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# Thesis title: Assessment of Environmentally Sustainable Pavement Maintenance Practices: A Case of Addis Ababa City Road Authority


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## Summary

Pavement maintenance (PM) introduces new environmental impacts because of the huge amount of resource consumption, depletion of natural resources, waste generation, and energy consumption, as a result, sustainability issues become a worldwide forefront agenda of transportation agencies (Khahro et al., 2021). Addis Ababa is experiencing rapid population growth and urbanization, necessitating extensive infrastructure development, particularly in road networks. However, the city faces challenges such as traffic congestion, inadequate maintenance, and pavement deterioration, alongside environmental issues like pollution and resource depletion. The main objective of this research was to assess the practice of environmentally sustainable pavement maintenance projects at Addis Ababa city road networks. The PSIM Rating framework is used as the main tool to assess the extent of sustainability across the projects. With indicators being the basis, categories incorporated in the assessment include material usage, maintenance techniques, management practices, energy and water consumption, and environmental impact. Data was collected via in-depth interviews with 8 stakeholders and field surveys across 6 project sites, integrating quantitative data with qualitative interpretations for a comprehensive evaluation. Using AACRA's Lot 1 and Lot 2 pavement maintenance projects as case studies, the research revealed significant variations in approach and outcomes associated with realizing environmental sustainability. Project Lot 1 generally performed better in terms of material usage and waste management, partially incorporating recycled materials and reusing construction waste, highlighting a disparity in resource efficiency. Lot 2 excelled in work zone management and safety measures, effectively reducing disruptions and enhancing safety during operations. While both projects demonstrate a degree of awareness and implementation of sustainable practices, neither consistently achieves exemplary levels across all evaluated categories. The findings show that adopting a proactive and data-driven approach to maintenance management is crucial for long-term environmental sustainability. It is recommended that AACRA standardizes the use of recycled materials across all projects, potentially reducing virgin material consumption. Furthermore, adopting preventive maintenance strategies could extend pavement life, significantly lowering overall environmental impact.

***Keywords***: *Sustainability, Pavement Maintenance, Pavement Sustainability Index, Environment*

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# Abbreviations

| Abbreviation | Full form |
|---|---|
| **AACRA** | Addis Ababa City Roads Authority |
| CMA | Cold Mix Asphalt |
| **GPS** | Global Positioning System |
| **GHG** | Greenhouse Gas |
| **HMA** | Hot Mix Asphalt |
| LED | Light-Emitting Diode |
| OM | Operation and Maintenance |
| **PM** | Pavement Maintenance |
| **PSI** | Pavement Sustainability Index |
| **PSIM** | Pavement Sustainability Index for Maintenance |
| **PPE** | Personal Protective Equipment |
| **RAP** | Recycled Asphalt Pavement |
| **VOCs** | Volatile Organic Compounds |
| **WMA** | Warm Mix Asphalt |

# 1. Introduction

## 1.1 Background

Maintenance of a road entails pavement rehabilitation, routine maintenance, restoration maintenance, and specific maintenance, all of which have an essential influence on the related social, economic, and environmental aspects (Sally et al. 2005). Indeed, pavement is one of the critical transportation infrastructures that needs a large amount of investment (Chiola et al., 2023). Therefore, it's crucial for sustainable management and monitoring of this infrastructure that plays a vital role in achieving national development and brings notable social and environmental benefits. Sustainable pavement maintenance goes beyond the scope of traditional maintenance practices, as it encourages the project team to not only address distresses but also enhance the overall performance of pavements (Torres-Machi et al., 2018). The United States of American Federal Highway Administration defined environmentally sustainable pavement maintenance as a practice of improving and preserving pavements while; i) minimizing environmental impact, ii) reducing the use of nonrenewable resources, iii) efficient energy use, and iv) utilizing eco-friendly techniques to decrease the need for frequent maintenance (Van Dam et al., 2015).

The government of Ethiopia places a high priority on the development and maintenance of its road infrastructure, as more than 95% of the country's passenger and freight transport relies on this network. The government is now focused on keeping road infrastructure sustainable and strengthening organizational structures (JICA, 2019). According to Girmay (2016), the growth of the Adis Ababa city has led to an increased demand of residents for sustainable road infrastructure. In Addis Ababa, the City Road Authority (AACRA) is responsible for maintaining, constructing, and administering the city road networks. It has the vision to enable Addis Ababa City to have efficient, quality, standardized, comprehensive, sustainable, and accessible transport infrastructure (Bihon, 2020). The city's efforts in integrating eco-friendly techniques and sustainable practices in pavement maintenance can serve as a case study for evaluating the extent of practices of such methods in a developing urban area.

Addis Ababa and the City Road Authority (AACRA) provide a unique case for studying eco-friendly pavement maintenance. The city's fast growth brings resource limits and environmental issues. AACRA's strategic vision also makes this study interesting. The insights gained from this case study can inform environmentally sustainable infrastructure practices in developing urban contexts, contributing to global efforts towards sustainable urban development.

## 1.2 Problem Statement

Pavement maintenance (PM) introduces new environmental impacts because of the huge amount of resource consumption, depletion of natural resources, waste generation, and energy consumption, as a result, sustainability issues become a worldwide forefront agenda of transportation agencies (Khahro et al., 2021). It is crucial to consider the environmental impacts of pavement maintenance practices and explore sustainable alternatives to mitigate these effects (Gransberg et al., 2014). In the case of Addis Ababa, the deteriorating road network results from inefficiencies and unsatisfactory road maintenance practices (Girmay, 2016), which underscores the necessity for the adoption of more sustainable and effective practices concerning pavement maintenance.

Addis Ababa is experiencing population growth and rapid urbanization which are necessitating extensive infrastructure development, including road networks. As the city grows, so does the demand for sustainable infrastructure increases (Dakito & Zerubabel, 2022). Moreover, the worsening of pavement conditions can lead to a reduction in access to important social services such as healthcare and education. This problem has been identified as a considerable challenge in recent years, which could potentially expose the social stability of Addis Ababa City, as it continues to experience rapid urbanization (JICA, 2019)

Research on PM in Addis Ababa aspects of maintenance strategies, surface type optimization, pavement section prioritization, and deterioration prediction models rather than sustainability. A sustainable approach is crucial for the road authority but there is no research directly focusing on sustainability. On the other hand, despite increasing awareness and efforts to incorporate environmentally sustainable practices in PM, there is an absence of a comprehensive understanding of the current environmental sustainability practices of AACRA. Additionally, Addis Ababa is dealing with environmental issues such as pollution and waste management and struggles with the depletion of nonrenewable resources.

Therefore, this research aims to address this gap by assessing the environmentally sustainable pavement maintenance practices in the two projects, with a focus on five specific areas of environmentally sustainable pavement maintenance practice indicators: material usage, maintenance techniques, energy and water consumption, maintenance management system, and environmental impacts.

**Objective**

To assess the practice of environmentally sustainable pavement maintenance projects at Addis Ababa city road networks. This study will be carried out through a comparative evaluation of two distinctive projects executed by the Addis Ababa City Road Authority (AACRA): the Lot-1 and Lot-2 projects.

**Research Question**

- ✓ To what extent do pavement maintenance projects practice environmental sustainability across the two different projects?

## 1.3 Relevance of Research

This research will study eco-friendly (environmentally sustainable) pavement maintenance projects in rapidly expanding cities like Addis Ababa. Analyzing AACRA's methods and execution practices of PM projects benefits other urban road authorities on how can adopt sustainable practices successfully. The finding is a valuable resource for pavement maintenance experts. It offers eco-friendly guidelines and helps policymakers and researchers from developing countries apply sustainable strategies and implies further or future research areas.

This research could greatly enhance the knowledge of eco-friendly (environmentally sustainable) pavement maintenance in developing countries. It promotes using these methods in different road management systems. Lessons from AACRA's experience can help other cities with similar challenges implement sustainable urban road upkeep effectively. Also, by examining the AACRA's strengths and weaknesses in environmental sustainability efforts the study identifies best practices and areas to improve which can then help create more effective strategies for future projects of AACRA's and contribute to global sustainable urban development goals.

This research also greatly boosts our understanding of eco-friendly pavement maintenance. Sharing AACRA's experience offers a helpful guide for other cities with similar issues. It may also encourage the adoption and enhancement of sustainable practices in road infrastructure. This fosters greener urban development.

# 2. Literature Review

## 2.1 Overview

Sustainable pavement current efforts prioritize reducing negative environmental impacts – think less pollution, resource depletion, and waste (Babashamsi et al., 2016). Minimizing negative impacts is a crucial step towards creating pavement projects with a positive environmental impact (Van Dam et al., 2015). Pavement is one of the important assets of a transportation infrastructure that significantly contributes to urban sustainability (Torres-Machi et al., 2018). In pavement maintenance, there is extensive consumption of natural resources, machinery, and fuel. Therefore, it is important during pavement construction and maintenance to use nonrenewable resources in an efficient manner and minimize negative environmental effects (Plati, 2019).

Gransberg et al (2014) examined environmentally sustainable pavement maintenance by the factor of emissions, noise, energy usage, substitute material usage, raw material consumption, management and monitoring of pavement in-service, and water quality. Montgomery et al, (2015) in their study highlight the importance of new technologies, materials, and processes that reduce energy and resource consumption and are key for improving environmental sustainability in pavement projects. The researcher Zhang (2016), in the study of development of sustainability evaluation for pavement maintenance projects, describes eight parameters: management, material, energy & water, technique, environment, safety, community, and innovation. Unfortunately, no standardized indicators exist but various articles and manuals detail such indicators to assess environmental sustainability across different areas. Thus, the environmental sustainability impacts areas such as material, monitoring & management, energy & water, environmental impact/emission, and methods/techniques are similar across the literature.

## 2.2 Sustainable Pavement Maintenance

Sustainable pavement maintenance goes beyond the scope of traditional maintenance practices, as it encourages the project team to not only address distresses but also enhance the overall performance of pavements (Torres-Machi et al., 2018). Environmentally sustainable pavement maintenance means finding a balance between using renewable resources at a sustainable rate, minimizing pollution generation, and conserving non-renewable resources for future generations (Venner, 2004). The United States of American Federal Highway Administration defined environmentally sustainable pavement maintenance as a practice of improving and preserving pavements while; i) minimizing environmental impact, ii) reducing the use of nonrenewable resources, iii) efficient energy use, and iv) utilizing eco-friendly techniques to decrease the need for frequent maintenance (Van Dam et al., 2015).

In this section materials and maintenance techniques that support sustainable pavement maintenance are investigated. It consists of three main areas: recycled materials; cold mix asphalt; and preventive maintenance. Recycled Asphalt Pavement (RAP) repurposes old asphalt. This conserves natural resources while enhancing durability and cutting emissions of greenhouse gases (Lee et al., 2010 & Zhao et al., 2021). Cold Mix Asphalt (CMA) is an energy-efficient alternative to traditional hot mix asphalt. It doesn't require high-temperature heating which lowers $CO_2$ emissions and saves energy (Rombi et al., 2023 & Dulaimi et al., 2022). Preventive maintenance techniques like crack sealing and pothole patching are essential for extending pavement life. They help minimize the need for major repairs and support environmental sustainability by conserving resources (Chiola et al., 2023 & Botella, 2022). This approach to road maintenance emphasizes using sustainable materials and methods to build strong and eco-friendly infrastructure.

**Recycled Materials**

Recycled Asphalt Pavement (RAP) comes from old asphalt that has been removed and processed for new pavement projects. This reduces the need for new materials and saves natural resources (Lee et al., 2010). Using recycled materials can extend a pavement's life by delaying repairs and lowering maintenance costs. RAP also cuts greenhouse gas emissions and reduces energy and water use during construction and maintenance. It supports environmental sustainability by limiting raw material production and decreasing landfill waste (Zhao et al., 2021).

Recycled asphalt is an eco-friendly choice commonly used in road repair to cut down on the use of raw materials. Recycling materials like crumb rubber and waste cooking oil with RAP make pavements last longer. This method also lowers environmental damage and cuts costs (Al-Mosawe & Mohammed 2023). Ahmed et al (2023) study shows that adding RAP to asphalt mixtures boosts indirect tensile strength and stability and improves deformation resistance. Research on the sameness of asphalt mixtures with RAP shows that mixing time and coarse aggregate distribution are key for good pavement. Using RAP and other recycled materials saves resources and makes roads tougher and more durable (Zhao et al., 2021).

Using Recycled Asphalt Pavement in pavement maintenance offers significant benefits for sustainability. It lowers environmental impact and saves money (Lee et al., 2010). Adding RAP to warm asphalt mixtures boosts tensile strength and bonding. Innovative rejuvenators with Castor wax and Corn oil enhance these mixtures resistance to moisture damage rutting and fatigue cracking resulting, in cost-effective durable outcomes (Ahmed et al., 2023). Using RAP in unbound pavement layers meets sustainability goals without losing strength with up to 40% RAP. Overall, incorporating RAP in pavement maintenance practices contributes significantly to sustainability by reducing waste, promoting cost-effectiveness, and improving pavement performance (Rout et al., 2023).

**Cold Mix Asphalt**

Cold Mix Asphalt is a type of asphalt mixture that is produced without the need for high-temperature heating, unlike traditional Hot Mix Asphalt. Instead of using hot materials CMA uses bitumen emulsions or foamed bitumen. This mix can be prepared and laid at room temperature making it ideal for cold areas and bad weather (Rombi et al.). 2023). CMA is drawing attention due to its environmental benefits such as lower energy use and reduced CO2 emissions compared to HMA. By not heating aggregates and bitumen it cuts energy consumption and lowers greenhouse gas emissions reducing the carbon footprint (Dulaimi et al.). 2022).

