end-of-life phase (e.g., demolition, recycling, or disposal of pavement materials). This focus is consistent with the primary goal of comparing the environmental impacts of conventional and alternative material choices during the construction stage of low-volume rural roads. The Figure 25 shows the different unit processes within the system boundary, with main inputs being energy, materials and water and the main outputs being emissions to air, emissions to soil, emissions to water and waste.

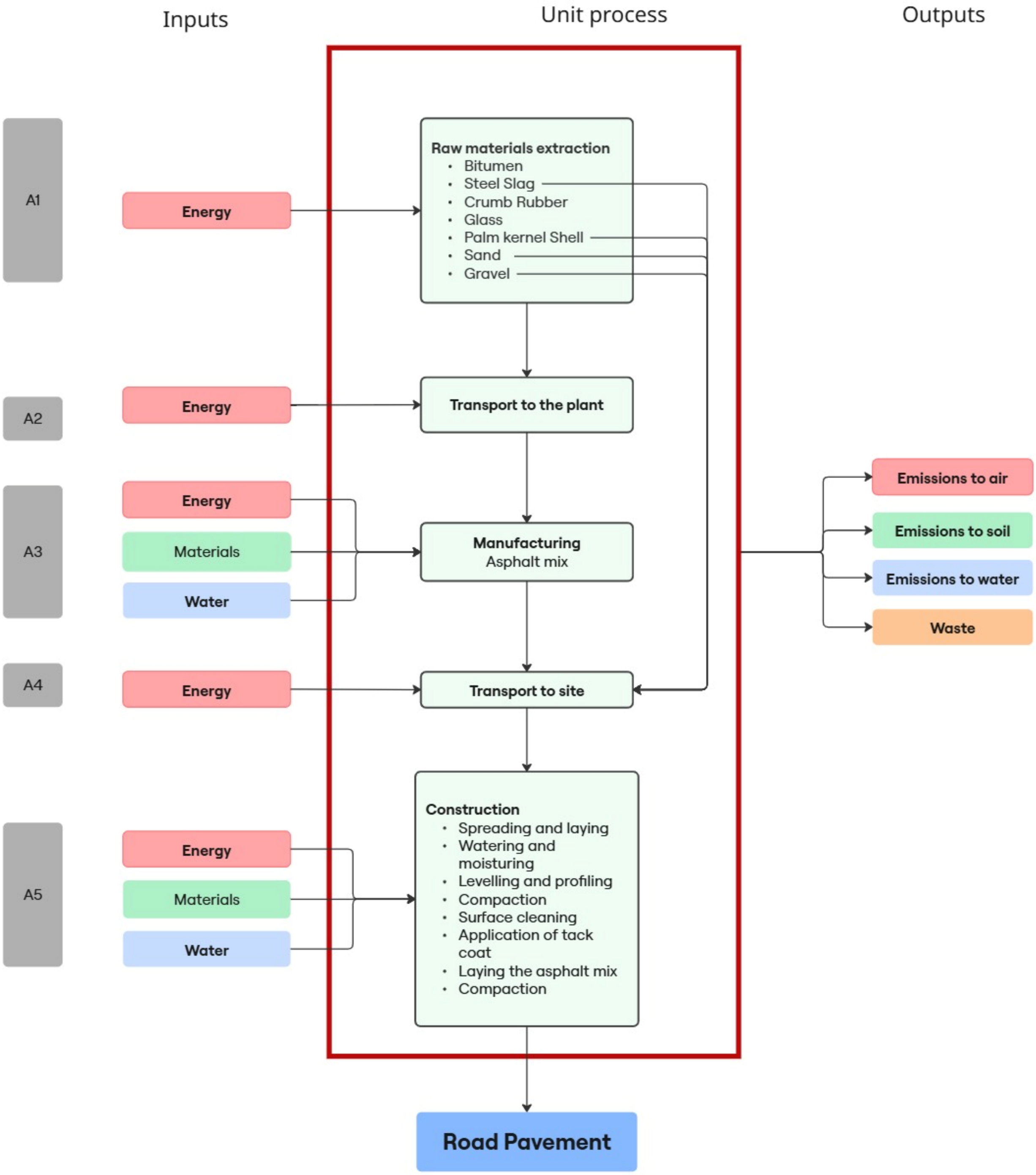


Figure 25. System modelling for road pavement construction

The following table (Table 5) presents the different materials existing in each pavement layer in the 4 scenarios to which LCA is going to be applied.

Table 5. Materials existing in each pavement layer of the 4 scenarios

Layer	Scenario 1 (reference)	Scenario 2	Scenario 3	Scenario 4
Asphalt (surface) layer	- Bitumen - Lateritic gravel - Lateritic sand - Filler	- Bitumen - Steel slag - Lateritic sand - Glass powder - filler	- Bitumen - Steel slag - Lateritic gravel - Crumb rubber - Lateritic sand - filler	- Bitumen - Palm kernel shells - Lateritic gravel - Lateritic sand - Filler
Base layer	- Lateritic gravel - Lateritic sand	- Steel slag - Lateritic gravel - Lateritic sand - Glass powder	- Steel slag - Lateritic sand	- Palm kernel shells - Lateritic sand
Sub-base layer	- Lateritic gravel	- Steel slag - Lateritic gravel	- Steel slag	- Palm kernel shells

A1: Raw material extraction

The life cycle of pavement construction starts with the extraction of raw materials. With 3 layer that are being considered for the study, the material extraction includes natural or secondary (for instance steel slag, glass, sand, crumb rubber, PKS and gravel), filler, and asphalt binder (bitumen). Throughout this stage, the environmental impacts are linked to emissions from crushing, screening, and mining operations for some aggregates.

A2: Transportation to the asphalt plant

The asphalt plant is located 3 km away from the construction site, the bitumen and steel slag would be imported from Senegal-Dakar, which is approximately 450 km to the asphalt plant, Virgin aggregates (sand and gravel) will be extracted from a quarry in Nhakra, that is located 124 km away from asphalt plant, crumb rubber transported 111 km to asphalt plant, Glass is hauled from Ziguinchor, which is 23 km away. Finally, the PKS is transported from Bissau with a distance of 123 km to the plant. On this stage, the environmental impacts are linked to the consumption of the fuel in the transportation (energy). The raw materials are delivered by heavy trucks to the asphalt plant.

A3: Asphalt mixture manufacturing

At the asphalt, the bitumen is heated; whilst the aggregates are dried and screened. Throughout this stage, the environmental impacts are linked to emissions diesel, gasoil and the electricity consumed by machinery in the drying, screening, heating and mixing processes.

A4: Transportation to the construction site

After the raw materials production stage, these materials are transported to the asphalt mixing plant (A2). Furthermore, after asphalt mixture manufacturing, the hot mix asphalt is loaded and transported via road to the construction site. The materials that are used in base and sub-base layer like virgin aggregates (sand and gravel), steel slags, PKS and glass waste, are transported directly from the source to the construction site. Throughout this stage, the environmental impacts are linked to the consumption of fuel and emissions from the heavy trucks.

A5: Road construction

The road construction comprises numerous processes such as cleaning of site, excavation, subgrade compaction and sub-base and base layer construction, paving of asphalt mixture, as well as the use of different types of paving machinery required to construct the pavement. For this study, only the sub-base, base and surface (asphalt) layers are considered. Throughout this stage, the environmental impacts are associated with diesel consumed by construction machinery: bulldozers or motor graders for levelling and compaction of granular sub-base and base layers, and road pavers and compactors for the surface layers. The emissions in this phase generally came from the diesel combustion (Energy), water and materials usage and some pollutants directly emitted during the construction of the different layers.

5.2.3. ASSUMPTIONS AND LIMITATIONS

Performing an LCA study relies on the accessibility of data and the methodology employed in the study. It is crucial to evaluate the availability of data, the time required to complete the study, and the financial resources needed in relation to the quality of the final outcomes based on the primary objectives of the project. The current study has been conducted with the following assumptions:

A1 to A3: Product Stage

- The bitumen used for this analysis is imported from Senegal, with the penetration grade of 80/100.
- Lateritic soil for fine aggregate extracted from a quarry in Safim.
- For Palm Karnel shell, as it is an agricultural waste, it is considered burden free (A1).
- The environmental impacts related to the construction or assembly of the asphalt plant, the associated machineries and electric installation are neglected. This study only considered the impacts of the asphalt mixture manufacturing process.
- The material used for asphalt mix manufacturing is in different places consequently different distances:
  - The transport distance to consider for steel slag and bitumen is 432 km.
  - The natural aggregate is extracted from the quarry located 124 km away.
  - Crushed Glasses are imported from Senegal with 23 km to the plant
  - Crumb Rubber required for asphalt mix is located 111 km and PKS 123 km away.
  - Water is provided by 20000 Liters Truck with 20 km to the water source.
- Materials are transported in trucks with transport capacity of 16 to 32 tons.
- Energy used in the asphalt plant are mostly Electricity, Diesel and Gasoil.

A4 to A5 Construction Stage

- For transportation to site, the asphalt plant is located 3 km away from the site. This study will be analysing the construction from the sub-base layer, so the work behind were overlooked. Some materials are directly transported from the source to the site, for these materials will be added 3 km in transportation.

- The environmental impacts associated with the loading of raw materials into trucks were overlooked. The environmental impacts linked to the transportation stage were considered for only a one-way trip or to way distance of raw materials to the asphalt plant, and the produced asphalt mixtures to the construction site. The return trips of empty trucks were neglected.
- The environmental impact associated with the opening of quarry were neglected.

5.2.4. DATA QUALITY REQUIREMENTS

Data classification and collection are among the most time-consuming and labour-intensive phases in a life cycle assessment (LCA) study, as they require numerous data points related to a wide variety of processes. The reliability of LCA outcomes is closely associated with the quality of the data used during the inventory phase. Life cycle inventories rely on data obtained from literature, databases, pilot studies, and laboratory experiments. This data must be adjusted to fit the specific boundaries of the current Life Cycle Assessment (LCA) study. In cases where appropriate data is unavailable, well-informed assumptions should be made to facilitate a consistent inventory analysis. Evaluating data quality in an LCA study is crucial for accurate representation, as well as for the precision and significance of its findings[136]. Generally, the Ecoinvent database, developed by the Swiss Center for a Life Cycle Inventory, was used in this study to evaluate the environmental burdens of most systems or phases. Some inputs, for instance, materials characterization, were taken from similar studies, LCA articles, and other sources.

5.3. LIFE CYCLE INVENTORY

This section provides a comprehensive characterization of the input data used in the life cycle inventory for designing the system components across different alternatives. It also details the main design parameters and material mass balances involved in the production processes of asphalt mixtures and the construction of the road. Additionally, the Ecoinvent database V3.6 supplies LCI data related to resource extraction, material and energy supply, and transportation within these processes (see *Table 6*). The entire analysis is conducted using SimaPro software V9.1 to assess the environmental impacts and burdens associated with each alternative.