Cold Mix Asphalt cuts energy use during pavement maintenance. Unlike traditional Hot Mix Asphalt (HMA), it doesn't require heating aggregates and bitumen. Instead, it uses emulsion (Chegenizadeh et al., 2022). It reduces CO2 emissions and environmental impacts as well. This helps manage transportation resources more sustainably (Shanbara et al., 2021). Dulaimi et al (2022) research shows that different types of CMA mixtures like open graded and dense graded need varying compaction energies to achieve ideal properties. This shows how important a good mix design is for energy-saving pavements. New foamed asphalt technologies in CMA production improve workability and performance. They provide potential energy savings and environmental benefits in asphalt construction (Rombi et al., 2023). CMA offers a sustainable option instead of traditional asphalt. It supports global efforts to lessen environmental impacts and enhance resource efficiency in pavement projects.

**Preventive Maintenance Techniques**

Preventive maintenance methods like crack sealing and pothole patching are crucial. They prolong pavement life and limit major repairs. These techniques keep pavements functional by addressing issues early before they become serious problems. This not only saves resources but also supports environmental sustainability (Chiola et al., 2023). These pavement maintenance methods support environmental sustainability by reducing the need for major rehabilitation projects that use many resources (Botella, 2022). For example, using recycled asphalt in maintenance can enhance sustainability by lowering new material demand and carbon footprints. Life cycle environmental impact assessments of techniques like fog seal with sand and micro-surfacing have shown these methods lower impacts significantly making them sustainable options for pavement repairs (Babashamsi et al. 2016). Innovative decision models that include construction length and performance indicators optimize pavement maintenance plans achieving high performance at low costs and promoting sustainability. Strategic use of pavement maintenance methods crack sealing and pothole patching preserves pavement extends service life and supports eco-friendly practices by minimizing resource use and impacts thus aiding resilient and sustainable transportation infrastructure (Babashamsi et al. 2016; Chiola et al. 2023).

Preventive maintenance techniques produce fewer greenhouse gas emissions and consume less energy compared to major rehabilitation projects. Maintaining roads in good condition conserves energy and lowers the environmental impact of road upkeep. These methods use fewer materials and create less waste which helps the environment. Extending pavement life reduces the need for new materials and cuts down the environmental footprint from their production and transport (Babashamsi et al., 2016). Training on sustainable factors and developing assessments that include carbon capture and resource renewal are vital for choosing eco-friendly pavement treatments. Using recycled materials like asphalt concrete and cement-treated recycled items in maintenance can greatly lessen environmental harm. The focus on minimizing the environmental impact of materials and procedures in pavement maintenance, design, and construction is essential for sustainable infrastructure (Botella, 2022).

## 2.3 Environmental Impacts of Pavement Maintenance

Pavement Maintenance (PM) is essential for infrastructure management, but it also has significant environmental impacts. Extracting and processing virgin materials like stone and gravel plus transporting them harms the environment (Montgomery et al., 2015 & Tiza et al. 2022). The energy used in these processes increases greenhouse gas emissions. Emissions from machines, dust generation, and asphalt production lower air quality (Barik 2015). Waste from maintenance and demolition makes waste management harder adding to environmental problems. Therefore, it is crucial to consider the environmental impacts of pavement maintenance practices and explore sustainable alternatives to mitigate these effects (Gransberg et al., 2014).

**Material Use and Depletion**

The environmental sustainability of PM is closely linked to material use and depletion, especially concerning the quarrying of virgin materials and the utilization of bituminous materials (Plati, 2019). Tiza et al. (2022) study highlights that material use and storage are linked to natural resource depletion. Extracting and processing raw materials have severe environmental effects like high energy usage and emissions of greenhouse gases (GHG) (Montgomery et al., 2015). Mining for aggregates in pavements harms the environment by destroying habitats and increasing carbon emissions (Gransberg et al., 2014). Bituminous materials from petroleum also pollute significantly during their extraction and processing phases. This process uses a lot of energy and releases many greenhouse gases contributing to climate change and ecological damage. (Plati, 2019).

Storing materials for pavement maintenance needs careful planning. We must consider environmental sustainability as well as traffic disruptions and effects on the community. Selecting an appropriate storage location is crucial to minimize traffic disruptions and ensure the convenience of hauling drivers (Yong,2019). The storage site should be wisely chosen based on the project's location and size and the surrounding community to reduce contamination and save resources (Negishi et al., 2022). For example: employing a material storage management system can centralize storage. This eliminates manual handling and boosts efficiency. A delivery mechanism within storage aisles can speed up item deliveries to different locations and improve operations (Kar & Jha, 2023). Using space-efficient storage units with slide rails increases safety and optimizes space use (Barik, 2015). An inventory of all stored materials on-site must be accurately recorded and accessible to the project crew to ensure smooth execution and adaptability (Misron et al., 2018).

Utilizing local materials in pavement maintenance projects offers significant environmental benefits, primarily by preserving energy and reducing emissions associated with material transportation. Local materials, defined as those sourced within 150 Km of the construction site can substantially cut down on fuel consumption and emission of greenhouse gases (Zhang & Mohsen, 2018). For instance, the transportation of aggregates over long distances is a major contributor to emissions of GHG in road construction, accounting for up to 26.5% of total emissions (Grilli & Balzi, 2023). Sourcing materials like gravel and steel slag locally reduces the need for long-haul transport. This cuts emissions and saves energy (Barik 2015). Using local resources also promotes environmental sustainability and boosts the local economy while ensuring projects finish on time (Mulyono & Anisah 2019).

### Energy Consumption

Energy use during a pavement maintenance project refer to the machinery and vehicles used. And the energy they consume throughout the maintenance process. Includes the energy required for material production, mix manufacturing, material transport, and the operation of maintenance equipment (Zhang, 2016).

Lower energy use in pavement maintenance by making equipment more efficient and improving transportation logistics. Utilizing fuel-efficient construction equipment or alternative fuels can mitigate energy-related environmental harms during construction (Wang et al., 2021). Preventive maintenance treatments, such as cold in-place recycling, have been shown to consume less energy (~22 GJ/lane/km/yr) compared to conventional methods (~33 GJ/lane/km/yr) (Babashamsia et al.,2016). Additionally, incorporating renewable energy sources, like the Solar Road System, can further lower greenhouse gas emissions and reduce reliance on fossil fuels (Svab et al., 2021). Efficient transport strategies are crucial; material transportation and crew movements for operation, investigation, supervision, inspection, and monitoring should be optimized to minimize travel distances and enhance transport efficiency. This can be achieved by designing optimal routes and using GPS tracking for haulage trucks to prevent delays and reduce fuel wastage (Zhang, 2016). Implementing these strategies reduces emissions from electricity production and fuel consumption. This contributes to a more environmentally friendly pavement maintenance process (Wang et al., 2021).

### Air Quality Impacts

Pavement maintenance projects significantly contribute to air pollution through emissions from machinery, dust generation, asphalt production, and waste generation. Machinery and vehicles used in these projects emit a collection of pollutants, including particulate matter, volatile organic compounds (VOCs), and greenhouse gases. For instance, the operation of road maintenance vehicles such as multiple tie tampers and ballast regulators generates substantial fugitive dust (FD) concentrations, which can be as high as 17.55 mg/m³ (Azarov et al., 2018). Additionally, the production and application of warm mix asphalt (WMA) and hot mix asphalt (HMA) release VOCs and hazardous air pollutants (HAPs), posing health risks to workers and nearby residents (Romanias et al., 2023). Dust generation is another critical issue, particularly from road dust and particulate matter (PM) resulting from traffic and construction activities. Road excavation and restoration work, for example, can produce high levels of particulate matter10, especially during road-cutting activities (Azarov et al., 2018). Moreover, the life-cycle stages of pavement maintenance, including material transportation, production, and resurfacing activities, contribute significantly to particulate matter2.5 emissions, with material supply chains and construction activities accounting for a large portion of the annual particulate matter2.5 intake (Rath, 2022). Emissions from asphalt plants, primarily from fuel combustion and particulate matter diffusion, also add to the pollution load, although advanced emission control systems like wet scrubbers and baghouse filters can mitigate these emissions (Azarov et al., 2018). Overall, the combined effects of machinery emissions, dust generation, asphalt production, and waste generation during pavement maintenance projects have substantial negative impacts on air quality and human health, necessitating the implementation of effective pollution control measures and sustainable practices (Rath, 2022). Overall, a comprehensive approach involving advanced machinery, effective dust control, and environmentally friendly practices is essential to mitigate the air pollution caused by pavement maintenance projects.

## 2.4 Pavement Sustainability Assessment Tools

Assessing environmental sustainability in the transportation sector is an emerging field, with a particular emphasis on its application to pavement maintenance projects (Ozer et al., 2016). It is challenging to establish a consistent, universally recognized approach to compare environmental sustainability. Typically, four main measurement tools are employed in evaluating sustainability aspects, namely performance assessments, sustainability rating systems, analysis of life cycle cost, and assessment of life cycle (Van Dam et al., 2015 & Ozer et al., 2016), a summary of these are presented in table 2.1.

Rating tools can serve as a valuable tool and as a metric-based management instrument for evaluating the success of projects or programs (Bryce et al,2017). In general, a rating system typically consists of a comprehensive list of potential scenarios involving sustainable elements that an organization or project may face. It assesses the performance of each situation within a project, and a resulting score is assigned to reflect the stage of sustainability achieved (Ozer et al., 2016). These rating tools are in detail discussed in the following sub-sections.

Table 2.1 Summary of pavement sustainability assessment methods

| Methods | Description | Focus Area and Applications |
|---|---|---|
| **Performance assessment** (Ozer et al., 2016) | Directly measures how well a pavement meets its intended purpose (strength, durability, smoothness, etc.) | focuses solely on technical performance<br>focuses on pavement functionality, not resource use or emissions |
| **Life-cycle cost analysis (LCCA).** (Babashamsia et al., 2016) | Considers all costs associated with a pavement over its entire lifespan (construction, maintenance, rehabilitation, etc.) | Doesn't directly assess environmental impacts.<br>Relies on accurate cost estimates, which can be challenging to predict. |
| **Life-cycle assessment (LCA).** (Wang et al.,2014) | Considers resource extraction, energy use, emissions, and potential for recycling | Can be complex and data-intensive, requiring specialized software and expertise |
| **Rating systems** (Ozer et al., 2016) | tools used to quantify and compare sustainability best practices through a common metric, often in the form of points | Provides a simple and easily understandable way to compare the sustainability of different pavement systems |

**Pavement Sustainability Rating Tools**

Sustainability rating tools are invaluable for assessing and improving the environmental impact of pavement maintenance projects. They offer a structured framework for evaluating various sustainability aspects, ultimately leading to more informed decision-making and promoting greener practices in the pavement industry (Ozturk, 2019). They can serve as an effective assessment method, evaluating a project's sustainability based on a list of sustainable situations and providing a score indicating its overall sustainability level (Zhang, 2016).

A number of these rating tools have been initiated for the purpose of use in the maintenance, construction, and operation of pavement systems with the aim of promoting environmental sustainability. According to the Bryce et al (2017) and Zhang & Mohsen (2018) study some of the more notable pavement sustainability rating systems are; 1) GreenLITES recognizes road project design, planning, maintenance, and operations practices, 2) GreenPave emphasizes specifically on design and construction of pavement stages, 3) $BE^2ST$ a sustainability rating tool used for road projects during the designing and planning stage 4) INVEST undertake an assessment of sustainability in agency's operational and maintenance methodologies, systems, and programs, and 5) PSIM practically quantify and assess pavement maintenance projects at the individual stage. It makes different sizes of individual maintenance projects easily comparable and is solely designed for pavement maintenance (Zhang & Mohsen, 2018). In the following section, each of the rating systems is discussed briefly.

**i. GreenLITES sustainability rating tool**

GreenLITES is a short form of Green Leadership in Transportation Environmental Sustainability. It is a pavement sustainability evaluation tool developed by the Transportation Department of New York State to make road projects more sustainable. It looks at how projects include eco-friendly practices, like using local materials and energy efficiently (Chiola et al., 2023). It started as an environmental assessment tool but grew into an approach covering the three pillars of sustainable development: environment, society, and economy. This tool helps ensure that transportation projects are environmentally friendly and consider long-term sustainability goals (Tran & Yang, 2021). Projects get certified based on credit scores: certified, silver, gold, or evergreen, depending on sustainability levels. Although maintenance projects don't have levels higher than certified, if a maintenance project gets more than 29 points, by using the standard GreenLITES rating system, it could be certified as evergreen, gold, or silver (Zhang & Mohsen, 2018). GreenLITES assesses all projects of pavement maintenance, whether they come with plan sheets or just proposals. The only direct reference to pavement maintenance is the minimization of hazardous materials in the Resources and Materials category (Zhang, 2016).

**ii. GreenPave sustainability rating tool**

Greenpave is a tool developed by the Ontario Ministry of Transportation to make pavements more sustainable. It helps designers and contractors make environmentally friendly choices when building roads. Their goals are based on discussions with stakeholders and other sustainability tools, making them practical and relevant. Greenpave aims to improve pavement sustainability by considering factors like longevity, environmental impact, and innovation in design (Bryce et al., 2017). GreenPave emphasizes the design and construction stages of pavement projects. The rating system has four categories and 14 subcategories for evaluating sustainability in pavement projects. Contractors and consultants use a simple spreadsheet to calculate points for their designs. Points are assigned based on guidelines provided in the GreenPave Reference Guide (Ozturk, 2019).

**iii. BE$^2$ST sustainability rating tool**

BE$^2$ST a sustainability rating tool that stands for (Building Environmentally and Economically Sustainable Transportation Infrastructure Highways) focuses on constructing transportation infrastructure like highways in a way that is good for the environment and the economy (Ozturk, 2019). BE$^2$ST sustainability rating tool helps in determining the different sustainability options priorities and evaluates projects in terms of sustainability, providing a way to measure and compare their sustainability level (Zhang,2016).

The aim is to build highways that are safe, and efficient, and consider the impact on the environment, economy, and society. This approach means looking at things like reducing energy use, managing costs effectively, ensuring safety, and protecting the environment. By following BE2 ST principles, highway projects can contribute to creating a sustainable society by balancing economic, environmental, and social values (Ozturk, 2019). However, BE$^2$ST does not address maintenance and operations, which are crucial for the long-term sustainability of pavement systems (Zhang & Mohsen, 2018).

**iv. INVEST sustainability rating tool**

INVEST sustainability rating tool stands for Infrastructure Voluntary Evaluation Sustainability Tool. It is a web-based tool created by the Federal Highway Administration to help transportation agencies make their highway projects more sustainable by following best practices (Tran & Yang, 2021). Projects receive a grade based on their INVEST score: bronze, silver, gold, or platinum, depending on the score percentage achieved. INVEST tool has been updated to version 1.3, which includes four modules with one focused on Operation and Maintenance (OM). The Maintenance and Operation module aims to evaluate the sustainability of an agency's maintenance and operations practices. (Zhang,2016)

Out of the 14 indicators under the OM module, 11 are specific to pavement maintenance. These indicators aim to meet the needs of transportation agencies, focusing on the management and planning of pavement maintenance, rather than the individual project level. As a result, it is advisable to utilize INVEST along with other rating tools when evaluating pavement maintenance projects.

**v. PSIM sustainability rating tool**

PSIM sustainability rating tool stands for the Pavement Sustainability Index for Maintenance and helps improve the sustainability projects of pavement maintenance. It looks at how maintenance impacts the environment and uses resources. PSIM works to connect theory with real-world sustainable practices in the pavement maintenance field. It finds areas to improve in current maintenance by focusing on specific sustainability indicators and project points. It evaluates projects with an index that lets users easily compare the sustainability of different activities. PSIM tracks and monitors sustainability features during and after project completion. This offers insights into how well sustainability goals are met. By involving stakeholders early on and raising public awareness over time while tracking goals it encourages a proactive approach to sustainable maintenance (Zhang 2016).

The evaluation process in PSIM is thorough and well-organized. Projects are assessed based on various rating categories, including material, management, safety, energy and water, technique, environment, innovation, and community. Each category contains specific indicators to measure relevant sustainability factors. Priorities and points are assigned to show their importance in the evaluation. After assessing a project and calculating its Pavement Sustainability Index (PSI) score certification levels from one to three stars are awarded. This signifies the project's sustainability achievements (Zhang & Mohsen,m 2018).

The determination of certification levels in PSIM hinges on several key factors. The PSI score shows the project's sustainability performance based on the number of indicators addressed and the points earned. This method covers a variety of sustainability aspects and rewards projects for being thorough and effective. The PSIM star system (one to three stars) clearly indicates a project's sustainability level. It helps in comparing projects and encourages best practices within pavement maintenance.

In conclusion, each of these pavement maintenance sustainability rating tools has its unique strengths and limitations. GreenLITES offers a comprehensive approach but may be complex to implement and the only indicator that directly references pavement maintenance. BE2ST and GreenPave provide detailed assessments for the design and construction stages but miss out on maintenance and operations. INVEST focuses on the management and planning of pavement maintenance, rather than the individual project level. PSIM practically quantifies and assesses pavement maintenance projects at the individual stage. It makes different sizes of individual maintenance projects easily comparable and is solely designed for pavement maintenance (Zhang & Mohsen, 2018). Therefore, this study will use these maintenance projects' Sustainability Index (PSIM) rating tool as the main tool to assess the extent of environmental sustainability among different pavement maintenance projects in Addis Ababa.

## 2.5 Conceptual Framework

However, for this study, based on the literature discussed above five environmental sustainability focus areas have been chosen, which are common indicators or similar across many literatures, with their specific indicators as being key components to promoting environmental sustainability. These chosen key indicators were material usage, maintenance techniques, energy and water consumption, maintenance management systems, and environmental impacts. By analyzing these aspects across two AACRA pavement maintenance projects (Lot-1 and Lot-2), the research will identify variations in their environmental sustainability and provide a comprehensive understanding of AACRA pavement maintenance projects' sustainability, as shown in the conceptual framework diagram in figure 2.1.

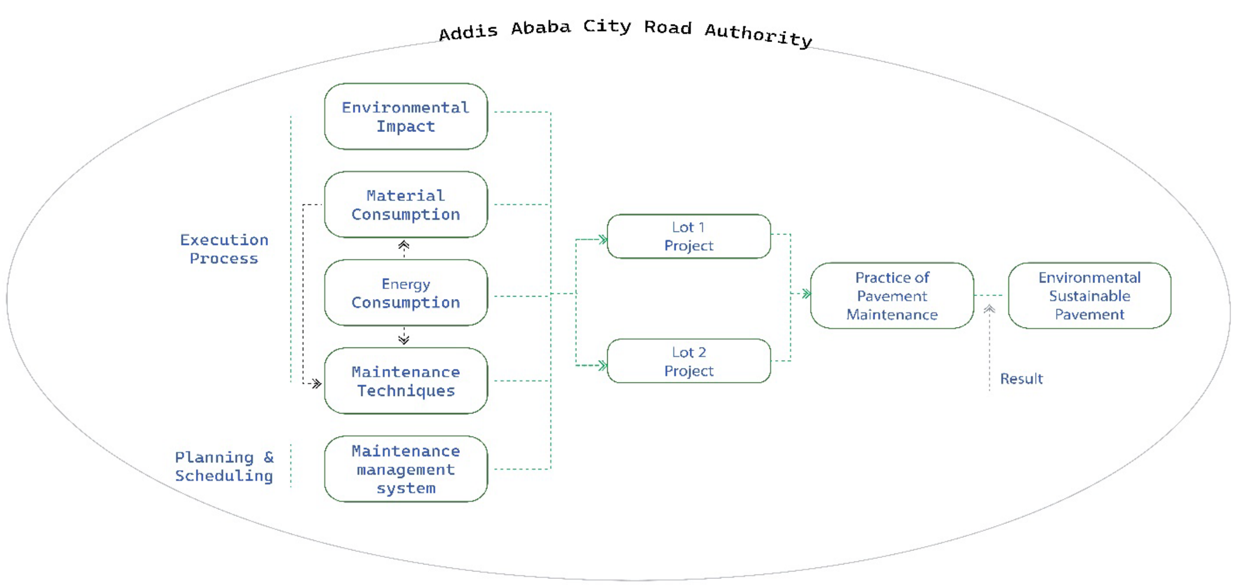



Figure 2.1 Conceptual Framework

# 3. Research design, methodology

## 3.1 Research Type and Approach

A mixed-method approach was used, combining both quantitative and qualitative data collection and analysis. These were integrating the quantitative and qualitative findings to create a holistic picture of environmentally sustainable pavement maintenance in Addis Ababa.

The PSIM Rating framework is used as the main tool to assess the extent of sustainability. Indicators are the basis for assessment. The assessment encompassed numerous categories, including material usage, maintenance techniques, management practices, energy and water consumption, and environmental impact. Each category was further subdivided into specific indicators, each assigned a maximum point value. The project's performance was evaluated against these indicators, and actual points were awarded accordingly.

## 3.2 Operationalization of Variables

This operationalization process provides a clear and comprehensive understanding of the conceptual framework presented in Chapter 2; hence table 3.1 outlines the primary concepts and variables, along with five main categories and 26 indicators, which are the basis for quantifying the sustainability of pavement maintenance projects. The table serves to specify the exact areas of investigation, the measurement of the indicators, and the overarching framework of the study. The measurement units are adapted from the PSIM framework, and the table describes only the total points attained by each indicator, but for each indicator detailed criteria are available with their rating points see Appendix 1.

A typical PSIM is composed of two integral factors: the total count of applicable indicators and the achievement percentage associated with those indicators. After the evaluation of maintenance projects by the indicators included, then consider both the percentage of earned points and indicators covered. The certification levels will be given based on achieving scores beyond predetermined thresholds (non-sustainable, one-star, two-star, and so on) see table 3.3. The number of stars indicates the environmental achievements of pavement maintenance projects from non-sustainable to more sustainable (Zhang, 2016).

Table 3.1: Operationalization of variables and indicators

| Concept | Category | Indicators | Description | Measurement unit (adapted from PSIM) |
|---|---|---|---|---|
| **Environmentally Sustainable Pavement Maintenance** | **Material usage** | recycle material | Considering the project, using recycled materials to replace raw materials whenever possible | the proportion of materials reclaimed & utilized, and the recycled construction materials percentage during the maintenance project. range of points of 0-5. |
| | | local material | To the extent that it is practical, consider acquiring construction materials from nearby sources | the proportion of local materials to total materials utilized. points range: 0-2 |
| | | alternative material | it includes alternative materials and can be reused for different structural from other industries' for layers of pavement | the amount of alternative materials used during maintenance. points range: 0-2 |
| | | material storage | Proper protection of construction materials is necessary while they are stored at the construction location. | material storage actual practices on site and document on file. points range: 0-2 |
| | | material production | The consideration of the sustainability of the asphalt/concrete plant is essential. | material production plant had a sustainability program certification. points: 0-4 |
| | **Maintenance Technique** | technique selection | It is essential to offer reasons for selecting specific maintenance techniques over others | Suitable justifications are given for maintenance technique selection. points: 0-2 |
| | | preventive maintenance | the practice of preservation is considered to mitigate distress | preventive practices are included in the project in percentage to the overall project. possible points: 0-2 |
| | | distress reason | Investigate the sources to determine the reasons behind distress to help with maintenance decisions | inspecting and analyzing distresses made before selection of maintenance technique points: 0-4 |
| | | uneven surface | It is required to take proper action to rectify the distinguishable differences between the pavements that are maintained and those that are adjacent. | around the manholes and edges of the maintenance area are improvements: 0-2 |
| | | standard procedure | Considering standard maintenance procedure | a maintenance working crew follows procedures of standard. points: 0-8 |
| | | drainage | It is essential to ensure the proper maintenance and protection of the drainage system | any drainage improvement. Possible Points: 0-10 |
| | **Maintenance Management** | maintenance schedule | Complete maintenance tasks on schedule; plan performance monitoring in advance | the pavement maintenance project has a schedule and plan. points: 0-3 |
| | | project record | the records of past and present maintenance work should be readily available | project documentation includes the recording of data, as well as the establishment of a database. points range: 0-4 |
| | | crew training | Construction team: be aware of procedures, equipment operation, standards, and sustainability | the crews are well trained as expected. points range: 0-4 |

| | | | | |
|---|---|---|---|---|
| Environmentally Sustainable Pavement Maintenance | | emergencies | It is essential to establish formal plans for emergencies to ensure the timely delivery of projects. | any plans for emergency work. points: 0-3 |
| | | work zone management | Ensure clear work zone setup, addressing the needs of workers, traffic, and nearby residents. | work zone management activities. points: 0-3 |
| | | project team | the project team must be informed of all project-related details, and the duties of each team member should be explicitly designated. | responsibility of the project team members is established and clear. points: 0-3 |
| | **Energy & water consumption** | Efficient lighting | It includes utilizing high-efficiency bulbs and renewable energy for both construction and road lighting. | in maintenance projects renewable energy, and highly efficient lighting are included. Points range: 0-3 |
| | | Transport energy usage | considers the energy consumption for moving construction materials, machinery, and the work team | the project site transporting vehicles energy usage is enhanced. Points: 0-2 |
| | | asphalt mixture energy usage | the energy consumption associated with heating aggregates to facilitate its mixing with asphalt is considered. | in pavement maintenance the applied percentage of warm mix asphalt. points range: 0-2 |
| | | Equipment energy usage | It takes into account the energy consumption of the construction equipment and the onsite workforce. | construction equipment energy usage is enhanced. Points range: 0-3 |
| | | Water consumption | It considers the water consumption during the project | the management of water and usage. Possible Points: points range: 0-2 |
| | **Environmental impact** | wastes | The waste generated by the project, such as construction debris, leftovers, or old pavement materials considered. | wastes are treated and well disposed of. points range: 0-6 |
| | | air quality | In the context of pavement maintenance, air quality is affected by the presence of various pollutants, such as emissions, smoke, and dust. | quality of air during the project emissions, smoke, and dust. points range: 0-4 |
| | | noise control | The noise generated by the project, both during construction and from traffic on the newly maintained pavement. | Any type of monitoring of onsite noise level, and the project team is keeping a record of traffic and construction noise. Points range: 0-4 |
| | | vibration control | The vibrations caused by construction activities on the pavement, which can impact nearby structures and residents. | Any type of monitoring of onsite vibration control, and the project team is keeping a record of vibration. Points range: 0-2 |

## 3.3 Study Area Description

This research uses the case study AACRA's Lot 1 and Lot 2 pavement maintenance projects, as the main strategy. This case study approach facilitates direct access to project personnel, offering opportunities for in-depth interviews and observations to gather qualitative and quantitative data on practices in environmental sustainability of pavement maintenance projects. The study focused on these two projects because the projects employed distinct project crews (with varying expertise and experience) and utilized different equipment creating an ideal opportunity for comparative analysis. Additionally, the projects' locations are in different areas of the city likely exposing them to unique maintenance management, maintenance techniques, and environmental impacts, see figure 3.1. This provides a richer dataset to assess the extent of the environmentally sustainable pavement maintenance practices that vary between the projects. However, both projects were executed under the AACRA umbrella, which means they likely operated under similar organizational guidelines, standards, and access to resources. Therefore, focusing on these two specific projects allows for a direct comparison of the extent of the project's environmental sustainability practices based on the material usage, maintenance techniques, energy consumption, and environmental impact under the PSIM rating tool.