Table 6.Inventory materials from ecoinvent database and EF database 3.1

Materials	Processes	Reference
Bitumen	Bitumen at refinery {CN} from crude oil | production mix, at refinery |38.7 MJ/kg net calorific value|	EF database
Lateritic sand	Sand {RoW} gravel and quarry operation | cut-off, U	ecoinvent
Lateritic gravel	Sand {RoW} gravel and quarry operation | cut-off, U	ecoinvent
Lime filler	Lime {RER} market for lime | cut-off, U	ecoinvent
Steel slag	Slag, basic oxygen furnace, at plant | Cut-off, U"	ecoinvent

Table 7.The main activity and machinery for the low-volume road construction

Activity	Machinery
The supply and implementation of the sub-base layer - Transportation of the aggregates for sub-base - Spreading and laying sub-base material - Watering and moisture conditioning - Levelling and profiling - Compaction	Dozers Dumpe trucks Tanker truck Motor graders Roller compactors
The supply and implementation of the sub-base layer - Transportation of the aggregates for sub-base - Spreading and laying sub-base material - Watering and moisture conditioning - Levelling and profiling - Compaction	
Surface Course - Surface cleaning - Application of tack coat - Transportation of mix asphalt - Laying the asphalt mix - Compaction	Sweepers or blowers Tack coat spreader Trucks Pavers Tandem compactors Pneumatic rollers
Asphalt mix production	Asphalt plant

5.3.1. CALCULATION OF THE VOLUME AND WEIGHT OF RESPECTIVE SCENARIOS

For the calculation of the volume and weight of materials in each scenario, it was considered 1 km road length, 8 meters width, and a total of 55 cm height, whereas the sub-base layer is 30 cm thick, the base layer is 20 cm thick, and the surface layer is 5 cm thick. The respective volume and weight of each material and each layer are shown in Table 8 to Table 11. Figure 26 is a representation of the road section with the dimensions for the study.

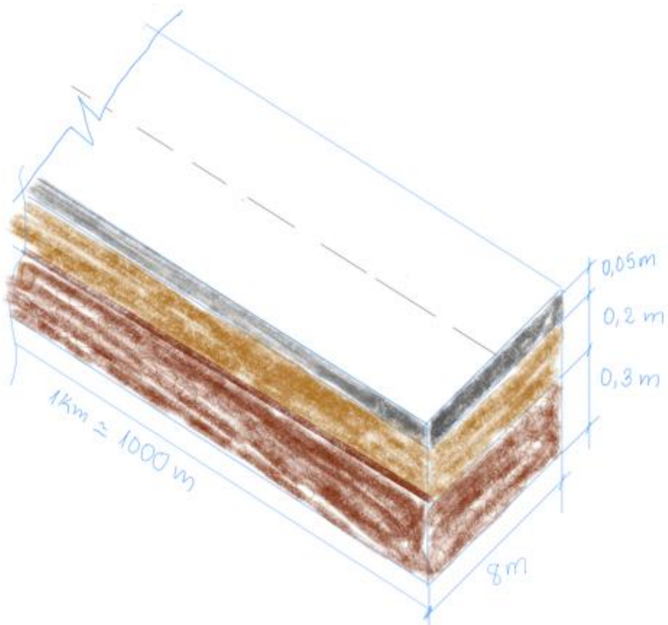


Figure 26. Road section

The densities of the materials for all scenarios have been taken from different papers with similar studies. The volume needed for 1 km road for each layer are:

- Surface layer – 400
- Base layer – 1600
- Sub-base layer – 2400

With the volume of each layer and the percentage, density of each material the calculation was made to obtain the quantity of the materials needed. This calculation was represented on the tables of each scenario.

For the conventional surfacing the application of a tack coat on a 1 km stretches of road with an 8 m width, approximately 2,400 L of bituminous emulsion are typically required. This estimation is based on a standard application rate of 0.3 L.

5.3.1.1. Scenario 1 (reference scenario)

For this study, low-volume road construction is divided into different stages, each carried out at different times. The construction work considered in this study began with the sub-base layer, followed by the subsequent layers. The necessary operations with all materials and machines were modelled for each layer. The sub-base layer in this conventional scenario was filled with lateritic gravel , the base on the other hand was modelled with a mixture of lateritic gravel and lateritic sand, and the surface course was conceived with a simple design, which is been used in Guinea-Bissau for low volume traffic roads, consisting of a mix of 50% gravel, 35% lateritic sand, 10% filler and 5% Bituminous binder in the hot mix asphalt.

Table 8. Calculation of the quantity of material for scenario 1

Input of materials						
Layers	Materials		Percentage	Volume	Density (t/	Weight (t)
Surface course	Bitumen		5	36.44	1.02	37.17
	Coarse aggregate	Lateritic gravel	50	195.64	1.90	371.70
	Fine aggregate	Lateritic sand	35	136.95	1.90	260.19
		Filler	10	30.98	2.40	74.34
Base course	Crushed lateritic gravel		85	1360	1.90	2584.0
	Lateritic sand		15	240	1.90	456.0
Sub-base course	Lateritic gravel		100	2400	1.90	4560.0

5.3.1.2. Scenario 2

In scenario 2, some sustainable material that were selected in the chapter 3 were included in the design. The sub-base layer in this scenario was filled with a combination of steel slag and lateritic gravel, the base in the other hand was modelled with a mixture of crushed gravel, steel slag, glass powder and lateritic sand. For the surface course in this scenario the design and material has changed and the proportion as well change to fulfil the requirement that each material has. For the asphalt mixture 50% of steel slag was used for the coarse aggregate, 15% lateritic sand and 20% glass powder were used as a fine aggregate, filler and Bitumen remind the same quantity as in the scenario 1, which is 10% and 5% respectively, also hot mix asphalt.

The respective volume and weight of each material and each layer are calculated in the Table 9

Table 9. Calculation of the material needed and their respective volume for scenario 2

Input of materials						
Layers	Materials		Percentage	Volume	Density (t/	Weight (t)
Surface course	Bitumen		5	44.02	1.02	44.90
	Coarse aggregate	Steel slag	50	172.68	2.60	448.97
	Fine aggregate	Lateritic sand	15	70.89	1.90	134.69
		Glass powder	20	74.83	2.40	179.56
		filler	10	37.41	2.40	89.79
Base course	Steel slag		45	613.63	2.60	1594.44
	Crushed Lateritic gravel		40	745.93	1.90	1417.28
	Lateritic sand		5	93.24	1.90	177.16
	Glass powder		10	147.63	2.40	354.32
Sub-base course	Steel slag		75	1648.3	2.60	4285.6
	Lateritic gravel		25	751.8	1.90	1428.5

5.3.1.3. Scenario 3

In scenario 3, a different combination of sustainable and conventional materials was incorporated into the road design. The sub-base layer is composed with 75% of steel slag and 25% of lateritic gravel. The base course blends 75% of steel slag, 10% lateritic gravel, and 15% lateritic sand. For the surface course, a diversified mix was selected to enhance sustainability and performance. 20% of SS and 30% of gravel were used as a coarse aggregate, for the fine aggregates, 4 % of Crumb rubber, was used to partially replacement, 31% of lateritic sand. The filler 10% and bitumen 5% were maintained at the same proportion as Scenario 1 to ensure binding and stability. Table 10 summarises the exact volume and mass requirements for each material used in all three layers of the pavement design.

Table 10. Calculation of the material needed and the respective volume for scenario 3

Input of materials						
Layers	Materials		Percentage	Volume	Density (t/	Weight (t)
Surface course	Bitumen		5	34.93	1.02	35.63
	Coarse aggregate	Steel slag	20	54.81	2.60	142.50
		Lateritic gravel	30	112.50	1.90	213.76
	Fine aggregate	Crumb rubber	4	24.78	1.15	28.50
		Lateritic sand	31	116.25	1.90	220.88
		filler	10	29.69	2.40	71.25
Base course	Steel slag		75	1160.03	2.60	3016.08
	Lateritic gravel		10	176.38	1.90	335.12
	Lateritic sand		15	311.3	1.90	591.40
Sub-base course	Steel slag		75	1800	2.60	4680.00
	Lateritic gravel		25	821.05	1.90	1560.00

5.3.1.4. Scenario 4

In the scenario, the PKS was added in every layer, the aim is to maximise the use of biowaste materials in this design, to create a low-carbon and resource-efficient road structure. The sub-base, is constructed primarily using PKS, replacing traditional aggregates entirely. The base course was filled with a mix of 85% of PKS and 15% of lateritic sand, and finally for surface course, the asphalt mixture contains 20% gravel and 30% PKS for the coarse aggregate, 35% lateritic sand for fine aggregate, filler and Bitumen remind the same quantity as in the scenario 1, which is 10% and 5% respectively, also hot mix asphalt. Based on this, the calculation of volume and weight of each material in each layer was made, and it is represented in the Table 11.

Table 11. Calculation of the material needed and their respective volume for scenario 4

Input of materials						
Layers	Materials		Percentage	Volume	Density (t/	Weight (t)
Surface course	Bitumen		5	27.47	1.02	28.02
	Coarse aggregate	Palm kernel shells	30	186.82	0.90	168.14
		Lateritic gravel	20	59.00	1.90	112.09
	Fine aggregate	Lateritic Sand	35	103.24	1.90	196.16
		Filler	10	23.35	2.40	56.05
5Base course	Palm kernel shells		85	1477.7	0.90	1329.90
	Lateritic sand		15	123.40	1.90	234.50
Sub-base course	Palm kernel shells		100	2400	0.90	2160.0

5.3.2. ENERGY AND FUEL CONSUMPTION

The energy and fuel consumption for various manufacturing, production, construction and site activities were obtained from second-hand sources, such as suppliers' technical sheets of equipment and other research studies. The following Table 12 and Table 13 present the energy and fuel consumption rates for the corresponding activities. The rate represents the energy required to process one ton.

There is no official or publicly documented standard specifying a particular type of asphalt plant or combustion system that is exclusively used in Guinea-Bissau. However, based on infrastructure development patterns, resource availability, and practices in similar West African contexts mobile batch-type asphalt plants, or Drum-mix plants, are the most common plants, usually brought in temporarily by foreign contractors for specific road projects. Most mobile and small-to-medium asphalt plants in West Africa, including Guinea-Bissau, use diesel or heavy fuel oil (HFO) for combustion [137], [138], [139]. For Batch Plant (Diesel-Fired), according to [140], [141], the energy consumption is around 250 to 300 MJ per tonne of asphalt produced, which corresponds approximately to 6.5 to 8 liters of diesel per tonne. Drum-Mix Plant (Diesel-Fired) in the other hand Energy consumption is around 200 to 250 MJ/tonne diesel, which corresponds to 5 to 6.5 litres per tonne[142]. And the electricity consumption is around 50.4 MJ/t.

For this study it will be considered a batch plant, as the asphalt plant for the project with an energy consumption of 250MJ/t.

Table 12. Energy consumption for asphalt production at plant

Activity	Rate	Unit	Reference
Asphalt production at plant (Diesel-Fired)	275	MJ/t	[137], [142]
Electricity	50.4	MJ/t	[137], [138]

Table 13. Energy consumption for site activities

Activities	MJ/t	Reference
Spreading and laying sub-base material	15.1	[143], [144]
Watering and moisture conditioning	6.5	[143], [145]
Levelling and profiling	8.6	[143], [146]
Compaction	19.6	[144], [147]
Spreading and laying base material	15.1	[144], [145]
Watering and moisture conditioning	6.5	[143], [145]
Levelling and profiling	8.6	[143], [147]
Compaction	19.6	[144], [147]
Surface cleaning	6.5	[146]
Application of tack coat	0.9	[146]
Laying the asphalt mix	34.4	[141]
Compaction	25.8	[141], [147]

For the materials that have not been found in the ecoinvent database, the data has been collected from different sources for their process creation, and the data needed are mostly electrivity and fuel consumption. The recycle glass process consist in washing the impurities and crushing. For this process the sources needed include Electricity, diesel consumption, and water usage. For the crumb rubber, it will be considered the electricity. Palm kernel shells as it is coming from agricultural waste the environmental impact linked to its production is not taken into account. In Table 14 it can be found the inventory of the materials from literature.