## 3.4 Data Collection and Sampling Method

### 3.4.1 Sampling Technique

**Sampling pavement sections**

Lot 1 and Lot 2 projects execute multiple road sections or segments. Considering the extensive and varied road network managed by the AACRA, a representative sample of pavement segments was carefully chosen for assessment. The Addis Ababa City Roads Authority manages the city's road network and road assets, categorizing roads based on traffic volume, function, and geometric attributes. These road classifications are Local Streets (LS), Collector Streets (CS), Sub-Arterial Streets (SAS), and Principal Arterial Streets (PAS) (JICA, 2019). This research focused on Principal and Sub-Arterial Street, pavement maintenance projects from January 2024 up to May 2024 either progress or completion. The time frame selection is because of the data availability by selecting the recent projects to get more data and the desire to analyze the most recent project.

The reasons why Principal & Sub Arterial Streets are a suitable choice for this research on environmentally sustainable pavement maintenance practices are. First, the Addis Ababa City Road Authority has already identified these two road types as a priority for maintenance and improvement, this makes them an ideal choice for studying environmentally sustainable pavement maintenance practices (Bihon, 2020). Second, given their importance, it's likely that more comprehensive data on maintenance activities, materials, and environmental impacts may be available for PAS & SAS compared to other road types.

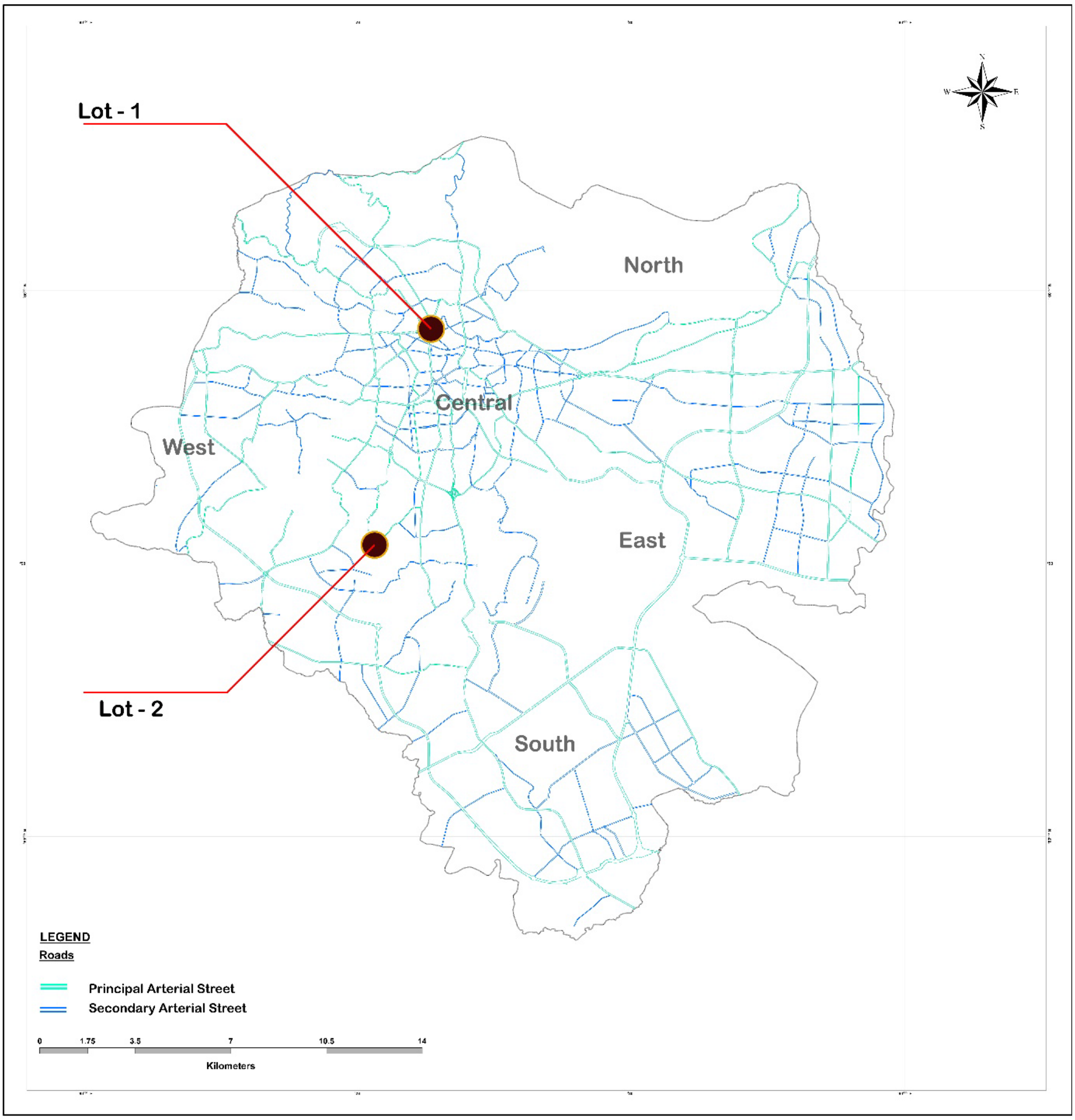
The researcher identified 16 road sections (9 from Lot 1 and 7 from Lot 2) classified as Principal or Sub Arterial Streets that were either completed or ongoing as of May 2024. These sections were maintained from January to May 2024. Three representative sections were then randomly selected from each project (Lot 1 and Lot 2) for further study.

**Sampling respondents**

The crucial factor in determining the respondents for the interview was their connection to and involvement in planning, scheduling, execution, monitoring, and managing AACRA pavement maintenance projects. The respondents are divided into three groups, AACRA officials and engineers directly involved in pavement maintenance projects (AACRA's Own Force Road Maintenance Department), AACRA road asset management staff, and Consultant staff working with AACRA maintenance projects. The selection of some respondents is based on the non-probability purposive sampling method. In table 3.2 a greater number of interviewees were selected from the AACRA's own force road maintenance department because the overall project is executed by this department and they are the key stakeholders, the other two are involved in less amount and their staff numbers are small.

Table 3.2 List of respondents

| **Department** | **Lot-1 Project** | | **Lot-2 Project** | |
|---|---|---|---|---|
| | Number | Respondents | Number | Respondents |
| AACRA's Own Force Road Maintenance department | 2 | Respondents from the Own Force Road maintenance lot -1 project designated as respondent 1($R_1$OL-1), respondent 2 ($R_2$OL-1) | 2 | Respondents from the Own Force Road maintenance lot -2 project designated as respondent 1($R_1$OL-2), respondent 2 ($R_2$OL-2) |
| AACRA Road Asset Management department | 1 | Respondents from the asset management lot -1 project (RAML-1) | 1 | Respondents from the asset management lot -2 project (RAML-2) |
| Consultant Staff | 1 | Respondents from the Consultant staff lot -1 project (RCSL-1) | 1 | Respondents from the Consultant staff lot -2 project (RCSL-2) |




Lot - 1 = Lot 1 pavement maintenance projects base (responsible for South and East city road networks)

Lot - 2 = Lot 2 pavement maintenance projects base (responsible for North, Central, and West city road networks)

Figure 3.1 Shows Addis Ababa City Road networks, Principal & Sub Arterial Streets

### 3.4.2 Data Collection Methods

**I. Field Survey**

Field survey data was collected with a standardized field survey datasheet, developed by the researcher according to the PSIM framework. This field survey sheet consists of the specific data of the project name, segment/section, categories, indicators, how to measure, rating strategy, and remarks. In this rating tool sheet, each indicator is described in detail to get information for a maintenance project and uses this information to assign a score or rating to the project. The rating system in the field survey sheet was designed as a checklist, questionnaire, or step-by-step guide, and involved different degrees of site observation, documentation and validation. see Appendix 1.

Two data collectors and one mentor were selected based on a rigorous set of criteria for field survey data collection; *Understanding of sustainability principles*: Demonstrated knowledge of sustainable practices and their experience in pavement construction and maintenance projects. *Effective communication*: Skilled at connecting with stakeholders like foremen and operators as well as technicians and engineers to gather precise and complete information. *Independence and objectivity:* A key requirement was the inspector's independence from pavement owners and project contractors to ensure impartiality and unbiased assessment, free from any influence by pavement owners or project contractors.

After their selection, the inspectors completed an online training program with Zoom meetings. The training featured two sessions 1.5-hour sessions each. The training focused on familiarizing them with the field survey sheet format and equipping them with the necessary skills to collect accurate and reliable data. To emphasize, I have recorded and maintained a database encompassing all these phases to enable the process to be revisited if necessary.

The inspectors collected data primarily through direct observation of pavement maintenance activities in the field. Also, the inspectors actively engage with foremen, operators, technicians, and engineers involved in specific projects to gather relevant information. A dedicated Telegram group has been established to facilitate ongoing communication, information sharing, and support among the data collector team. This ensures real-time coordination and fosters a collaborative approach to data collection.

#### II. Interview

In an effort to deepen the understanding of the field survey findings, I have reached out to key informants to provide information on the research questions and objectives. The semi-structured questions were prepared, and interviews were conducted with AACRA officials and engineers directly involved in each project and consultant staff involved in those projects. The intention of the interview was to critically assess the practices of sustainable pavement maintenance projects and increase the trustfulness, reliability, and accuracy of the practices obtained through the field survey. Additionally, during the interview more efforts were made to identify more implementation practices and challenges that were not identified through the field survey studies; and to get their perceptions on improvement strategies. The interview format and questions are attached in Appendix 2.

## 3.5 Data Analysis Approach

The research analysis integrates quantitative data with qualitative interpretations to thoroughly evaluate the pavement maintenance project. The PSIM certification level serves as the established benchmark for evaluation. Each case is assessed against this standard to determine its adherence to sustainability criteria. Sustainability performance data for each project is collected and presented in tabular format, detailing scores or ratings against various PSIM indicators. The PSI score, a percentage derived through the following calculation, is a key metric:

1. Count the number of indicators contained in the project (C).
2. Compute the maximum attainable points (Mp).
3. Rigorously assess sustainability measures implemented in the project against each indicator and sum the actual points earned (Ep).
4. Compute PSI as (C) / (Ep / Mp) x 100%.
5. Assign the corresponding PSIM certification level as per Table 3.3.

Beyond numerical presentation, the analysis provides descriptive interpretations of results, highlighting project strengths and weaknesses, and pinpointing factors contributing to low scores.

The analysis further compares overall sustainability scores by synthesizing field survey findings and interview results. Semi-structured interviews, transcribed and incorporated into Microsoft Word, form part of the qualitative data management process. Subsequent coding and analysis are conducted using Atlas.ti software. This comparative analysis dissects the evaluation into specific categories (material usage, maintenance techniques, etc.), enabling a detailed comparison of cases' performance across various sustainability aspects.

Table 3.3 Pavement Sustainability Index for Maintenance (PSIM) Certification Levels (Zhang, 2016)

| Approximate scoring rate | Quantity of Indicators | | |
|---|---|---|---|
| | 10 to 15 | 16 to 20 | 21 to 30 |
| less than 40% | Not sustainable | Not sustainable | ★ |
| 40% to 59% | Not sustainable | ★ | ★★ |
| 60% to 79% | ★ | ★★ | ★★★ |
| greater than 80% | ★★ | ★★★ | ★★★(Demonstration Project) |

### 3.6 Validation and Reliability

This research follows a triangulation strategy for the validation and reliability of the study. The data gathering took place in different ways from different sources which are field survey data collection and semi-structured interviews were employed. In the process of field survey data collection to ensure the reliability of the study the inspectors were selected with a key requirement, which was the inspector's independence from pavement owners and project contractors to ensure impartiality and unbiased assessment, free from any influence by pavement owners or project contractors. In addition, for the validation of these studies and to increase the trustfulness, reliability, and accuracy of the data obtained through the field survey, semi-structured questions were prepared, and interviews were conducted with AACRA officials and engineers directly involved in each project. And to ensure more validity the perspectives and experiences of consultant staff (Ethiopian Construction & Supervision Works Corporation) involved in those projects were included in this interview. Moreover, it is essential to note that every stage of the study, along with the data sources, has been carefully documented. A database has been established to facilitate the review of the entire process, should the need arise in the future.

Since both projects are executed under the same organization (AACRA), many external factors (e.g., regulations, and funding sources) are likely to be consistent. This enhances internal validity, allowing the research to attribute any observed differences in environmental sustainability more confidently to the specific project characteristics (management, techniques, equipment, material, etc.)

The study was conducted with a strong emphasis on ethical considerations. Participants were informed about the purpose of the research and the handling of their information. Their consent was obtained before proceeding, and their privacy was fully respected. Interviews were recorded solely with the participant's consent, and the recordings were deleted upon completion to protect their confidentiality.

# 4. Results, analysis and discussion

## 4.1 Introduction

This chapter presents results by integrating the quantitative and qualitative findings to create a holistic picture of environmentally sustainable pavement maintenance in Addis Ababa. The results are presented in this chapter in four sections.

In the first section, 4.2 the assessment results of Lot 1 pavement maintenance projects are analyzed and discussed. Three case studies from the Lot 1 project are presented here. This section examines the sustainability practices used in these projects based on the PSIM framework.

The second section 4.3 looks at Lot 2 pavement maintenance projects. The results are discussed to highlight the different environmental sustainability practices used in these projects as a similar structure to the first section, which includes three case studies of the Lot-2 project.

In the third section, 4.4 a comparative analysis of two projects, Lot 1 and Lot 2 is presented in this section. The comparison focuses on five areas: material usage; maintenance techniques; energy and water consumption; maintenance management systems; and environmental impacts. This section also identifies the strengths and weaknesses of each practice to determine best practices for future pavement maintenance projects. In the fourth section, 4.5 a critical reflection on the findings means a general discussion of the study's findings and their implications.