Table 14. Inventory materials from literature

Material	Resources	Consumption for 1 kg of material	Reference
Recycle glass aggregate	Diesel	0.01 MJ	[148]
	Electricity	0.15 MJ	
Crumb rubber	Electricity	0.18 MJ	[149], [150]
Palm kernel shell	-	-	-

5.3.3. TRANSPORT DISTANCE

Long-distance of transport consumes diesel through the use of dump trucks, the materials were collected from different region, in some case like steel slag were collected from different country. The transportation route of the raw materials were recorded using Google Earth (see Figure 27 and Figure 28. Trucks with transport capacity of 16- to 32-ton are used for transportation operations. The materials were transported from the material banks to the production plants and the site, and from the production plants to the site. Find in Table *15* the inventory transportation from ecoinvent database and Table *16* lists the distances considered for each of the suppliers.

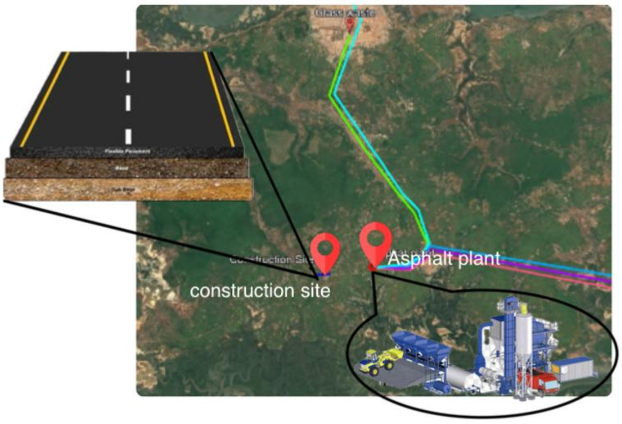


Figure 27. Location of construction site and asphalt plant

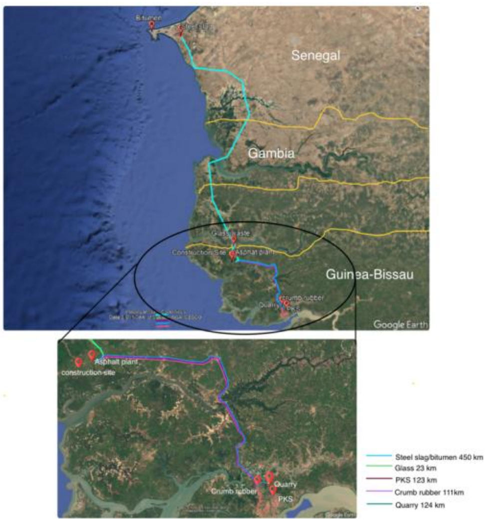


Figure 28.Road and materials source location

Table 15.Inventory transportation from ecoinvent database

Type	Process	Reference
Transport	Transport, freight, lorry 16-32 metric ton, euro3 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, U	ecoinvent

Table 16. Transport distance

Travel distances for each material		
Bitumen to asphalt plant	450	km
Steel slag to asphalt plant	450	km
Quarry to asphalt plant	124	Km
Glass to asphalt plant	23	Km
Crumb rubber to asphalt plant	111	Km
Palm kernel shells to asphalt plant	123	km
Asphalt mix to the site	3	Km
Water source to the site	20	km
Quarry to the site (material for base and sub-base)	114	km

5.4. LIFE CYCLE IMPACT ASSESSMENT

The environmental assessment was carried out using SimaPro software with the Ecoinvent and EF 3.1 databases for the life cycle inventory (LCI) components.

The LCIA phase simplifies the detailed input and output flows from the LCI into a set of impact category indicators, each highlighting a specific environmental issue. Among various assessment methods, ReCipe uses 18 midpoint indicators to address multiple environmental concerns. These midpoints track the cause–and–effect chain, starting with input/output flows and leading to impacts on human health, ecosystems, and resource availability. In this study, ReCipe 2016 Midpoint (E) V1.08 / World (2010) indicators were used to compare solutions with SimaPro 9.5® software.[151]. The LCI phase establishes the basis for this assessment by measuring all relevant environmental flows, including raw material extraction, energy consumption, air and water emissions, and waste throughout the road construction lifecycle. While it offers detailed data on quantities and energy inputs, it does not directly address the potential environmental impacts. This is where the LCIA phase becomes crucial, as it transforms raw data into impact indicators, allowing for scenario comparisons and emphasizing the environmental effects of various road material and design choices.

The major aim of this study is to compare the potential environmental impacts of the studied scenarios in order to identify the road design alternative with the lowest overall impact on the environment. The selected impact categories, presented in Table 17, form the baseline indicators used in the Life Cycle Impact Assessment (LCIA). A subset of key ReCiPe 2016 Midpoint indicators was chosen, as they capture some of the most pressing environmental concerns related to road construction, including climate change, air quality degradation, water ecosystem damage, and resource depletion [151]. These include Global Warming (GWP, kg CO_2-eq), Fine Particulate Matter Formation (PMF, kg PM_2.5-eq), Marine Ecotoxicity (METP, kg 1,4-DCB-eq), Human Carcinogenic Toxicity (HCTP, kg 1,4-DCB-eq), Fossil Resource Scarcity (FRS, kg oil-eq), and Water Consumption (WC, m^3).

- Global Warming Potential (GWP, kg CO_2-eq): Represents the potential contribution of greenhouse gas emissions (such as CO_2, CH_4, N_2O) to climate change over a set time horizon, expressed relative to carbon dioxide. Associated impacts include rising sea levels, severe weather events, and biodiversity loss.

- Fine Particulate Matter Formation (PMF, kg $PM_2.5$-eq): Accounts for emissions of fine particles and precursors (SO_2, NOx, NH_3) that contribute to $PM_2.5$ formation. These particles are strongly linked to respiratory and cardiovascular diseases, reduced life expectancy, and premature deaths.
- Marine Ecotoxicity (METP, kg 1,4-DCB-eq): Estimates the potential toxic effects of chemical emissions on marine ecosystems, expressed in 1,4-dichlorobenzene equivalents. It highlights risks of species decline, bioaccumulation, and disruption of marine food chains.
- Human Carcinogenic Toxicity (HCTP, kg 1,4-DCB-eq): Reflects the potential health impacts of carcinogenic chemical emissions on humans through inhalation, ingestion, or dermal contact. Expressed in 1,4-dichlorobenzene equivalents, it links emissions to long-term cancer risks.
- Fossil Resource Scarcity (FRS, kg oil-eq): Measures the depletion of fossil resources such as oil, coal, and natural gas, expressed in kilograms of oil equivalent. It indicates future extraction costs and challenges related to long-term resource availability.
- Water Consumption (WC, m^3), represents the net freshwater use of a system, expressed in cubic meters. It highlights potential impacts on water scarcity, agriculture, and ecosystem integrity, particularly in water-stressed regions

Table 17. impact categories and method of assessment

Impact categories	Unit	Method
Global warming (GWP)	kg CO2 eq	ReCiPe 2016 Midpoint (E) V1.08
Stratospheric ozone depletion (ODP)	kg CFC11 eq	ReCiPe 2016 Midpoint (E) V1.08
Ionizing radiation (IR)	kBq Co-60 eq	ReCiPe 2016 Midpoint (E) V1.08
Ozone formation. Human health (OFHH)	kg NOx eq	ReCiPe 2016 Midpoint (E) V1.08
Fine particulate matter formation (PMF)	kg PM2.5 eq	ReCiPe 2016 Midpoint (E) V1.08
Ozone formation. Terrestrial ecosystems (OFTE)	kg NOx eq	ReCiPe 2016 Midpoint (E) V1.08
Terrestrial acidification (AP)	kg SO2 eq	ReCiPe 2016 Midpoint (E) V1.08
Freshwater eutrophication (FEuP)	kg P eq	ReCiPe 2016 Midpoint (E) V1.08
Marine eutrophication (MEuP)	kg N eq	ReCiPe 2016 Midpoint (E) V1.08
Terrestrial ecotoxicity (TETP)	kg 1.4-DCB	ReCiPe 2016 Midpoint (E) V1.08
Freshwater ecotoxicity (FETP)	kg 1.4-DCB	ReCiPe 2016 Midpoint (E) V1.08
Marine ecotoxicity (METP)	kg 1.4-DCB	ReCiPe 2016 Midpoint (E) V1.08
Human carcinogenic toxicity (HCTP)	kg 1.4-DCB	ReCiPe 2016 Midpoint (E) V1.08
Human non-carcinogenic toxicity (HnCTP)	kg 1.4-DCB	ReCiPe 2016 Midpoint (E) V1.08
Land use (LU)	m2a crop eq	ReCiPe 2016 Midpoint (E) V1.08
Mineral resource scarcity (MRS)	kg Cu eq	ReCiPe 2016 Midpoint (E) V1.08
Fossil resource scarcity (FRS)	kg oil eq	ReCiPe 2016 Midpoint (E) V1.08
Water consumption (WC)	m3	ReCiPe 2016 Midpoint (E) V1.08

5.4.1. LCIA RESULTS FOR THE SCENARIOS

5.4.1.1. Impact Assessment

The impact assessment results for all four scenarios are shown in Table 18 to Table 26 below. The first four tables display the results for each phase of the road pavement lifecycle covered in this study, from cradle to practical completion (A1 to A5). The subsequent data summarizes the total impact assessment results for each scenario. An overall comparison of the characterization outcomes for the four asphalt mixture types is provided in the next section.

Table 18. Impact category results of raw material extraction

A1-Raw material extraction					
Impact category	Unit	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**
Global warming	kg CO2 eq	47554.41	68395.70	52924.39	14252.71
Stratospheric ozone depletion	kg CFC11 eq	0.03	0.06	0.05	0.01
Ionizing radiation	kBq Co-60 eq	4492.30	6544.79	3604.49	473.47
Ozone formation. Human health	kg NOx eq	244.51	389.62	374.82	60.32
Fine particulate matter formation	kg PM2.5 eq	109.71	164.93	131.01	29.48
Ozone formation. Terrestrial ecosystems	kg NOx eq	246.32	391.80	376.53	61.60
Terrestrial acidification	kg SO2 eq	238.18	355.97	301.12	80.24
Freshwater eutrophication	kg P eq	13.19	16.90	8.49	1.82
Marine eutrophication	kg N eq	1.03	1.37	0.82	0.19
Terrestrial ecotoxicity	kg 1.4-DCB	21775.90	33054.36	28281.02	12560.63
Freshwater ecotoxicity	kg 1.4-DCB	131.20	135.71	100.74	36.23
Marine ecotoxicity	kg 1.4-DCB	623625.73	656398.65	495462.88	150605.94
Human carcinogenic toxicity	kg 1.4-DCB	3824.89	4620.41	3666.58	2879.75
Human non-carcinogenic toxicity	kg 1.4-DCB	1068408.21	1283649.55	1016834.55	782574.42
Land use	m2a crop eq	2112.75	2707.39	2169.07	1090.43
Mineral resource scarcity	kg Cu eq	182.94	158.67	128.97	53.71
Fossil resource scarcity	kg oil eq	44933.00	57889.64	45945.83	27701.39
Water consumption	m3	14464.83	8260.53	7138.43	2913.94

Table 19. Impact category results for transport to the asphalt plant

A2 - Transport to the asphalt plant					
Impact category	Unit	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**
Global warming	kg CO2 eq	17522.85	42708.25	24537.65	13182.32
Stratospheric ozone depletion	kg CFC11 eq	0.01	0.02	0.01	0.01
Ionizing radiation	kBq Co-60 eq	1600.04	3899.77	2240.58	1203.70
Ozone formation. Human health	kg NOx eq	120.16	292.86	168.26	90.39
Fine particulate matter formation	kg PM2.5 eq	29.00	70.69	40.61	21.82
Ozone formation. Terrestrial ecosystems	kg NOx eq	120.26	293.10	168.40	90.47
Terrestrial acidification	kg SO2 eq	68.00	165.73	95.22	51.15
Freshwater eutrophication	kg P eq	2.14	5.22	3.00	1.61
Marine eutrophication	kg N eq	0.13	0.31	0.18	0.09
Terrestrial ecotoxicity	kg 1.4-DCB	6375.21	15538.23	8927.36	4796.03
Freshwater ecotoxicity	kg 1.4-DCB	18.59	45.31	26.03	13.99
Marine ecotoxicity	kg 1.4-DCB	104828.95	255498.50	146794.44	78862.08
Human carcinogenic toxicity	kg 1.4-DCB	21.58	52.60	30.22	16.24
Human non-carcinogenic toxicity	kg 1.4-DCB	8197.81	19980.45	11479.59	6167.16
Land use	m2a crop eq	928.29	2262.50	1299.90	698.34
Mineral resource scarcity	kg Cu eq	33.16	80.82	46.44	24.95
Fossil resource scarcity	kg oil eq	6149.53	14988.18	8611.33	4626.25
Water consumption	m3	29.97	73.04	41.96	22.54

Table 20. Impact category results for asphalt mix production

A3 - asphalt mix prodution					
Impact category	Unit	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**
Global warming	kg CO2 eq	28163.42	34016.59	26992.78	21232.81
Stratospheric ozone depletion	kg CFC11 eq	0.01	0.01	0.01	0.01
Ionizing radiation	kBq Co-60 eq	1039.92	1256.04	996.69	784.01
Ozone formation. Human health	kg NOx eq	239.29	289.02	229.34	180.40
Fine particulate matter formation	kg PM2.5 eq	30.07	36.32	28.82	22.67
Ozone formation. Terrestrial ecosystems	kg NOx eq	239.37	289.12	229.42	180.47
Terrestrial acidification	kg SO2 eq	130.43	157.53	125.01	98.33
Freshwater eutrophication	kg P eq	4.96	5.99	4.75	3.74
Marine eutrophication	kg N eq	0.31	0.38	0.30	0.24
Terrestrial ecotoxicity	kg 1.4-DCB	2209.63	2668.86	2117.79	1665.88
Freshwater ecotoxicity	kg 1.4-DCB	30.38	36.69	29.11	22.90
Marine ecotoxicity	kg 1.4-DCB	14.48	17.49	13.88	10.91
Human carcinogenic toxicity	kg 1.4-DCB	1.60	1.93	1.53	1.20
Human non-carcinogenic toxicity	kg 1.4-DCB	41.31	49.90	39.60	31.15
Land use	m2a crop eq	385.38	465.47	369.36	290.54
Mineral resource scarcity	kg Cu eq	17.76	21.45	17.02	13.39
Fossil resource scarcity	kg oil eq	8879.44	10724.84	8510.36	6694.34
Water consumption	m3	154.42	186.51	148.00	116.42

Table 21. Impact category results for transport to the building site

A4 - Transport to the building site					
Categoría de impacto	Unit	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**
Global warming	kg CO2 eq	162533.95	510143.69	594821.64	79162.73
Stratospheric ozone depletion	kg CFC11 eq	0.08	0.24	0.28	0.04
Ionizing radiation	kBq Co-60 eq	14841.28	46582.19	54314.29	7228.50
Ozone formation. Human health	kg NOx eq	1114.52	3498.14	4078.79	542.83
Fine particulate matter formation	kg PM2.5 eq	269.01	844.33	984.47	131.02
Ozone formation. Terrestrial ecosystems	kg NOx eq	1115.44	3501.03	4082.16	543.28
Terrestrial acidification	kg SO2 eq	630.72	1979.65	2308.25	307.20
Freshwater eutrophication	kg P eq	19.88	62.38	72.74	9.68
Marine eutrophication	kg N eq	1.16	3.66	4.26	0.57
Terrestrial ecotoxicity	kg 1.4-DCB	59133.54	185601.86	216409.63	28801.20
Freshwater ecotoxicity	kg 1.4-DCB	172.44	541.24	631.08	83.99
Marine ecotoxicity	kg 1.4-DCB	972345.62	3051891.43	3558470.13	473584.35
Human carcinogenic toxicity	kg 1.4-DCB	200.20	628.35	732.65	97.51
Human non-carcinogenic toxicity	kg 1.4-DCB	76039.19	238663.45	278278.83	37035.16
Land use	m2a crop eq	8610.35	27025.22	31511.09	4193.70
Mineral resource scarcity	kg Cu eq	307.59	965.44	1125.69	149.81
Fossil resource scarcity	kg oil eq	57040.22	179031.55	208748.72	27781.64
Water consumption	m3	277.97	872.45	1017.27	135.39

Table 22. Impact category results for the construction phase

A5 - Construction					
Impact category	Unit	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**	**SCENARIO 4**
Global warming	kg CO2 eq	38040.86	46289.27	49267.93	19817.32
Stratospheric ozone depletion	kg CFC11 eq	0.03	0.04	0.04	0.02
Ionizing radiation	kBq Co-60 eq	3164.72	3850.97	4100.31	1647.56
Ozone formation. Human health	kg NOx eq	465.15	566.01	602.45	242.31
Fine particulate matter formation	kg PM2.5 eq	109.26	132.96	141.55	56.89
Ozone formation. Terrestrial ecosystems	kg NOx eq	465.19	566.05	602.49	242.33
Terrestrial acidification	kg SO2 eq	216.77	263.77	280.75	112.92
Freshwater eutrophication	kg P eq	2.71	3.30	3.51	1.41
Marine eutrophication	kg N eq	0.13	0.16	0.17	0.07
Terrestrial ecotoxicity	kg 1.4-DCB	8091.76	9846.37	10482.63	4213.49
Freshwater ecotoxicity	kg 1.4-DCB	40.55	49.35	52.52	21.12
Marine ecotoxicity	kg 1.4-DCB	224542.43	273233.36	290936.27	116889.12
Human carcinogenic toxicity	kg 1.4-DCB	2.63	3.20	3.41	1.37
Human non-carcinogenic toxicity	kg 1.4-DCB	16035.39	19512.58	20776.80	8347.48
Land use	m2a crop eq	547.20	665.85	708.71	285.05
Mineral resource scarcity	kg Cu eq	44.72	54.41	57.92	23.29
Fossil resource scarcity	kg oil eq	12414.68	15106.56	16078.98	6467.18
Water consumption	m3	29.97	36.47	38.81	15.61

Table 23. Impact category results for scenario 1

Impact category	Unit	**SCENARIO 1**
Global warming	kg CO2 eq	293815.49
Stratospheric ozone depletion	kg CFC11 eq	0.15
Ionizing radiation	kBq Co-60 eq	25138.26
Ozone formation. Human health	kg NOx eq	2183.63
Fine particulate matter formation	kg PM2.5 eq	547.06
Ozone formation. Terrestrial ecosystems	kg NOx eq	2186.58
Terrestrial acidification	kg SO2 eq	1284.10
Freshwater eutrophication	kg P eq	42.88
Marine eutrophication	kg N eq	2.77
Terrestrial ecotoxicity	kg 1.4-DCB	97586.04
Freshwater ecotoxicity	kg 1.4-DCB	393.16
Marine ecotoxicity	kg 1.4-DCB	1925357.20
Human carcinogenic toxicity	kg 1.4-DCB	4050.89
Human non-carcinogenic toxicity	kg 1.4-DCB	1168721.92
Land use	m2a crop eq	12583.96
Mineral resource scarcity	kg Cu eq	586.17
Fossil resource scarcity	kg oil eq	129416.85
Water consumption	m3	14957.15

Table 24. Impact category results for scenario 2

Impact category	Unit	**SCENARIO 2**
Global warming	kg CO2 eq	701553.49
Stratospheric ozone depletion	kg CFC11 eq	0.37
Ionizing radiation	kBq Co-60 eq	62133.76
Ozone formation. Human health	kg NOx eq	5035.65
Fine particulate matter formation	kg PM2.5 eq	1249.22
Ozone formation. Terrestrial ecosystems	kg NOx eq	5041.10
Terrestrial acidification	kg SO2 eq	2922.65
Freshwater eutrophication	kg P eq	93.80
Marine eutrophication	kg N eq	5.87
Terrestrial ecotoxicity	kg 1.4-DCB	246709.68
Freshwater ecotoxicity	kg 1.4-DCB	808.30
Marine ecotoxicity	kg 1.4-DCB	4237039.42
Human carcinogenic toxicity	kg 1.4-DCB	5306.49
Human non-carcinogenic toxicity	kg 1.4-DCB	1561855.94
Land use	m2a crop eq	33126.43
Mineral resource scarcity	kg Cu eq	1280.79
Fossil resource scarcity	kg oil eq	277740.78
Water consumption	m3	9428.99

Table 25. Impact category results for scenario 3

Impact category	Unit	**SCENARIO 3**
Global warming	kg CO2 eq	748544.40
Stratospheric ozone depletion	kg CFC11 eq	0.39
Ionizing radiation	kBq Co-60 eq	65256.36
Ozone formation. Human health	kg NOx eq	5453.66
Fine particulate matter formation	kg PM2.5 eq	1326.47
Ozone formation. Terrestrial ecosystems	kg NOx eq	5459.00
Terrestrial acidification	kg SO2 eq	3110.34
Freshwater eutrophication	kg P eq	92.49
Marine eutrophication	kg N eq	5.73
Terrestrial ecotoxicity	kg 1.4-DCB	266218.42
Freshwater ecotoxicity	kg 1.4-DCB	839.49
Marine ecotoxicity	kg 1.4-DCB	4491677.59
Human carcinogenic toxicity	kg 1.4-DCB	4434.39
Human non-carcinogenic toxicity	kg 1.4-DCB	1327409.37
Land use	m2a crop eq	36058.13
Mineral resource scarcity	kg Cu eq	1376.04
Fossil resource scarcity	kg oil eq	287895.22
Water consumption	m3	8384.48

Table 26. Impact category results for scenario 4

Impact category	Unit	**SCENARIO 4**
Global warming	kg CO2 eq	147647.89
Stratospheric ozone depletion	kg CFC11 eq	0.07
Ionizing radiation	kBq Co-60 eq	11337.24
Ozone formation. Human health	kg NOx eq	1116.26
Fine particulate matter formation	kg PM2.5 eq	261.89
Ozone formation. Terrestrial ecosystems	kg NOx eq	1118.14
Terrestrial acidification	kg SO2 eq	649.84
Freshwater eutrophication	kg P eq	18.26
Marine eutrophication	kg N eq	1.16
Terrestrial ecotoxicity	kg 1.4-DCB	52037.22
Freshwater ecotoxicity	kg 1.4-DCB	178.23
Marine ecotoxicity	kg 1.4-DCB	819952.40
Human carcinogenic toxicity	kg 1.4-DCB	2996.07
Human non-carcinogenic toxicity	kg 1.4-DCB	834155.36
Land use	m2a crop eq	6558.07
Mineral resource scarcity	kg Cu eq	265.15
Fossil resource scarcity	kg oil eq	73270.79
Water consumption	m3	3203.89

5.4.1.2. Normalization

In this study, normalization factors were obtained from SimaPro, which are based on the ReCiPe method and represent average annual impacts in a reference region. By applying these factors, the results highlight which environmental impact categories contribute most significantly to the total footprint of the road construction scenarios, thereby improving comparability across categories that differ in units and magnitude. Normalization does not change the absolute impacts but provides an indication of their relative importance within a broader environmental context. The normalization results are presented in the Table 27.