The figure 4.1 presents the case studies sections for both Lot-1 and Lot-2 pavement maintenance projects, providing a visual representation of the projects and their respective locations.

## 4.2 Lot-1 Pavement Maintenance Project

The general information about the Lot 1 project, the client, the contractor, and the consultant is given in table 4.1.

Table 4.1 General information on the Lot-1 project

| | |
|---|---|
| Project | Lot-1 Road Maintenance Project |
| Contractor | Own Force Road Maintenance Lot-1 Project |
| Client | Addis Ababa City Roads Authority Asset Management Directorate |
| Consultant | Ethiopian Construction & Supervision Works Corporation (ECSWC) Transport Design Supervision Works Sector |
| Financed by | Road Fund and Addis Ababa City Administration |
| Project Location | Addis Ababa City (North, Central, and West Regions) |
| Type of works | Maintenance of Existing Pavement, Rehabilitation Work, Patching and Overlay<br>Drainage (Cleaning and Maintenance)<br>Curb Stone Maintenance and Construction<br>Access Road Maintenance |

The Own Force Road Maintenance Lot-1 Project has established project offices around St. George Church Piassa for the Lot-1 Road Maintenance Project.

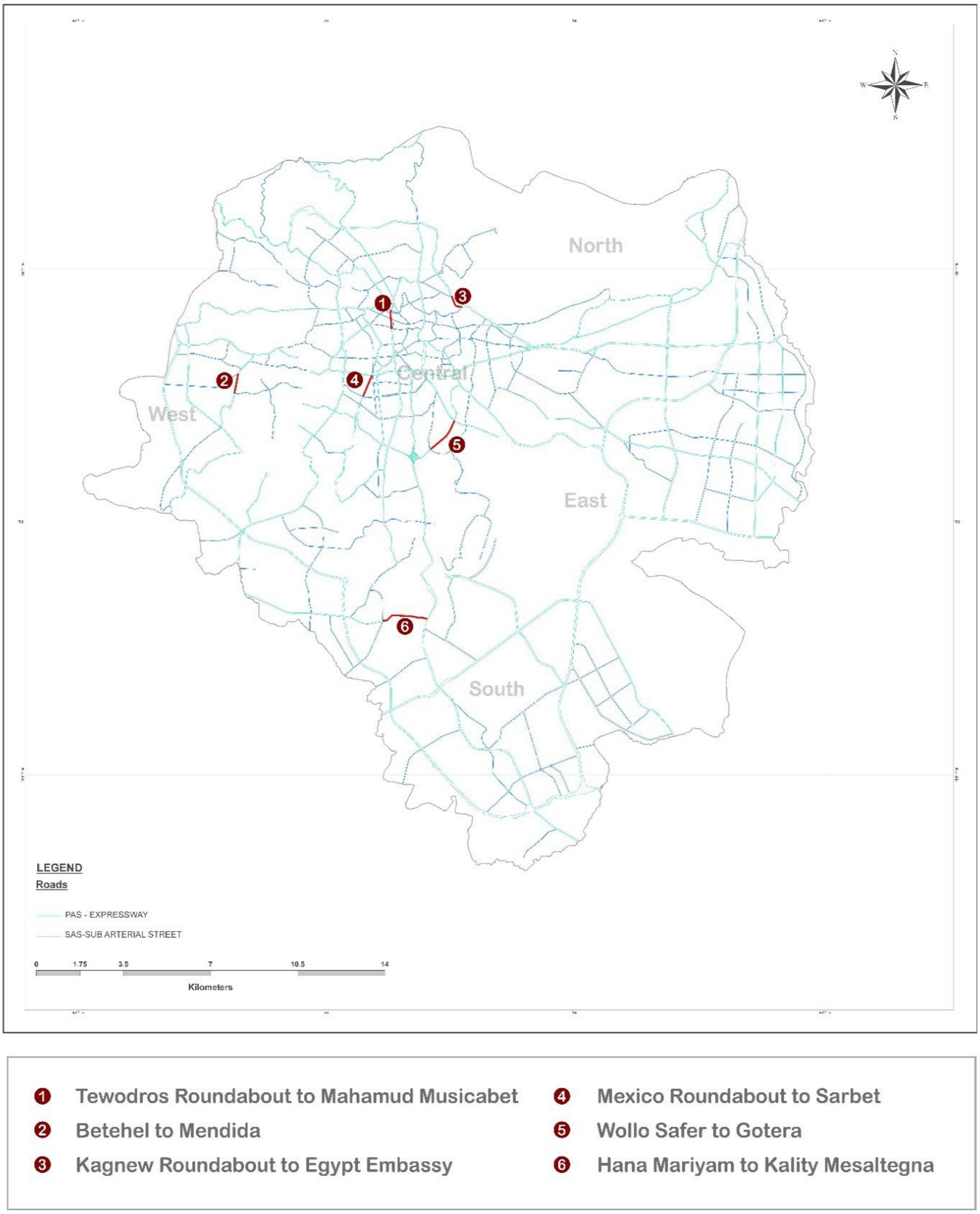



Figure 4.1Shows case study road sections for both Lot-1 and Lot-2 projects

**Case Study 1**

The first case study selected was the **Betehal** to **Mendida** sub-arterial road section mill and overlay maintenance project. This road section is a sub-arterial road, and its project length is about 1.5 km and its width is approximately 15-20m. The assessment result of this road section is presented in Table 4.2.


Photograph 1 Field view of the Betehal to Mendida project site

In the photograph 1 of the Betehal to Mendida project site shows a few issues that are worth addressing to improve the sustainability of the maintenance project. First, waste and debris are scattered around the site, which could pose a hazard to workers and passersby. Second, the absence of traffic signs could lead to confusion and disorganization, potentially causing accidents. Third, the placement of machinery on walkways is a significant safety concern. This issue could result in accidents, injuries, or even fatalities. Therefore, it's essential to keep machinery away from walkways and designate separate areas for equipment and pedestrian traffic. Lastly, the uneven surface around the edges of the maintenance area, the maintained pavement and the old adjacent pavement section, could pose a tripping hazard. To ensure the safety of workers and pedestrians, it's crucial to maintain a smooth and even surface throughout the site.

Table 4.2 Betehel to Mendida pavement maintenance project

| Category | Indicators | Maximum points | actual points | Explanation |
|---|---|---|---|---|
| Material usage | local material | 2 | 2 | material within reasonable distances was used within a radius of 150km from the project site |
| | material storage | 2 | 0 | materials are not properly handled, wastage of materials observed |
| Maintenance Technique | technique selection | 2 | 1 | they selected the maintenance technique by considering aspects of the financial and longevity |
| | preventive maintenance | 2 | 0 | overall, no preventive maintenance is included in the project |
| | distress reason | 4 | 3 | distress data collected through the roughness-detecting vehicle and mobile visual inspections then analyzed for repair type determination |
| | uneven surface | 2 | 0 | around the edges of the maintenance area, the surface is not smooth |
| | standard procedure | 8 | 4 | milling and overlay followed the standards of the AACRA manual |
| | drainage | 10 | 0 | the drainage issue was not addressed, some wastes and debris were observed that blockage of the drainage line |
| Maintenance Management | maintenance schedule | 3 | 2 | the starting and finishing times of the projects were published through Telegram |
| | project record | 4 | 2 | the project data was recorded on contractors' database like weekly, monthly |
| | work zone management | 3 | 0 | the asphalt milling machine was parked on the walkway, and traffic signs were not placed |
| | crew training | 4 | 2 | the crew members are experienced, but the training isn't common |
| | project team | 2 | 1 | the project has a designated team leader, and the team isn't aware of their specific duties. |
| Energy & water consumption | Transport energy usage | 2 | 1 | data on energy usage for transportation has been compiled |
| | Equipment energy usage | 3 | 2 | the construction equipment fuel utilization track system is available like GPS to control working hour |
| | Water consumption | 2 | 0 | N/A |
| Environmenta l impact | wastes | 6 | 4 | all milled materials are reused for access roads, but some wastes are not clear from the site well |
| | air quality | 4 | 1 | there is a dust control mechanism, showering with water |
| Total points | | 65 | 25 | |

Table 4.2 presents the PSIM rating tool assessment result of the **Betehel** to **Mendida pavement maintenance project** based on different environmental sustainability indicators. The project was evaluated under 18 PSIM indicators. It earned 25 points out of 65 possible points. This led to a PSI score of 18/38.46%. This indicates the project did not achieve the PSIM certification for environmental sustainability. It failed in several key areas.

The Bethel to Mendida pavement maintenance project failed to be sustainable due to major issues with drainage, that undermine the sustainability and effectiveness of road infrastructure. Waste and debris weren't cleared and caused blockages in the drainage lines. This affects road durability and safety. This aligns with findings from Bihon's study, which identified poor side drainage systems as a severe cause of road pavement failure (Bihon, 2020). Effective drainage is crucial for maintaining road integrity, as water accumulation can lead to rapid deterioration and increased maintenance costs. Poor work zone management was another problem; there were no traffic signs and machinery was placed on walkways. This endangers both workers and the public and shows a need for better safety measures. Also, materials were mishandled and improperly stored which led to wastage and inefficiency. This issue is reflective of broader challenges in road maintenance practices across Africa, where inadequate financing, lack of technical expertise, and poor administration hinder sustainable highway infrastructure. To address these issues, integrating GIS-based techniques into road maintenance management can enhance systematic planning and execution, promoting sustainability (Ngene et al., 2021).

While the project demonstrated strengths in data collection, in which the project team effectively collected and analyzed distress data to determine the appropriate repair type, demonstrating a commitment to evidence-based maintenance strategies. Communication of the project schedule through Telegram enhanced awareness and transparency among stakeholders. However, these positives were overshadowed by earlier mentioned issues.

**Case Study 2**

The "**Tewodros Roundabout** to **Mahamud Musicabet"** patching and tiny overlay project was one of the corridor development projects of Lot-1. This road section is a principal arterial road and its project length is about 1.4 km and its width approximately 25-30m. The assessment result of this road section is attached in Appendix 3 table 1.

Photograph 2 Field view of Tewodrose Roundabout to Mahamud Musicabet the project site

The photograph 2 displays the Tewodros Roundabout project during the road maintenance process, with a specific focus on the maintenance area. No noticeable enhancements were implemented around the manholes in the area mentioned above.

The environmental sustainability of a pavement maintenance project of a road section from "**Tewodros Roundabout to Mahamud Musicabet"** was assessed with 20 PSIM indicators, *see Appendix 3 table 1*. Hence, the project was evaluated under 20 indicators of PSIM and earned 33 points out of a possible 74, resulting in a PSI score of 20/44.6%. This score indicates that the project achieved one PSIM star, signifying a moderate level of sustainability. While the project demonstrated some positive aspects in terms of material sourcing and project management, there were significant shortcomings in areas such as recycled material use, preventive maintenance, drainage, and environmental impact. The project did not fully capitalize on the benefits of using RAP, which has been shown to be environmentally advantageous by reducing the exploitation of natural resources and lowering processing and hauling costs (Reta et al., 2018). Additionally, the project lacked a robust preventive maintenance strategy, which is crucial for addressing medium distress and avoiding the need for complete reconstruction, thereby extending the lifespan of the pavement and reducing long-term costs (Rout et al., 2023). The drainage system also appeared to be inadequate, which is a critical component in road construction to prevent water accumulation and subsequent damage to the pavement structure.

**Case Study 3**

The third case study selected from the Lot-1 project was the **Kagnew Roundabout** to **Egypt Embassy** pavement maintenance. This road section is a Sub-arterial road, and its project length is about 1.0 km, and its width is approximately 10-12 meters. The PSIM assessment result of this road section is attached in Appendix 3 table 2.


Photograph 3 Field view of the Kagnew Roundabout to Egypt Embassy project site

The photograph 3 depicts the field perspective of a cement preparation process for the purpose of stabilizing and on-site recycling of base course material at the Kagnew Roundabout maintenance project. Furthermore, the image depicts the recycled materials following the reprocessing procedure.

The PSIM rating tool assessed the results of the **Kagnew Roundabout to Egypt Embassy** pavement maintenance project using various environmental sustainability indicators, *see Appendix 3 table 2.* The evaluation covered 22 PSIM indicators. Hence this Kagnew roundabout to Egypt Embassy pavement project in Addis Ababa scored a Pavement Sustainability Index (PSI) of 22/61.54%, earning it two PSIM certification stars, indicating a commendable level of sustainability.

The project showcased several strengths: high recycled material use, proactive distress analysis and inspection, and a careful maintenance technique selection process. The base course used more recycled materials/in situ recycling base course/ than raw ones for better environmental sustainability. The use of RAP in the base course, as highlighted in multiple studies, underscores the project's commitment to environmental sustainability by reducing the exploitation of natural resources and minimizing construction waste (Reta et al., 2018). This approach aligns with global trends in road construction and maintenance, where recycled materials are increasingly used to balance economic progress with environmental preservation (Tatyrek & Mestanova, 2022). The project also demonstrated proactive distress analysis and inspection, which are crucial for identifying and addressing pavement issues before they escalate. Identifying and fixing pavement issues with techniques like cement stabilization showed data-driven decisions and a focus on long-term performance. The techniques of cement stabilization not only enhance the structural integrity of the pavement but also extend its lifespan, thereby ensuring long-term performance (Bressi et al., 2022).

However, the project also exhibited notable weaknesses, primarily in work zone management and emergency preparedness. The lack of traffic signs and poor management in the work zone put workers and road users at risk. Inadequate emergency response plans could make unexpected incidents worse.

## 4.3 Lot-2 Pavement Maintenance Project

General Information

The general information about the Lot 2 project, the client, the contractor, and the consultant is given in table 4.3.