Table 27. Normalized results for the 4 scenarios

Impact Category	Normalization	SCENARIO :	SCENARIO 2	SCENARIO 3	SCENARIO 4
Global warming	0.000125	36.73	87.69	93.57	18.46
Stratospheric ozone depletion	16.7	2.58	6.14	6.58	1.24
Ionizing radiation	0.00208	52.29	129.24	135.73	23.58
Ozone formation. Human health	0.0486	106.12	244.73	265.05	54.25
Fine particulate matter formation	0.0391	21.39	48.84	51.86	10.24
Ozone formation. Terrestrial ecosystems	0.0563	123.10	283.81	307.34	62.95
Terrestrial acidification	0.0244	31.33	71.31	75.89	15.86
Freshwater eutrophication	1.54	66.03	144.45	142.44	28.12
Marine eutrophication	0.217	0.60	1.27	1.24	0.25
Terrestrial ecotoxicity	0.0000658	6.42	16.23	17.52	3.42
Freshwater ecotoxicity	0.0397	15.61	32.09	33.33	7.08
Marine ecotoxicity	0.023	44283.22	97451.91	103308.58	18858.91
Human carcinogenic toxicity	0.0971	393.34	515.26	430.58	290.92
Human non-carcinogenic toxicity	0.000032	37.40	49.98	42.48	26.69
Land use	0.000162	2.04	5.37	5.84	1.06
Mineral resource scarcity	0.00000833	0.005	0.01	0.01	0.002
Fossil resource scarcity	0.00102	132.01	283.30	293.65	74.74
Water consumption	0.00375	56.09	35.36	31.44	12.01

5.4.1.3. Environmental prices

In this study, environmental prices were used as weighting factors to convert midpoint LCA results into external costs in monetary terms. By multiplying characterized results (e.g., kg CO_2-eq, kg NOx-eq) with the corresponding environmental price, the environmental burden is expressed in euros. These environmental prices were calculated by CE Delft and presenting in the form of handbooks [152]. Find the prices taken from CE Delft handbooks for this study in Annex A.

Environmental prices provide a single-score indicator of total external environmental cost. Such monetisation allows for direct comparison with economic parameters, supports cost-benefit style interpretations, and enhances the relevance of LCA results for policy-making and decision-making in infrastructure planning. The value in the Table *28* are obtain in the environmental prices at the mid-point level

Table 28. Environmental prices of the scenarios

Impact Category	Unit	Euro (€)	SCENARIO 1 (€)	SCENARIO 2 (€)	SCENARIO 3 (€)	SCENARIO 4 (
Global warming	€/kg CO2-eq.	0.13	38196.01	91201.95	97310.77	19194.23
Stratospheric ozone depletion	€/kg CFC-11-eq.	29.1	4.50	10.70	11.46	2.15
Ionizing radiation	€/kBq Co-60-eq.	0.00422	106.08	262.20	275.38	47.84
Ozone formation. Human health	€/kg NOx-eq.	2.17	4738.48	10927.36	11834.43	2422.28
Fine particulate matter formation	€/kg PM2.5-eq.	99.2	54268.10	123923.07	131585.86	25979.36
Ozone formation. Terrestrial ecosystems	€/kg NOx-eq.	0.416	909.62	2097.10	2270.95	465.15
Terrestrial acidification	€/kg SO2-eq.	5.27	6767.19	15402.36	16391.48	3424.66
Freshwater eutrophication	€/kg P-eq.	3.74	160.37	350.81	345.92	68.30
Marine eutrophication	€/kg N-eq.	14.25	39.45	83.62	81.61	16.56
Terrestrial ecotoxicity	€/kg 1.4-DCB-eq.	0.00064	62.46	157.89	170.38	33.30
Freshwater ecotoxicity	€/kg 1.4-DCB-eq.	0.0209	8.22	16.89	17.55	3.73
Marine ecotoxicity	€/kg 1.4-DCB-eq.	0.0032	6161.14	13558.53	14373.37	2623.85
Human carcinogenic toxicity	€/kg 1.4-DCB-eq.	3.99	16163.07	21172.91	17693.21	11954.31
Human non-carcinogenic toxicity	€/kg 1.4-DCB-eq.	0.071	82979.26	110891.77	94246.07	59225.03
Land use	€/m2 a crop-eq.	0.099	1245.81	3279.52	3569.76	649.25
Mineral resource scarcity	€/kg Cu-eq.	0.014	8.21	17.93	19.26	3.71
Fossil resource scarcity	€/kg oil-eq.	0.028	3623.67	7776.74	8061.07	2051.58
Water consumption	€/m3	0.407	6087.56	3837.60	3412.48	1303.98
Total			**221529.20**	**404968.96**	**401670.99**	**129469.27**

6
RESULTS AND DISCUSSION

6.1. IMPACT ASSESSMENT INDICATORS

The output of the LCA was expressed using 6 impact category indicators, each of which summarizes the effect of multiple flows of materials, energy, pollutants and waste on as many environmental categories under an equivalent unit of measurement. The complete list of indicators for the 4 scenarios under analysis is given in Table *17* in the chapter 5 in section LCIA results. Aiming to analyse the environmental impact of using sustainable materials in road construction, 6 indicators, namely the, GWP, PMF, METP, HCTP, FRS, and WC, were selected, broken down into the main processes of the life cycle and shown in Figure 29. A detailed examination of the percentage contribution of each life cycle stage reveals key insights into the environmental performance of the four road construction scenarios regarding global warming potential, fine particulate matter formation, human carcinogenic toxicity, fossil resource scarcity, marine ecotoxicity, and water consumption. The analysis highlights how material selection, transport logistics, and construction processes contribute differently to these categories across Scenarios 1 through 4.

In most of the categories, transport to the construction site (Stage A4) emerges as the dominant contributor, overshadowing raw material extraction (A1), transport to the asphalt plant (A2), asphalt production (A3), and the construction process itself (A5). This reinforces previous studies [153], [154] that identify material logistics as a critical driver of environmental impact in infrastructure projects, particularly in developing regions with weak supply chains.

For better understanding, it is important to know that the value in percentages presented for each life cycle stage (A1–A5) for the fallowing analyses, represents the relative share of that stage in relation to the total environmental impact of the corresponding scenario. In other words, the contribution of raw material extraction, transport, asphalt production, transport to the construction site, and construction activities is expressed as a fraction of the overall impact calculated for each design alternative. This means that while scenarios may differ in their absolute impact values, the percentages used here allow for a comparative understanding of how burdens are distributed within each scenario's life cycle. The table with the calculation can be found in Annex A (Table 29 to *Table 34*).

For GWP, in Scenario 3, the design incorporating crumb rubber and steel slag records the highest relative contribution from Stage A4, which accounts for 79.46% of total emissions. This is followed by 72.72% of scenario 2 which also incorporate steel slag on the design, scenario 1 (conventional) with 55.32%, and Scenario 4 using palm kernel shell in the design with 53.62%. These values clearly illustrate the significant role of long-distance transport in influencing the environmental footprint of road construction. Despite the circular benefits of using steel slag and crumb rubber, its environmental advantage is effectively undermined by the fossil fuel intensity of its logistics chain. In contrast, Scenario 4 benefits from the localized sourcing of palm kernel shells, which substantially reduces transportation burdens and results in a more distributed emission profile across A1 (9.65%), A2 (8.93%), and A3 (14.38%). Moreover, by limiting the need for long-haul logistics, the impacts in A4 (53.62%) remain lower compared to scenarios dependent on imported materials, while A5 (13.42%) reflects only the direct construction-related activities. Looking closely to the conventional design, it shows a moderately balanced distribution of GWP across stages, with 16.19% attributed to raw material extraction (A1), 5.96% to transport to the asphalt plant (A2), and 9.59% to asphalt mix production (A3). However, transport to the construction site (A4) still accounts for more than half of the total emissions (55.32%), construction (A5) plays a notable role as well, contributing 12.95% of GWP, likely due to the diesel fuel consumption of compaction and paving machinery on site. This stage is similarly relevant in Scenario 4, where it contributes 13.42%, suggesting that even in the most environmentally favourable scenarios, improvements in on-site energy use could further reduce climate impacts.

In terms of fine particulate matter formation, the pattern largely mirrors the GWP results. Scenario 3 again performs the worst, with 78.35% of total PM emissions originating from Stage A4. Scenario 2 follows at 67.59%, while Scenarios 1 and 4 show lower shares at 49.17% and 50.03%, respectively. These results confirm that long-distance transportation not only elevates carbon emissions but also exacerbates local air pollution through the release of $PM_{2.5}$ from diesel combustion. Scenario 4 again distinguishes itself by distributing impacts more evenly, with significant shares in A1 (11.26%), A2 (8.33%), A3 (8.66%), and A5 (21.72%). Notably, the contribution from the construction phase in Scenario 4 is the highest among all scenarios, highlighting a potential trade-off between reduced transport as it is a late weight material and it is locally sourced, still the construction process is the same as the other scenarios.

Scenario 1's high A1 contribution to PM formation (20.06%) is consistent with the on virgin lateritic gravel and sand, which are associated with significant emissions during extraction. Meanwhile, the construction phase (A5) accounts for nearly 20% of PM emissions in this scenario. Scenario 2's PM profile reflects its reliance on steel slag, with slightly lower A1 (13.20%) and A5 (10.64%) contributions, but a pronounced A4 impact (67.59%), as expected due to the transport distance and the heavy weight of this material.

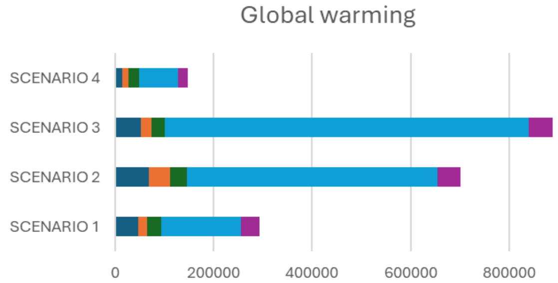
In the human carcinogenic toxicity category, the raw material extraction phase (A1) dominates all scenarios. Scenario 4 exhibits the highest A1 contribution at 96.12%, followed closely by Scenario 1 (conventional design) (94.42%), Scenario 2 (87.07%), and Scenario 3 (79.57%). These results suggest that the composition and treatment of raw materials, such as bitumen, lateritic gravel, or steel slag, are the primary sources of carcinogenic emissions. Scenario 3's relatively lower A1 share is offset by a higher transport-related burden (A4 at 19.73%), reflecting the emissions associated with transporting steel slag over long distances. These findings are consistent with earlier studies [155] which associate industrial byproducts like steel slag with trace metal emissions during extraction and processing, thereby increasing human toxicity scores.

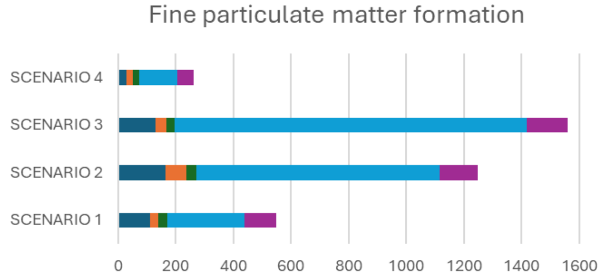
In terms of fossil resource scarcity, the impact is again most prominent in the transport stage (A4) for all scenarios, although to varying degrees. Scenario 3 shows the highest A4 contribution at 76.80%, followed by Scenario 2 (64.46%), Scenario 1 (44.07%), and Scenario 4 (37.92%). Scenario 3 also presents the lowest A1 contribution at 13.59%, reflecting the lesser fossil resource burden of reusing tire-derived rubber and steel slag compared to virgin aggregates. However, this advantage is offset again by the intensive fuel requirements of transporting rubber and steel slag. Scenario 4 performs best in balancing extraction and transport phases.

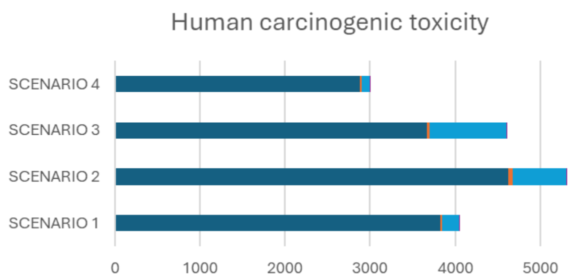
The marine ecotoxicity category presents a similar trend to global warming and particulate matter: transport to the building site (A4) is again the leading contributor, ranging from 50.50% in Scenario 1 to a striking 83.83% in Scenario 3. Scenario 2 (steel slag) shows a high A4 share at 72.03%, while Scenario 4 maintains a moderate figure (57.76%).

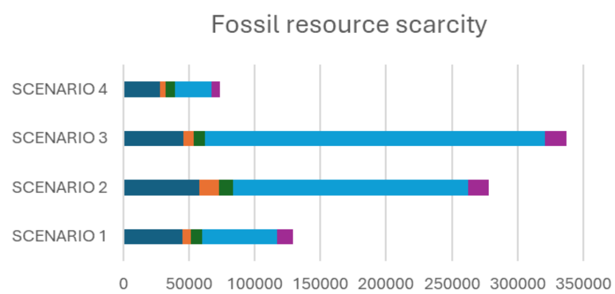
With respect to water consumption, raw material extraction (A1) again emerges as the predominant source of environmental burden. Scenario 1 shows the highest A1 share (96.71%), driven by the water-intensive processes associated with conventional asphalt production. Scenario 2 follows with 87.61%, Scenario 3 with 74.93%, and Scenario 4 with 90.95%. However, transport (A4) contributes minimally (<5%) in all cases, highlighting that water-related impacts are largely confined to the material production chain rather than logistics.

The multi-category comparison confirms a recurring trend: transport to the building site (A4) is the most environmentally impactful stage across categories where emissions are airborne or fossil fuel–dependent (e.g., GWP, PM, ecotoxicity, fossil depletion). Conversely, raw material extraction (A1) is dominant in categories such as human toxicity and water consumption, reflecting the direct resource and health effects of virgin or processed input materials. Scenario 3 generally performs the worst due to the high A4 burdens associated with transporting a large amount of steel slag (for subbase, base and surface course) from long distance compered to others materials. Scenario 4 consistently demonstrates a more balanced profile, excelling particularly in categories sensitive to logistics, while maintaining reasonable impacts in extraction- and construction-related stages.









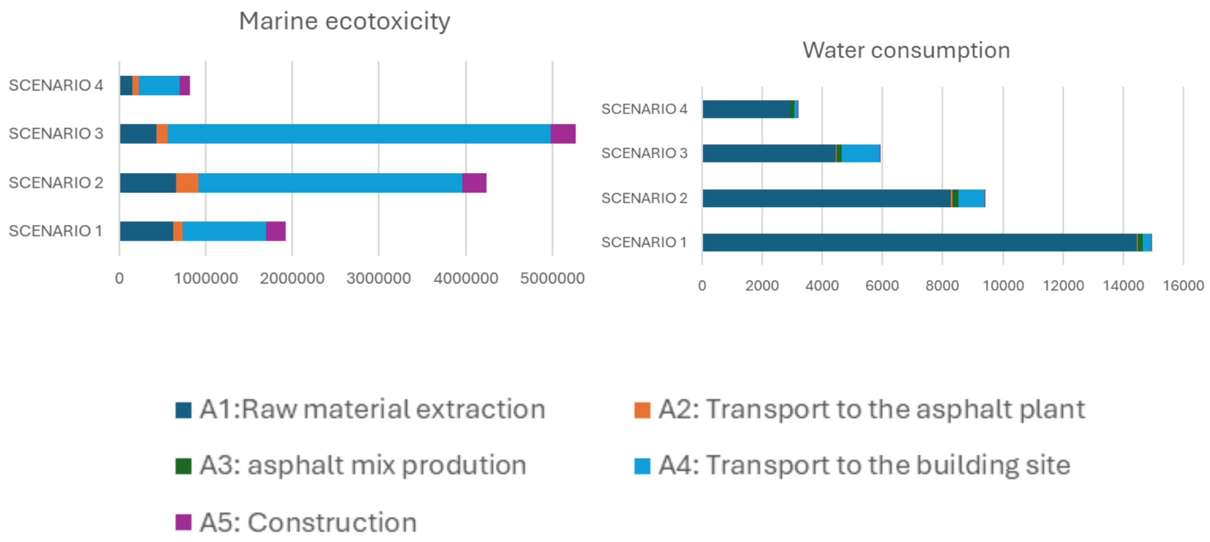


Figure 29. Impact assessment indicators of the solutions under analysis

6.2. COMPARATIVE ANALYSES BY SCENARIO

6.2.1. NORMALIZATION RESULTS

In this analysis, the results are based on normalized data across all selected environmental impact categories, ensuring comparability between the different scenarios. Normalization was conducted using the ReCiPe 2016 midpoint normalization with a global reference, which allows impacts of different categories to be expressed on a common scale. Following normalization, the impact scores were aggregated by summation to provide a single composite indicator for each road layer. For more information, find the normalization value and calculations in Annex A.

In the surface layer (Figure *30*), Scenarios 1 and 2 show the highest environmental impacts, largely due to the use of large quantities of gravel, sand, and bitumen. Scenario 1, the conventional design, relies heavily on virgin gravel and sand, both of which are resource-intensive in extraction (A1). Scenario 2 introduces steel slag as a primary aggregate substitute but still uses a high mass of materials, particularly slag and bitumen, which contributes to its substantial environmental footprint. In contrast, Scenarios 3 and 4 show reduced surface layer impacts, attributable to lower total material input and the substitution of conventional materials with alternative resources. Scenario 3 uses crumb rubber, less gravel, less steel slag compare to scenario 2, and can be a reason why it has less impact in A1. Scenario 4, the most efficient in this layer, combines locally sourced materials like palm kernel shells (PKS) and modest gravel content.

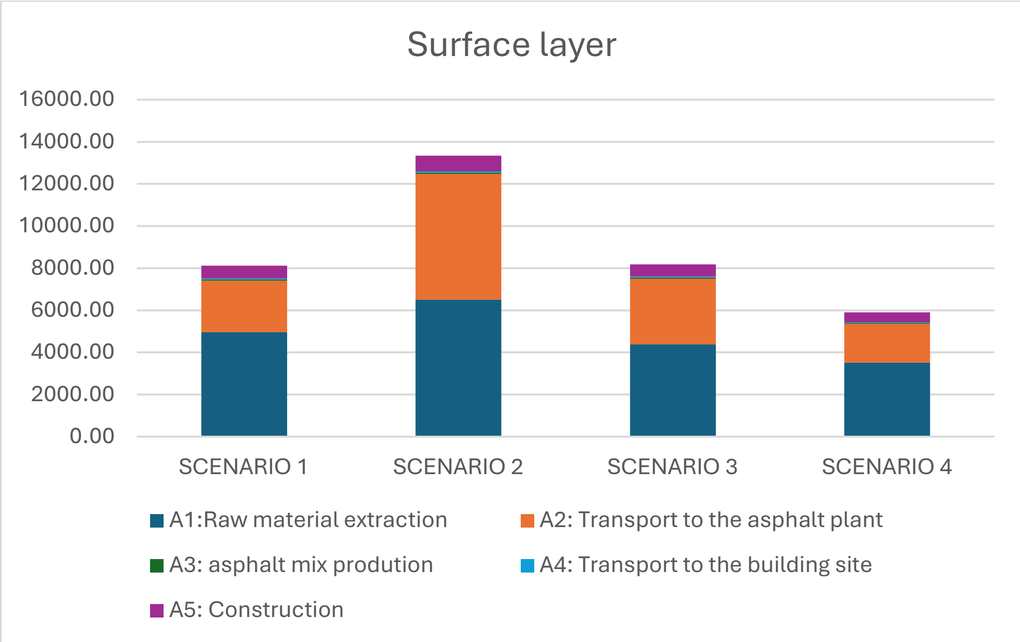


Figure 30.Impact of the surface layer

In the base layer (Figure *31*), Scenario 2 records the highest overall impact, driven mainly by the large quantity of steel slag used. Its raw material extraction (A1) is the most significant contributor, while transport to the building site (A4) also adds a noticeable burden due to the weight of slag. Scenario 1 also shows a relatively high impact, with extraction of virgin gravel and sand dominating its results, although it performs better than Scenario 2. Scenario 3 performs moderately, with lower extraction impacts compared to Scenarios 1 and 2 but a high contribution from the construction stage (A5), which offsets its material savings. Scenario 4 again performs best, with drastically lower results across all stages; the use of palm kernel shells (PKS) and limited gravel minimizes both raw material extraction and construction burdens, making it the most efficient design for the base layer.

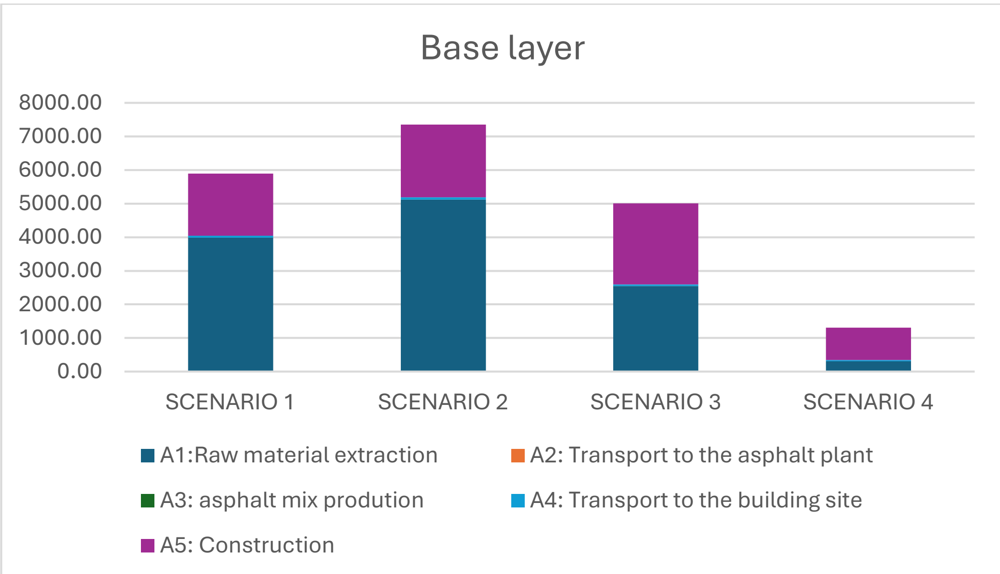


Figure 31.Impact of the base layer

The subbase layer (Figure *32*) shows the highest burdens for Scenarios 2 and 3, reflecting their heavy reliance on steel slag. Scenario 2 is the most impactful design in this layer, as both extraction (A1) and transport to the building site (A4) are elevated by the high mass and density of slag, while construction (A5) adds substantially to the total. Scenario 3, although slightly lower in extraction compared to Scenario 2, shows the highest construction impact (A5), resulting in the second-worst performance. Scenario 1 records a mid-range impact, with gravel-based extraction and construction contributing strongly but still lower than the slag-heavy scenarios. Scenario 4, in contrast, demonstrates by far the lowest impact: with PKS requiring no extraction (A1), lighter transport (A4), and relatively modest construction effort (A5), it emerges as the most sustainable option in the subbase layer.