Table 4.3 General information on the Lot-2 project

| | |
|---|---|
| Project | Lot-2 Road Maintenance Project |
| Contractor | Own Force Road Maintenance Lot-2 Project |
| Client | Addis Ababa City Roads Authority Asset Management Directorate |
| Consultant | Ethiopian Construction & Supervision Works Corporation (ECSWC) Transport Design Supervision Works Sector |
| Financed by | Road Fund and Addis Ababa City Administration |
| Project Location | Addis Ababa City (South and East Regions) |
| Type of works | Maintenance of Existing Pavement, Rehabilitation Work, Patching and Overlay<br>Drainage (Cleaning and Maintenance)<br>Curb Stone Maintenance and Construction<br>Access Road Maintenance |

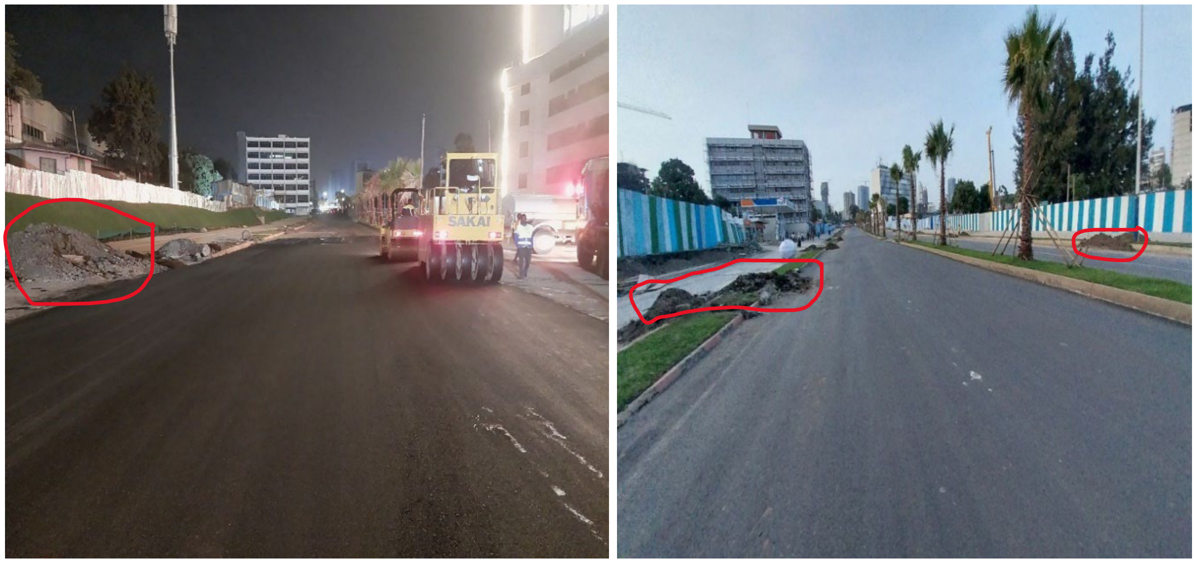
The Own Force Road Maintenance Lot-2 Project has established project offices around Germany Square Makaniassa for the Lot-2 Road Maintenance Project

**Case Study 4**

The "**Mexico Roundabout to Sarbet"** Pavement Maintenance Project was selected from Lot 2 projects, which is the principal arterial road section. It is a patching and overlay project with a starching length of 1.4 km and a width of approximately 35-40 meters. The PSIM assessment result of this road section is presented in Appendix 3 table 3.

In the photograph 4 of the Mexico Roundabout to Sarbet project site shows the waste and debris are scattered around the site, which could pose a hazard to workers and passersby. This issue is worth addressing to improve the sustainability of the maintenance project.

The **"Mexico Roundabout to Sarbet"** pavement maintenance project was evaluated with the Pavement Sustainability Index for Maintenance (PSIM) tool. It achieved 27 points across 17 PSIM indicators. With a PSI score of 17/45%, it qualifies as sustainable and received a one-star PSIM certification, *see Appendix 3 table 3*.




Photograph 4 Field view of the Mexico Roundabout to Sarbet project site

The project demonstrated commendable performance in multiple aspects. It used materials sourced within 150km of the site to support sustainability. The upgraded drainage system with a new design improves the drainage system of the road section. Proactive traffic control and work zone safety show a commitment to reducing risks and ensuring worker well-being.

The assessment also highlighted areas needing attention. Mishandling & wasting materials and leftover waste management (not clear after finishing the project) cause worries about resource efficiency and costs, *see also photograph 4*. No emergency response plans make the project prone to surprises. Also missing information on the project's environmental impact; this needs improvement for better awareness and reporting.

### Case Study 5

The second case study selected from the Lot-2 project was the **"Wollo Safer** to **Gotera"** pavement maintenance. This road section is a Sub-arterial road, and its project length is about 1.8 km, and its width is approximately 15-18 meters. The assessment of this road section is presented in Table 4.4.

The assessment of the **"Wollo Safer to Gotera"** pavement maintenance project shows significant neglect of sustainable practices. Using 19 PSIM indicators for evaluation gave the project just 27 out of 74 points. This results in a PSI score of 19/36.48%. The score shows that the project was not sustainable and raises serious concerns about its long-term environmental impact.

Table 4.4 Wollo Safer to Gotera pavement maintenance project

| Category | Indicators | Maximum points | Actual points | Explanation |
|---|---|---|---|---|
| Material usage | recycle material | 5 | 0 | It is not common to observe the practice of utilizing a mix of virgin and recycled materials |
| | local material | 2 | 2 | local material within reasonable distances was used |
| | material storage | 2 | 1 | the project had material storage instructions, but the field materials had no protection |
| | material production | 4 | 0 | Information not available |
| Maintenance Technique | technique selection | 2 | 0 | maintenance technique selection only considering the financial aspect |
| | standard procedure | 8 | 3 | some maintenance activities follow the standard procedure of AACRA manual |
| | distress reason | 4 | 1 | there were inspections of distress along the road section but not analyzed for deciding the repair type |
| | drainage | 10 | 4 | during maintenance, manhole inlets improved, ditches cleaned |
| Maintenance Management | maintenance schedule | 3 | 2 | telegram group communication methods exist to update the entire project team on schedule adjustments |
| | project record | 4 | 2 | the data collector records the project data like length, width, surface type |
| | crew training | 4 | 2 | the crew was experienced |
| | work zone management | 3 | 3 | the management of the workplace was well managed and proactive in addressing traffic control, work zone safety management |
| | project team | 2 | 2 | the project had a designated team leader, and the team was aware of their specific duties. |
| Energy & water consumption | Equipment energy usage | 3 | 1 | the project had an equipment energy usage track format |
| | asphalt mixture energy usage | 2 | 0 | Information not available |
| | Water consumption | 2 | 1 | water used during the project was non-potable |
| Environmental impact | wastes | 6 | 2 | wastes were managed appropriately but after completion of the project it has been some waste noted |
| | air quality | 4 | 1 | water showering is used to minimize dust |
| | noise control | 4 | 0 | there were no noise control mechanisms, during the project air compressor generated large noise |
| Total points | | 74 | 27 | |

Several factors contributed to the low score. The project failed to include recycled materials in its usage. While there were instructions for material storage they weren't followed properly on-site which caused waste and inefficiency problems. The project focused only on financial aspects when choosing maintenance techniques without considering environmental or social impacts. It also did not analyze the causes of road distress properly leading to ineffective repairs. The project's drainage management was also worrisome. Despite some efforts to clean ditches and improve manhole inlets, the overall drainage issue was not adequately addressed, which could lead to premature pavement deterioration and increased maintenance needs in the future. The project also overlooked noise control measures which disrupted the nearby communities and harmed the environment.

The project excelled in managing work zones and actively took charge of traffic control and safety. It also used local materials nearby to cut down on transportation emissions. Still, major flaws in other areas led the project to an unsustainable result overall.

**Case Study 6**

The "**Hana Mariyam** to **Kality Mesaltegna"** road section rehabilitation project was one of the Lot-2 project located in southern Addis Ababa. This road section is a principal arterial road and its project length is about 2.1 Km and its width approximately 35-40m. The assessment result of this road section is attached in Appendix 3 table 4.

Photograph 5 Field view of Hana Mariyam to Kality Mesaltegna project

The photograph 5 depicts a road maintenance scene. The surroundings include a dirt shoulder with some construction debris and equipment. On the right side of the road, the drainage issue was not addressed, some wastes and debris were observed that blockage of the drainage line. In the background, several construction vehicles, including a water tanker were parked and the traffic signs were properly placed.

The assessment of a pavement maintenance project undertaken from the **"Hana Mariyam** to **Kality Mesaltegna"** road section using the PSIM rating tool. These evaluate environmental sustainability across five categories with 16 indicators assigned points, *see Appendix 3 table 4*. The project earned 20 out of 58 points for a PSI of 16/34.48%. The score shows that the project was not sustainable based on the PSIM assessment.

The project's low PSI score stems mainly from ignoring environmental factors and poor maintenance methods. Failure to manage drainage can lead to premature road failures due to increased moisture content in pavement materials. Additionally, the production of excessive dust during brooming operations indicates a lack of environmental care, which is essential for sustainable project outcomes. This aligns with findings that emphasize the importance of understanding ecological recovery trajectories and implementing robust management arrangements for pavement maintenance projects to ensure successful maintenance. Furthermore, the unorganized method of storing materials and the sole reliance on cost when selecting maintenance techniques reflect poor materials management, which is a known contributor to project delays, cost overruns, and compromised quality in maintenance projects and finally makes the project unsustainable (Kar & Jha, 2023). The project's sustainability is further compromised by the absence of a comprehensive approach to environmental assessments, which are crucial for addressing the broader impacts of environmental issues on different road projects.

## 4.4 Comparative Analysis and Discussion

The environmental sustainability assessments conducted on the two maintenance projects (Lot 1 and Lot 2) of the Addis Ababa City Road Authority, alongside the six selected case studies previously presented, are summarized in Table 4.5.

Evaluation of the projects using the PSIM certification level revealed varying sustainability outcomes. In Lot 1, two of the three road sections were deemed sustainable, while one section did not meet the criteria for sustainability. Conversely, in Lot 2, only one out of the three case studies demonstrated sustainability, with the remaining two sections falling short of sustainability standards.

In the following section, the two projects are compared and contrasted with the environmental sustainability indicators. This analysis includes categories such as material usage, maintenance techniques, energy and water consumption, maintenance management systems, and environmental impacts.

Table 4.5 Summary of evaluation results of six case studies

| **AACRA Maintenance projects** | **Lot-1 Road Maintenance Project** (North, Central, and West Regions) | | | **Lot-2 Road Maintenance Project** (South and East Regions) | | |
|---|---|---|---|---|---|---|
| Road section name | Tewodros Roundabout to Mahamud Musicabet | Betehal to Mendida | Kagnew Roundabout to Egypt Embassy | Mexico Roundabout to Sarbet | Wollo Safer to Gotera | Hana Mariyam to Kality Mesaltegna |
| case study number | 1 | 2 | 3 | 4 | 5 | 6 |
| Number of indicators | 20 | 18 | 22 | 17 | 19 | 16 |
| Earned points in percentage | 44.60% | 38.46% | 61.54% | 45% | 36.48% | 34.48% |
| PSIM Certification Level | ★ | – | ★★ | ★ | – | – |

### a) Material usage

The environmental sustainability of pavement maintenance is closely linked to material use and depletion, especially concerning the quarrying of virgin materials and the utilization of bituminous materials (Plati, 2019). Incorporating recycled materials in pavement maintenance practices contributes significantly to environmental sustainability by reducing waste, promoting cost-effectiveness, and improving pavement performance (Rout et al., 2023). However, in both Lot 1 and Lot 2 projects the use of recycled materials was minimal to non-existent across most projects, which would have significantly reduced their environmental impact. Missing opportunities for resource conservation and waste reduction. Relatively Lot 1 demonstrated a slightly better approach with partial use of recycled materials in a few projects like (Kagnew Roundabout to Egypt Embassy), while Lot 2 did not use recycled materials at all. *"…we used onsite cement stabilization in our projects like Kagnew Roundabout to Egypt Embassy maintenance project, Wingat to Medhanialem road maintenance sections…"* (RAML-1, 2024). However, this trend of Lot 1 and Lot 2 projects' reliance on raw materials and quarrying virgin materials like aggregates for pavements depletes natural resources and harms the environment through habitat destruction and increased carbon emissions from extraction processes (Gransberg et al., 2014). *"In my experience, the AACRA Lot 2 maintenance project does not prioritize the use of recycled or alternative materials in pavement maintenance projects to a significant extent."* (RCSL-2, 2024).

Both Lot 1 and Lot 2 projects predominantly utilized local materials, reducing transportation emissions. Utilizing local materials in pavement maintenance projects offers significant environmental benefits, primarily by preserving energy and reducing emissions associated with material transportation (Zhang & Mohsen, 2018). *"We definitely prioritize local sourcing whenever possible… our decision-making process involves assessing material availability within that radius, comparing transportation energy consumption for different options, and weighing the overall…"* (R2OL-1, 2024). By sourcing materials locally, the need for long-haul transportation is minimized, leading to lower emissions and energy use.

Overall, in the category of material consumption, relatively Lot 1 has a better approach as it partially utilizes recycled materials and effectively sourced local materials. However, the other sections of Lot 1 did not use any recycled materials, leading to potential wastage. While Lot 2 did not utilize any recycled materials in any of the sections, and all materials were sourced locally. The lack of recycled materials and inadequate material storage in some sections of Lot 2 is leading to environmentally unsustainable maintenance practices.

## b) Maintenance techniques

The pavement maintenance technique category in this research is designed to assess the technique related to environmental sustainability practices including technique selection, preventive maintenance, distress reason, removal of uneven surfaces, standard procedure, and drainage. Regarding this category, the lot-1 maintenance project has started to incorporate techniques of maintenance for sustainability criteria into its decision-making, but this is not yet consistently applied across all projects. This project considered financial and environmental factors for technique selection but lacked preventive maintenance, leading to uneven surfaces and drainage issues. Lot 2's maintenance techniques were chosen primarily based on financial aspects but distress analyses were made. The neglect of drainage issues in some sections of Lot 2 also indicates an unsustainable approach.