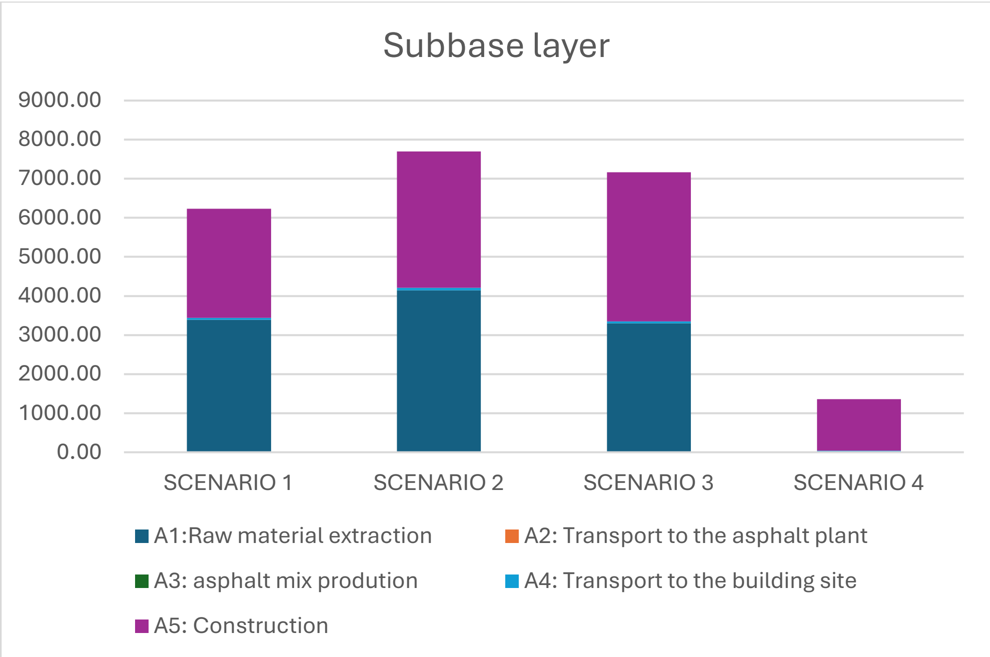


Figure 32.Impact of the subbase layer

6.2.2. ENVIRONMENTAL PRICES RESULTS

The monetisation of midpoint impact categories using environmental prices provides an integrated view of the external costs associated with the four road design scenarios. This approach allows direct comparison between scenarios by expressing their environmental burdens in euros, thereby highlighting which designs impose the greatest socio-economic costs. The total external costs vary substantially across the four scenarios (See Figure 33). Scenario 2 (€404,969) and scenario 3 (€401,671) exhibit the highest environmental prices, followed by scenario 1 (€221.529), while scenario 4 (€129,469) presents the lowest cost burden. This ranking suggests that scenario 4 is the most environmentally favourable design when socio-economic damage is considered, whereas scenarios 2 and 3 are the least favourable. Across all scenarios, three impact categories dominate the total external costs (see Table *28*). Fine particulate matter formation has €131,586 in scenario 3 and €123,923 in scenario 2, emerging as the largest single contributor. This reflects the high damage costs of $PM_{2.5}$ emissions on human health, consistent with literature that identifies air pollution as a primary source of welfare loss in construction activities. Human non-carcinogenic toxicity also contributes significantly, particularly in scenario 2 (€110,892) and scenario 1 (€82,979). The third is the global warming potential, which is another important driver (ranging from €19,194 in scenario 4 to €97,311 in scenario 3), showing the climate-related costs of greenhouse gas emissions from energy-intensive materials.

Other notable contributions include human carcinogenic toxicity (peaking at €21,173 in Scenario 2) and marine ecotoxicity, which, while lower in absolute value, still adds several thousand euros to each scenario's external cost. Categories such as ionizing radiation, stratospheric ozone depletion, and freshwater ecotoxicity contribute minimally in comparison, suggesting limited relevance within the studied road designs.

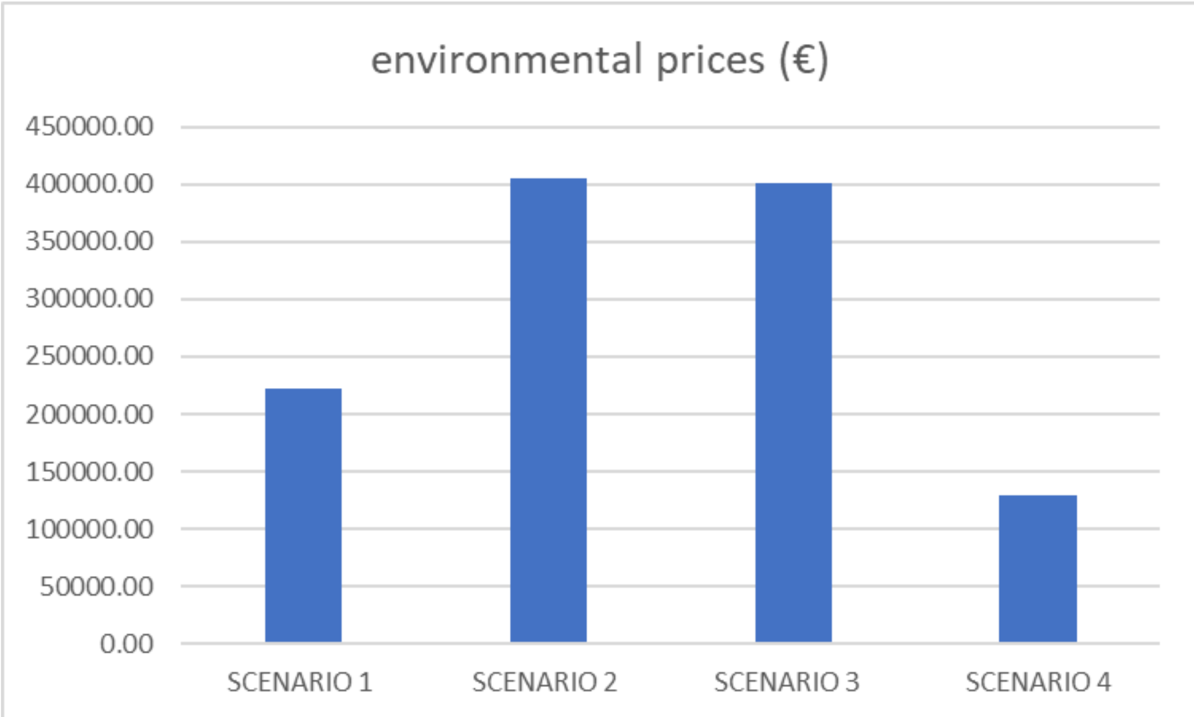


Figure 33.Comparison of environmental prices across four road design scenarios

Summarizing, scenario 1 shows a moderate impact profile, largely driven by fine particulate matter and non-carcinogenic toxicity, but substantially lower than scenarios 2 and 3, which are almost equivalent in their total costs, both heavily influenced by fine particulate matter, toxicity impacts, and global warming. These scenarios therefore represent the least sustainable options. Scenario 4 stands out with significantly lower costs across nearly all categories, especially in particulate matter and toxicity, suggesting that the material substitutions in this design deliver clear environmental benefits.

7
CONCLUSIONS

This dissertation work set out to explore how the integration of alternative and sustainable materials, like steel slag, crumb rubber, palm kernel shells (PKS), and glass powder, could contribute to more environmentally responsible practices in low-traffic road construction in Guinea-Bissau. Using Life Cycle Assessment (LCA) as the central analytical framework, the study compared four distinct pavement design scenarios across multiple environmental impact categories and life cycle stages (A1 to A5). The findings offer important insights not only for material selection and engineering practices but also for shaping national infrastructure policies aimed at sustainability, circularity, and climate resilience.

The use of sustainable material to construct roads brings numerous benefits and opportunities for sustainable road infrastructure. These materials can contribute to waste diversion, reduced resource consumption, energy savings, reduced greenhouse gas emissions, improved performance, local sourcing, reduced transportation impacts, and overall cost-effectiveness. However, it is essential to acknowledge that each material has its own merits and demerits, that must be carefully considered. The materials presented on this study, offer advantages in resource conservation and waste diversion. Their use can reduce the need for virgin materials, minimize waste disposal, and potentially improve the performance of road surfaces.

It is important to note that the sustainability of these specific materials may vary based on availability of resources (location), regulations, and many other factors. Incorporating recycled and secondary materials in road construction holds great promise for sustainable infrastructure development. In order to assess how these materials are sustainable in the context of Guinea-Bissau low traffic road construction, the LCA was implemented as a toll to access these materials and compare scenarios where they were used.

The results obtained after the assessment demonstrated that, scenario 4, which utilized locally available agro-waste materials such as PKS, emerged as the most environmentally favourable option. Not only did it perform best across key indicators like global warming potential, particulate matter formation, and fossil resource scarcity, but it also distributed environmental burdens more evenly across life cycle stages. This scenario benefitted from low material density, reduced transport distances, and minimal processing requirements were key factors in lowering total impact. Its success underscores the value of locally sourced bio-based and recycled materials in developing countries with limited industrial infrastructure but rich in agricultural and domestic waste streams. In the other hand, scenario 3, that incorporate crumb rubber and steel slag, presented a more complex picture. While steel slag as byproduct and rubber reuse aligned with circular economy principles and reduced extraction-stage impacts, the environmental advantage was compromised by the significant emissions associated with long-distance transport, especially the high density of steel slag increased the energy demand for transport. Scenario 2, also design with steel slag but in less quantity than scenario 3, performed moderately well compere to scenario 3, but still it was ultimately limited by the volume and weight of materials used, especially in the subbase layer. Although it made significant reductions in raw material extraction impacts (A1). This highlights an essential nuance in sustainable infrastructure design, not all industrial by-products are inherently "greener," particularly when considered within geographically dispersed supply chains. The study reinforces that in regions like Guinea-Bissau, where infrastructure development is heavily shaped by logistical constraints, material proximity is just as important as material type.

Although the conventional design (Scenario 1) is design fully on virgin materials, which was extracted directly from nature, but it presented better result than scenario 2 and scenario 3 in terms of impact across categories, with especially pronounced contributions in stage related to raw material extraction (A1).

Environmental prices provided an additional layer of insight by monetising the midpoint impacts into external costs expressed in euros. This allowed the study to integrate diverse environmental burdens into a single score and compare scenarios more holistically. The results confirmed Scenario 4 as the most favourable option with the lowest external cost (€129,469), followed by Scenario 1 (€221,529), while Scenarios 2 and 3 showed significantly higher burdens (over €400,000 each). Importantly, this analysis revealed that although Scenario 3 was more impactful in several midpoint categories, Scenario 2 resulted in higher total external costs when monetised. Across all scenarios, fine particulate matter formation, human toxicity, and global warming were the dominant contributors to total costs. This monetisation step strengthens the conclusion that Scenario 4 is not only environmentally superior but also the most cost-efficient for society when externalities are considered.

In conclusion, the findings underscore the importance of strategic material sourcing and site proximity in minimizing the environmental footprint of road construction. While recycled and industrial by-products offer benefits in some categories, their sustainability is contingent upon short, efficient supply chains and reduced processing intensity. Thus, for Guinea-Bissau and similar contexts, Scenario 4, which combines local sourcing of bio-based and recycled materials with minimal transport needs, presents the most environmentally viable pathway across all impact categories.