Investigating the sources of distress is also important for making informed maintenance decisions, as it allows for targeted repairs and the implementation of preventative measures. Both Lot 1 and Lot 2 projects' distress data was collected in standard procedures and adherence to best practices. Its distress analysis follows the procedure of inspections and assessments the condition survey data such as road width, road name and coding, road class, defect type, and severity are observed and registered as per the specific road section defected. Subsequently, roads are classified based on their current state: those in good or fair condition, which do not necessitate immediate maintenance, those requiring minor repairs and classified as light maintenance, and those in need of substantial repairs and designated as heavy maintenance. For instance, Lot 2 incorporates an electronic device of an advanced nature, such as a mobile phone, equipped with an application for the capture of defect images, identification of location, and retrieval of the datasheet to input the necessary parameters into the data system. These road-related data are subsequently aggregated within the system and utilized by the maintenance department for future decision-making regarding the best maintenance technique selection and method. *"the analysis of distresses made before selection of maintenance…like results from the inspections and assessments are used to determine appropriate repair method to designated sections… …" ($R_1$OL-1, 2024) and "…we use electronic device like mobile phone having applications installed on them for capturing the defect image, location and datasheet to feed the required parameters…" (RAML-2, 2024)*

The project's drainage management was worrisome. Despite some efforts to clean ditches and improve manhole inlets, the overall drainage issue was not adequately addressed, which could lead to premature pavement deterioration and increased maintenance needs in the future. Relatively Lot 2 showed partial effectiveness in drainage maintenance and better management practices in certain areas (e.g., Hana Mariyam to Kality Mesaltegna). *"…for surface water to drain the crown slope is kept by using asphalt depth gage and level machine and side drain by using AACRA drainage manual" ($R_1$OL-2, 2024).*

The projects in both lots predominantly focused on corrective maintenance rather than preventive maintenance. The "Kagnew Roundabout to Egypt Embassy" project in Lot 1 did consider environmental factors in technique selection, but the absence of preventive measures undermines long-term sustainability. Preventive maintenance, which is maintaining roads in good condition conserves energy and lowers the environmental impact of road upkeep. These methods use fewer materials and create less waste which helps the environment. Extending pavement life reduces the need for new materials and cuts down the environmental footprint from their production and transport (Babashamsi et al., 2016).

To sum up, both projects lacked a focus on preventive maintenance, which could extend pavement life and reduce the need for future repairs. However, both projects actively addressed existing pavement distress data collection & analysis, and the Lot 2 project showed better implementation of drainage improvements, contributing to better long-term performance, and reduced environmental impact due to less frequent interventions (Ozer et al., 2016). But overall drainage management is a concern for both lots.

**c) Maintenance Management**

Maintenance management is a systematic approach to ensuring that construction projects are properly maintained, and upkeep is performed on schedule. This involves creating and following a maintenance schedule, keeping accurate records of past and present maintenance work, and providing proper training for the construction team (Zhang & Mohsen, 2018). Lot 1's management system demonstrated good project organization, communication, and record-keeping but lacked proper engagement with neighbors and effective traffic control measures. The management lacked efficient emergency response strategies, and work zone management. It is essential to have formal plans in place to address emergencies and ensure timely delivery of projects. On the other hand, the Lot 2 project showcased proactive work zone management and safety measures. Lot 2 project work zone management practices are carefully planned and executed to ensure the safety of workers, the smooth movement of traffic, and minimal disruption to nearby residents. Specific practices include scheduling maintenance work during nights and weekends and implementing worker safety measures such as creating awareness and providing personal protective equipment (PPE) to workers. Traffic movement is kept safe through the use of flag persons, traffic control devices like barriers, cones, water-filled barriers, and signs to ensure the safety of both the workers and the residents during operations. *"…we* *schedule work during off-peak hours to minimize disruptions, we also make efforts to minimize disruptions to residents and businesses by scheduling work during the night shift and weekends and providing alternative routes where possible"* ($R_2$OL-2, 2024).

Both projects demonstrated areas of strength in communication and record-keeping practices. They had daily data collection practices in which the effectiveness and efficiency of material, energy, fuel, and other relevant resources were controlled, checked, and evaluated. For example, if we took pieces of machinery, fuel consumption, daily output, and working hours were checked against the standard. This consistency in project management supports sustainability by promoting a data-driven decision-making process. The project team is informed of all project-related details and that each team member's duties are clearly designated these are crucial for sustainability in road projects. A well-executed maintenance management plan promotes efficiency, safety, and the overall environmental sustainability of the road construction project.

**d) Energy and Water Consumption**

The energy consumption associated with material processing, transportation, and construction equipment is a major concern, leading to increased greenhouse gas emissions and climate change (Barik, 2015). Lot 1 project had a mixed approach to energy & water consumption, with some sections implementing energy-saving measures and tracking energy usage (Kagnew roundabout project), while others lacked relevant data. While Lot 2 has implemented renewable energy and high-efficiency bulbs on some projects but a lack of consistent energy usage and exhibited water wastage (Mexico to Sarbet project).

Efficient transport strategies on projects are crucial such as material transportation and crew movements for operation, investigation, supervision, inspection, and monitoring should be optimized to minimize travel distances and enhance transport efficiency. This can be achieved by designing optimal routes and using GPS tracking for haulage trucks to prevent delays and reduce fuel wastage (Zhang, 2016). Both Lot 1 and Lot 2 projects showed better organization at transport energy-efficient strategies. They tracked the crew movements, material transportation, and machinery fuel consumption by GPS mounting on the vehicle. *"…also the vehicle is tracked by GPS device mounted on them during the operation and fuel consumption is checked accordingly"* ($R_1$OL-1, 2024) and *"Energy like fuel usage is checked and monitored by installing GPS tracking devices on the vehicles…"* (R2OL-2, 2024).

Utilizing high-efficiency bulbs and renewable energy for both construction and road lighting is crucial. In this regard, the Lot 1 project made efforts to use renewable energy such as the Tewodros project made some effort to save energy with measures like using solar lighting for street lighting and LED lighting for night shift work. Svab et al (2021) state that incorporating renewable energy sources, like the Solar Road System, can further reduce reliance on fossil fuels and lower GHG emissions. *"…in recent projects, we've seen a shift towards using LED lighting for nighttime work zones."* (RCSL-1, 2024). Lot 2's energy consumption practices include the use of streetlights with sensors to conserve energy by turning them on and off during the day/nighttime automatically. However, water consumption is not optimized, leading to unnecessary wastage. *"From an energy consumption point of view, street lights are currently practiced to have sensors to turn on during the night and turn off during the day…"* (RAML-2, 2024)

In summary, both Lot 1 and Lot 2 projects have made efforts to reduce energy consumption through various measures, but there is still room for improvement in terms of adopting more energy-efficient equipment and machinery and optimizing water use. Lot 1 had slightly better measures (e.g., solar lights and fuel tracking), while Lot 2 projects, particularly Hana Mariyam to Kality Mesaltegna, showed minimal but not well-documented water usage. Consistent application of energy-saving measures and a focus on water conservation is necessary to fully achieve the goal of reducing environmental impact.

**e) Environmental Impact**

Pavement maintenance projects significantly contribute to air pollution through emissions from machinery, dust generation, asphalt production, and waste generation. These combined effects during pavement maintenance projects have substantial negative impacts on air quality and human health, necessitating the implementation of effective pollution control measures and sustainable practices (Rath, 2022). Lot 1 Project's environmental impact practices have both positive and negative aspects. The waste management practices are generally commendable, with the reuse of materials such as asphalt milling and rebar from demolished structures. However, there is still room for improvement in the area of waste disposal, as some waste is not properly cleared from the site, such as those in Betehel to Mendida. Air quality management is partially addressed through dust control measures (Kagnew Roundabout to Egypt Embassy), but noise pollution remains a significant concern, leading to disruptions and pollution. *"…the asphalt milling is used for access roads, the rebar of demolished existing structures goes to steel factor and waste material goes to the disposal site based on their properties"* ($R_1$OL-1, 2024).

On the other hand, Lot 2 Project's environmental impact practices are more problematic. Waste management practices are inadequate, leading to a large amount of waste being sent to landfills. Noise pollution is also poorly managed, with many projects, such as those in the Akaki Kality area, not adequately addressing noise concerns. While some attempts are made to manage noise pollution, implementation is inconsistent. *"Noise pollution is often poorly managed, during many projects, such as those in the Akaki Kality area, do not adequately address noise concerns…"* (RCSL-2, 2024).

Both projects have tried to address environmental impact practices but still need much improvement. While Lot 1 showcases better waste management, both projects need to prioritize and strengthen their overall environmental impact practices to minimize negative consequences. Improved waste management practices, consistent noise management, and a focus on air quality are all critical areas for improvement.

## 4.5 Critical Reflection

An analysis of the Addis Ababa City Road Authority's Lot 1 and Lot 2 maintenance projects reveals challenges and opportunities in achieving environmental sustainability in road development. Both projects show some sustainable practices but fall short of exemplary standards across all categories.

Discrepancies in material usage with Lot 1 outperforming Lot 2 in the utilization of recycled materials. This highlights the challenge of balancing recycled and virgin materials while conserving non-renewable resources. This finding aligns with Routs' research that states multifaceted challenges that hinder the widespread adoption of recycled materials in developing countries (like government supervision, project constraints, and varying behavioral intentions among stakeholders) (Rout et al., 2023). Both lots lack preventive maintenance. This reactive management approach could lead to higher resource consumption and more environmental impact in the long term.

The project's maintenance management practices reveals the crucial role of effective communication, record-keeping, and proactive work zone management in ensuring sustainable outcomes. The findings of this study support the notion that a holistic approach to maintenance management, encompassing both technical and organizational aspects, can significantly enhance environmental performance (Zhang & Mohsen, 2018).

Different energy and water use patterns show the need for consistent implementation of energy-saving measures and a more comprehensive approach to resource management. Both lots have made progress in using renewable energy and tracking fuel use. However, they can still improve water conservation and adopt more energy-efficient equipment.

The environmental impact assessment shows a key area that both projects need to improve. Lot 1 shows better waste management. However, poor handling of noise and air pollution in both lots highlights the need for stricter adherence to environmental regulations and the integration of pollution control measures into project planning.

# 5. Conclusions

## 5.1 Conclusion

**Purpose and background information**

Environmentally sustainable pavement maintenance is defined as practices that minimize environmental impact, reduce non-renewable resource use, promote energy efficiency, and utilize eco-friendly techniques to decrease maintenance frequency (Van Dam et al., 2015). The Ethiopian government recognizes the importance of sustainable infrastructure in managing rapid urbanization and has made it a focus in their national development plan, "Growth and Transformation Plan II." (JICA, 2019). Improving eco-friendly pavement practices can reduce pollution and preserve natural resources for a cleaner urban environment (Babashamsi et al., 2016).

Addis Ababa is experiencing population growth and rapid urbanization which are necessitating extensive infrastructure development, including road networks. As the city grows, so does the demand for sustainable infrastructure increases (Dakito & Zerubabel, 2022). Despite significant efforts, Addis Ababa faces considerable challenges related to road infrastructure, including traffic congestion, inadequate maintenance, and deterioration of pavement quality (Bihon, 2020). Moreover, Addis Ababa is currently dealing with environmental issues including pollution and waste management while struggling from the depletion of nonrenewable resources. As a result, this research addresses this gap by assessing the environmentally sustainable pavement maintenance practices in the two projects of AACRA, with a focus on five specific areas of environmentally sustainable pavement maintenance practice indicators.

The main objective of this research was to assess the practice of environmentally sustainable pavement maintenance projects at Addis Ababa city road networks. The PSIM Rating framework is used as the main tool to assess the extent of sustainability. The analysis focusing on five specific aspects will help in identifying the variation of environmental sustainability across the two AACRA pavement maintenance projects (Lot-1 and Lot-2), which will provide a comprehensive understanding of AACRA pavement maintenance projects' sustainability.

**Conclusion of main findings**

The comparative analysis of environmental sustainability in the maintenance projects (Lot 1 and Lot 2) of the Addis Ababa City Road Authority reveals significant variations in their approach and outcomes. The analysis of the results based on PSIM certification, as a benchmark, showed that Lot 1 had two out of three road sections meeting sustainability criteria; but Lot 2 reduced by one, having only one sustainable section meeting the criteria.

**Material Usage:** The use of recycled materials in both projects was minimum, which hindered their potential in reducing environmental impact. Lot 1 demonstrated a slightly better approach by incorporating some recycled materials in a few projects. The projects' reliance on raw materials and quarrying virgin materials like aggregates for pavements depletes natural resources and harms the environment through habitat destruction and increased carbon emissions from extraction processes (Gransberg et al., 2014). Yet, since the projects heavily depend on quarrying virgin materials, there is significant missed opportunity for resource conservation and waste reduction, which are vital for sustainable practices. Both projects benefited from using locally sourced materials, which minimizes energy use and transportation emissions (Zhang & Mohsen, 2018).

**Maintenance Techniques:** Both projects primarily focused on corrective rather than preventive maintenance. Preventive maintenance is critical as it extends the pavement life, conserves energy, and lowers the environmental impact of road upkeep (Babashamsi et al., 2016). Lot 1 incorporated some environmental considerations into its maintenance techniques, like financial and environmental factors, but lacked consistency in applying these criteria across all sections. Lot 2 demonstrated better drainage management in certain areas, which is essential for preventing premature pavement deterioration and reducing future maintenance needs (Ozer et al., 2016). Both projects relied on informed decision-making and targeted repairs through data collection and analysis from standard procedures and electronic devices. However, the limited attention given to the overall preventive maintenance undermines their long-term sustainability.