From a broader perspective, the study also affirms the utility of LCA as a decision-support tool in civil engineering. By quantifying environmental trade-offs across layers, stages, and materials, LCA provides a structured and evidence-based approach for making complex design decisions. Ultimately, this research advocates for a paradigm shift in how road infrastructure is conceived and constructed in low-income countries. Sustainable development in this sector cannot be reduced to adopting novel materials or technologies in isolation. Rather, it requires a holistic systems-thinking approach that accounts for environmental, logistical, and social dimensions. The findings suggest that leveraging local waste resources, reducing transport burdens, and designing for material efficiency are not just environmentally sound, they are economically and contextually appropriate strategies for Guinea-Bissau.

Looking ahead, future studies could build on this work by incorporating economic and social life cycle indicators, performing durability assessments of alternative materials in situ, and extending the analysis to include maintenance and end-of-life phases. Such extensions would provide a more complete understanding of sustainability over the full lifespan of road assets. For now, this thesis contributes a strong foundational case for sustainable materials adoption and offers actionable guidance for more climate-conscious and resource-efficient road building in Guinea-Bissau and comparable regions from an environmental standpoint. Researchers especially the ones from zone that have abundant PKS should research more about this material for road construction because PKS has almost zero upstream emissions, being an agricultural by-product, and its use in road construction prevents open dumping or burning, common practices that contribute to air pollution in rural zones. The substitution of natural aggregates with PKS helps preserve quarry resources and promotes an ecologically restorative construction approach. Additionally, using PKS in both unbound and bound layers offers a cohesive material strategy that minimizes logistical complexity and encourages local material recovery chains.

8
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A

ANNEXES

A1. CALCULATION OF THE SIX IMPACT CATEGORIES SELECTED

The following Table 29 to *Table 34* shows the impact values of the six categories that have been chosen for the analyses in the section 6.1.

Table 29.Global warming

Global warming	A1	A2	A3	A4	A5
SCENARIO 1	47554.41	17522.85	28163.42	162533.95	38040.86
SCENARIO 2	68395.70	42708.25	34016.59	510143.69	46289.27
SCENARIO 3	52924.39	24537.65	26992.78	594821.64	49267.93
SCENARIO 4	14252.71	13182.32	21232.81	79162.73	19817.32
Value in percentage					
SCENARIO 1	16.19%	5.96%	9.59%	55.32%	12.95%
SCENARIO 2	9.75%	6.09%	4.85%	72.72%	6.60%
SCENARIO 3	7.07%	3.28%	3.61%	79.46%	6.58%
SCENARIO 4	9.65%	8.93%	14.38%	53.62%	13.42%

Table 30. Fine particulate matter formation

Fine particulate matter formation	A1	A2	A3	A4	A5
SCENARIO 1	109.71	29.00	30.07	269.01	109.26
SCENARIO 2	164.93	70.69	36.32	844.33	132.96
SCENARIO 3	130.26	36.88	28.82	1221.61	141.55
SCENARIO 4	29.48	21.82	22.67	131.02	56.89
Value in percentage					
SCENARIO 1	20.06%	5.30%	5.50%	49.17%	19.97%
SCENARIO 2	13.20%	5.66%	2.91%	67.59%	10.64%
SCENARIO 3	8.35%	2.37%	1.85%	78.35%	9.08%
SCENARIO 4	11.26%	8.33%	8.66%	50.03%	21.72%

Table 31. Human carcinogenic toxicity

Human carcinogenic toxicity	A1	A2	A3	A4	A5
SCENARIO 1	3824.89	21.58	1.60	200.20	2.63
SCENARIO 2	4620.41	52.60	1.93	628.35	3.20
SCENARIO 3	3666.17	27.45	1.53	909.12	3.41
SCENARIO 4	2879.75	16.24	1.20	97.51	1.37
Value in percentage					
SCENARIO 1	94.42%	0.53%	0.04%	4.94%	0.06%
SCENARIO 2	87.07%	0.99%	0.04%	11.84%	0.06%
SCENARIO 3	79.57%	0.60%	0.03%	19.73%	0.07%
SCENARIO 4	96.12%	0.54%	0.04%	3.25%	0.05%

Table 32. Fossil resource scarcity

Fossil resource scarcity	A1	A2	A3	A4	A5
SCENARIO 1	44933.00	6149.53	8879.44	57040.22	12414.68
SCENARIO 2	57889.64	14988.18	10724.84	179031.55	15106.56
SCENARIO 3	45828.09	7820.14	8510.36	259030.51	16078.98
SCENARIO 4	27701.39	4626.25	6694.34	27781.64	6467.18
Value in percentage					
SCENARIO 1	34.72%	4.75%	6.86%	44.07%	9.59%
SCENARIO 2	20.84%	5.40%	3.86%	64.46%	5.44%
SCENARIO 3	13.59%	2.32%	2.52%	76.80%	4.77%
SCENARIO 4	37.81%	6.31%	9.14%	37.92%	8.83%

Table 33. Marine ecotoxicity

Marine ecotoxicity	A1	A2	A3	A4	A5
SCENARIO 1	623625.73	104828.95	14.48	972345.62	224542.43
SCENARIO 2	656398.65	255498.50	17.49	3051891.43	273233.36
SCENARIO 3	427679.45	133307.32	13.88	4415607.14	290936.27
SCENARIO 4	150605.94	78862.08	10.91	473584.35	116889.12
Value in percentage					
SCENARIO 1	32.39%	5.44%	0.0008%	50.50%	11.66%
SCENARIO 2	15.49%	6.03%	0.0004%	72.03%	6.45%
SCENARIO 3	8.12%	2.53%	0.0003%	83.83%	5.52%
SCENARIO 4	18.37%	9.62%	0.0013%	57.76%	14.26%

Table 34. Water consumption

Water consumption	A1	A2	A3	A4	A5
SCENARIO 1	14464.83	29.97	154.42	277.97	29.97
SCENARIO 2	8260.53	73.04	186.51	872.45	36.47
SCENARIO 3	4445.68	38.11	148.00	1262.30	38.81
SCENARIO 4	2913.94	22.54	116.42	135.39	15.61
Value in percentage					
SCENARIO 1	96.71%	0.20%	1.0324%	1.86%	0.20%
SCENARIO 2	87.61%	0.77%	1.9780%	9.25%	0.39%
SCENARIO 3	74.93%	0.64%	2.4945%	21.28%	0.65%
SCENARIO 4	90.95%	0.70%	3.63%	4.23%	0.49%

A2. NORMALIZATION

The normalized values across all impact categories were added together to create a single score for each life cycle stage (A1–A5) and each scenario. This aggregation makes it possible to directly compare scenarios at the layer level.

Table 35. Normalization value

Impact Category	**Normalization**
Global warming	0.000125
Stratospheric ozone depletion	16.7
Ionizing radiation	0.00208
Ozone formation. Human health	0.0486
Fine particulate matter formation	0.0391
Ozone formation. Terrestrial ecosystems	0.0563
Terrestrial acidification	0.0244
Freshwater eutrophication	1.54
Marine eutrophication	0.217
Terrestrial ecotoxicity	0.0000658
Freshwater ecotoxicity	0.0397
Marine ecotoxicity	0.023
Human carcinogenic toxicity	0.0971
Human non-carcinogenic toxicity	0.000032
Land use	0.000162
Mineral resource scarcity	0.00000833
Fossil resource scarcity	0.00102
Water consumption	0.00375

The following *Table 36* to *Table 38* summarizes the final normalized and aggregated results that correspond to the figures presented in Chapter 6 section 6.2 .

Table 36. Normalized scenario value for surface layer

Surface layer	A1	A2	A3	A4	A5
SCENARIO 1	4959.00	2445.50	54.56	52.29	608.79
SCENARIO 2	6512.06	5960.40	65.90	63.16	735.31
SCENARIO 3	4388.50	3109.86	52.29	50.12	583.48
SCENARIO 4	3517.85	1839.74	41.13	39.42	458.95

Table 37.Normalized scenario value for base layer

Base layer	A1	A2	A3	A4	A5
SCENARIO 1	3987.67	0.00	0.00	52.29	1858.36
SCENARIO 2	5123.29	0.00	0.00	63.16	2165.85
SCENARIO 3	2549.40	0.00	0.00	50.12	2410.37
SCENARIO 4	307.60	0.00	0.00	39.42	956.08

Table 38.Normalized scenario value for subbase layer

Subbase layer	A1	A2	A3	A4	A5
SCENARIO 1	3389.52	0.00	0.00	52.29	2787.54
SCENARIO 2	4141.99	0.00	0.00	63.16	3492.98
SCENARIO 3	3302.56	0.00	0.00	50.12	3814.53
SCENARIO 4	0.00	0.00	0.00	39.42	1320.41

A.3. ENVIRONMENTAL PRICES

Environmental pricing was applied to provide a monetized expression of environmental impacts. This approach assigns a monetary value (€/unit) to each impact category, reflecting the societal cost of the damage. Environmental prices were taken from CE Delft environmental Prices Handbook 2024: EU27 version, which provides recommended values for LCA studies (see *Table 39*).

Table 39.Environmental prices for LCA: ReCiPe 2016 midpoints for the EU27, in €2021 per unit [152]

	Unit	Lower	Central	Upper
Climate change	€/kg CO_2-eq.	€ 0.05	€ 0.13	€ 0.16
Ozone depletion	€/kg CFC-11-eq.	€ 15.2	€ 29.1	€ 69.6
Ionising radiation	€/kBq Co-60-eq.	€ 0.00275	€ 0.00422	€ 0.00594
Oxidant formation, human health	€/kg NO_x-eq.	€ 1.28	€ 1.86	€ 2.97
Oxidant formation, terrestrial ecosystems	€/kg NO_x-eq.	€ 0.416	€ 0.416	€ 0.526
Particulate matter formation	€/kg $PM_{2.5}$-eq.	€ 58.5	€ 84.7	€ 138.1
Acidification	€/kg SO_2-eq.	€ 2.67	€ 5.28	€ 9.30
Freshwater eutrophication	€/kg P-eq.	€ 2.56	€ 3.74	€ 10.13
Marine eutrophication	€/kg N-eq.	€ 7.64	€ 14.25	€ 27.60
Terrestrial ecotoxicity	€/kg 1.4-DCB-eq.	€ 0.00045	€ 0.00064	€ 0.00083
Freshwater ecotoxicity	€/kg 1.4-DCB-eq.	€ 0.0148	€ 0.0209	€ 0.0271
Marine ecotoxicity	€/kg 1.4-DCB-eq.	€ 0.0022	€ 0.0032	€ 0.0041
Human toxicity, cancer-related	€/kg 1.4-DCB-eq.	€ 2.70	€ 3.99	€ 6.01
Human toxicity, non-cancer-related	€/kg 1.4-DCB-eq.	€ 0.048	€ 0.071	€ 0.106
Land use	€/m^2 a crop-eq.	€ 0.070	€ 0.099	€ 0.128
Mineral extraction	€/kg Cu-eq.	€ 0	€ 0.0140	€ 0.0826
Fossil extraction	€/kg oil-eq.	€ 0	€ 0.028	€ 0.163
Water consumption	€/m^3	€ 0	€ 0.407	€ 0.811
NO_2-mortality *	€/kg NO_x-eq.	€ 4.02	€ 5.94	€ 8.90

* The NO_2 mortality is an extra calculation step that can be performed in addition to the LCA analysis to ensure that NO_2 is included in the external cost estimates properly.