**Maintenance Management:** According to Zhang & Mohsen (2018), effective maintenance management involves systematic planning, record-keeping as well as ensuring a timely pace. Lot 1 showed good project organization and communication; but it lacked efficient emergency response strategies and effective traffic control methods, risking project delays and during maintenance activities. However, Lot 2 showed proactive work zone management and safety measures, which include scheduling work during off-peak hours as well as implementing traffic control devices. Both projects emphasized daily data collection practices, which support sustainability by promoting data-driven decision-making and efficient resource management.

**Energy and Water Consumption:** Svab et al (2021) state that incorporating renewable energy sources, like the Solar Road System, can further reduce reliance on fossil fuels and lower GHG emissions. In the case of Addis Ababa, Lot 1 implemented some energy-saving measures, such as using solar lighting and LED bulbs in the Tewodros to Mohamud Musicabet project, which contribute to reducing greenhouse gas emissions. Lot 2 also showed efforts to conserve energy with streetlights equipped with sensors but lacked consistent energy usage and exhibited water wastage. Efficient transport strategies on projects to conserve energy can be achieved by designing optimal routes and using GPS tracking for haulage trucks to prevent delays and reduce fuel wastage (Zhang, 2016). With this regard, both Lot 1 and Lot 2 projects showed better organization at transport energy efficient strategies. They tracked the crew movements, material transportation, and machinery fuel consumption by GPS mounting on the vehicle. Overall, consistent application of energy-saving measures and a focus on water conservation is needed to reduce environmental impact.

**Environmental Impact:** Pavement maintenance projects during the execution period contribute to air pollution, noise pollution, and waste generation (Rath, 2022). With this regard, Lot 1's waste management practices included reusing materials like asphalt milling and rebar, which are commendable. Inadequate waste disposal and noise pollution management remain concerns. Dust control was only partially implemented. Noise pollution causes disruptions and potential health issues. On the other hand, Lot 2 faced major waste management problems. This led to a lot of waste going to landfills. Noise pollution wasn't managed well during the projects since those concerns were ignored. Both projects need to improve their environmental practices by focusing on better waste management and consistent noise control. Enhanced air quality measures are also needed to reduce negative impacts on the environment and public health.

To sum up, the assessment of Addis Ababa City Road Authority's maintenance projects, Lot 1 and Lot 2, reveals variations in sustainable practices, with neither achieving exceptional standards across all categories. Differences in material usage highlight the challenge of balancing recycled and virgin materials. The lack of preventive maintenance reflects a reactive approach to infrastructure management. Energy and water consumption patterns need consistent implementation of energy-saving measures and comprehensive resource management. Environmental impact assessments reveal both projects need better waste management as well as noise and air pollution by focusing on improving environmental performance and resource handling.

## 5.2 Recommendations

These findings have significant implications for the Addis Ababa City Road Authority and other infrastructure development agencies in developing countries. The findings show that adopting a proactive and data-driven approach to maintenance management is crucial for long-term environmental sustainability. This shift should focus on adopting preventive maintenance strategies. It should also increase the use of recycled materials and take a broad look at managing resources like energy, water, and waste.

Moreover, the study highlights the need to involve stakeholders such as local communities and environmental agencies in planning and executing maintenance projects. Engagement leads to better decisions and more transparency. This results in sustainable outcomes. And regularly collecting and analyzing data on material use and energy and water consumption can offer valuable insights into environmental impacts. This practice would enable the identification of areas for improvement and facilitate progress tracking towards sustainability goals.

By adopting a more holistic approach to environmental sustainability and addressing these key areas, future AACRA pavement projects can yield substantially better outcomes for both the environment and the communities they serve.

## 5.3 Suggestion for future work

In order to expand upon the research surrounding environmentally sustainable pavement maintenance practices, future studies could focus on incorporating a wider range of road classifications into their analysis. By examining various types of roads researchers can gain a more comprehensive understanding of how sustainable practices can be implemented across different contexts. Additionally, expanding the timeframe of the study would also be beneficial, as it would allow for the examination of long-term trends and the impact of sustainability initiatives over time.

Moreover, future research could investigate the effectiveness of specific interventions aimed at improving environmental sustainability in road maintenance projects. This could include evaluating the impact of financial incentives for using recycled materials, developing standardized guidelines for preventive maintenance, and assessing the long-term environmental benefits of adopting renewable energy sources. Also, research could investigate how policy frameworks and institutional capacity promote sustainable practices in road infrastructure. By identifying the barriers and enablers of sustainable maintenance management, policymakers and practitioners can develop more effective strategies for achieving a balance between non-renewable material usage and environmental protection.

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# Appendix 1: Field Survey Sheet

| Field survey sheet | | | | | |
|---|---|---|---|---|---|
| Project : | | | | | |
| Location | | | | | |
| Section | | | Date; | | |
| **Category** | **Indicators** | **How_To_Measure** | **Rating_strategy** | **Actual_points** | **Remark** |
| **Material usage** | recycle material (construction materials have been recycled) | Determine the ratio of reclaimed materials incorporated and the percentage of materials that were recycled during the construction phase | 0--No recycled materials at all. | | |
| | | | 1 point earns 25% of construction waste materials produced during mantenance phase are recycled | | |
| | | | 2 pts earns if more than 50% of waste materials are recycled. | | |
| | | | 3 pts earned when all the waste materials produced during the maintenance project is recycled | | |
| | recycle material (Recycled materials have been used ) | | 1 point earns during maintenance materials recycled substitute raw materials at any percentage | | |
| | | | 2 pts earned during maintenance the percentage of usage of recycled material is greater than the raw material usage | | |
| | local material | Evaluate the ratio of materials obtained from local sources(100 mils radius) as compared to the total materials consumed | 0--There are no local materials used at all. | | |
| | | | 1 point earns 50% of materials are obtained from local source | | |
| | | | 2 poits earns all materials from local source | | |
| | alternative material | Evaluate the proportion of alternative materials incorporated in the maintenance phase. | 0--There are no alternative materials used at all. | | |
| | | | 1 pt- alternative materials are utilized to substituite a minimum of 10% of the binders or aggregates | | |
| | | | 1 pts- using some materials in construction to enhance performance characteristics, without the aim of replacing it | | |
| | material storage | material storage actual practices on site and document on file | 0--No materials storage instructions and the field materials have no protection | | |
| | | | 1 pts the materials are stored and well located | | |
| | | | 1 pts signs, signboards, and tags are given to indicate information. | | |
| | material production | See the sustainability certification of the material production plants have | 0--There is no certification at all for material production plants | | |
| | | | 2 pts - 50% of materials are produced by plants which have ESA-certification | | |
| | | | 4 pts - all material production plants has ESA-certification | | |

| | | | | | |
|---|---|---|---|---|---|
| Maintenance Technique | technique selection | see the suitable justifications are given for maintenance technique selection | [0]--maintenance technique selectionis only considering the financial aspect | | |
| | | | [1]--maintenance technique selection considers more than one aspect of the financial, environmental, or social | | |
| | | | [2]--maintenance technique selection is fully considering the financial, environmental, and social aspect | | |
| | preventive maintenance | See if preventive practices are included in the project in percentage to the overall project | [0]--no preventive maintenance is included in the project | | |
| | | | [1]--up to 75% of project portions include preventive maintenance practice | | |
| | | | [2]--more than 75% of project portions include preventive maintenance practice | | |
| | distress reason | Check inspection and analyzation of distresses made before selection of maintenance technique points | [0]--analyzing and inspecting distress is not made | | |
| | | | [2]--analyzing and inspecting distress is included as problem solving for decision making | | |
| | | | [+2]--Further examination procedures are being conducted for distress | | |
| | uneven surface | check around the manholes and edges of the maintenance area are improvements | [0]--there is no improvements around the manholes and edges | | |
| | | | [+1]--there is slopes are provided to remove faulting | | |
| | | | [+1]--elevvation difference is removed around inlets, manhols | | |
| | standard procedure | Ensure a maintenance working crew follows procedures of standard | [0]--any step that is not performed during the standard procedure | | |
| | | | [2]--maintenance operations are executed by relying on experiential knowledge, rather than solely following standard procedures | | |
| | | | [6]--work crew is committed to following the formal procedures prescribed by the local agency | | |
| | | | [8]--the work crew is committed to following the formal procedures prescribed by the country level | | |
| | drainage (Issue with the current drainage system) | ensure any drainage improvement made and a written guideline available | [0]--If any activity that hindering drainage ability is noticed and not addressed | | |
| | | | [4]--during maintenance, drainage capacity is reduced, but the issue is subsequently addressed | | |
| | drainage (Enhancements to the Drainage System) | | [+1]--waste and debris are removed from the drainage way | | |
| | | | [+2-4]--a newly designed type of drainage structure is set in place | | |
| | | | [+1]--permeable pavement has been implemented | | |
| Maintenace Management | maintenance schedule( include night & day time work) | check the provision of the project schedule and pavement maint enance plan | 0--No communication methods exist to update the entire project team on schedule adjustments | | |
| | | | 2--A communication methods exist to update the entire project team on schedule adjustments | | |
| | | | 2--A communication methods exist to participate neighborhood to update schedule adjustments | | |
| | schedule(Maintenance Tasks Timeline) | | 1--given the availability of the schedule for subsequent maintenance tasks | | |
| | project record | Ensure the project's documentation includes the recording of data, as well as the establishment of a | 0--there is no documentation of the project | | |
| | | | 1--poorly documentation/record of the project | | |
| | | | 2--well documentation/record and accessible but no established database. | | |
| | | | 3--Database available and documentation well recorded | | |
| | crew training | Ensure that the staff on the job have und ergone the required training and if any experienced indi viduals are involved. | [0]--the workers do not have sufficient training | | |
| | | | [+1]The work team has received training in the basic use of devices, equipment, materials,and tools. | | |
| | | | [+1]The work team has received training on awareness of safety and procedure of pavement maintenance | | |
| | | | [+2]The work team has received training on awareness of sustainability principles | | |
| | | | [+1]In every team, there is always at least one experienced member who directs or is part of the group. | | |
| | emergencies | check any plans for emergency work | [0]-- no provision for an emergency response strategy. | | |
| | | | [+1]-- emergency addressing strategies available | | |
| | | | [+2]--the onsite working crew has an understanding of typical emergency situations and is prepared to take appropriate action. | | |
| | work zone management | Check any actions at work that could com promise the safety or efficiency of the workplace | [0]--Poor management or lack of management attention in workplace | | |
| | | | [+2]--The workplace is effectively managed, with any issues being promptly addressed. | | |
| | | | [+1]--The work zone's lifecycle is composed of a series of carefully planned and documented activities | | |
| | project team | Ensure that the project team is established and that each member is aware of their specific duties. | [0]--for the project doesn't have a designated team leader | | |
| | | | [1]--for the project has a designated team leader but the team is not aware of their specific duties. | | |
| | | | [2]-- the project has a designated team leader and the team is aware of their specific duties. | | |

| | | | | | |
|---|---|---|---|---|---|
| **Energy & water consumption** | Efficient lighting | Ensure if in maintenance projects renewable energy, and highly efficient lighting are included | [0]--traditional lights are used/ no energy-saving | | |
| | | | [+1]--energy-saving lights are used at project | | |
| | | | [+1]--data on electricity usage for lighting has been compiled | | |
| | | | [+1]--renewable energy options are implemented | | |
| | Transport energy usage | see if the project site transporting vehicles energy usage is enhanced | [1]--more than half of the transportation vechils used utilizes fuel-efficient or alternative fuel technologies. | | |
| | | | [+1]--route design is implemented for material transportation, trucks hauling at project duration | | |
| | | | [+1]--data on energy usage for transportation has been compiled | | |
| | | | [0]--the situations mentioned herein have not been substantiated | | |
| | Asphalt mixture energy usage | ensure that in pavement maintenance projects the applied percentage of warm mix asphalt | [1]--more than half of asphalt mixture was warm mix asphalt used in the pavement maintenance projects | | |
| | | | [2]--overall warm mix asphalt was used in the pavement maintenance project duration and the mixing temperature was reduced | | |
| | | | [0]--no warm mix asphalt used overall the project duration | | |
| | Equipment energy usage | Examine if the energy usage of construction equipment is operating at an optimal level | [2]--more than half of the construction equipment in use utilizes fuel-efficient or alternative fuel technologies. | | |
| | | | [+1]-- In the case of overseeing multiple construction sites at once, or when the project is extensive in size, route design is implemented | | |
| | | | [+1]--data on energy usage for equipment has been compiled | | |
| | | | [0]--the situations mentioned herein have not been substantiated | | |
| | Water consumption | check the management of water and usage | [0]--It has been observed that there is a considerable waste of excess uncontaminated water during and after the execution of the project; the amount of potable water in the total consumed is more than 50% | | |
| | | | [1]--It has been observed that there is less waste of uncontaminated water during and after the execution of the project; the amount of non-potable water in the total consumed is more than 50% | | |
| | | | [+1]--data on water usage for project has been compiled | | |
| **Environmental impact** | wastes | check the wastes are treated and well disposed of | [0]--after completion of the project, it has been noted that waste disposal remains untreated and inappropriately managed. | | |
| | | | [2-6]--All waste is disposed of in an appropriate manner, earned up to 6 maximum points regarding responsible disposal of waste | | |
| | | | [+2]--if any hazardous waste exist, it managed and disposed of in a responsible manner, with all necessary precautions taken. | | |
| | air quality | ensure the quality of air during the project emissions, smoke, and dust | [0]--If any instance of air pollution be identified without the implementation of necessary measures to address it | | |
| | | | [1]--half of the vehicles and construction equipment employed are equipped with energy-efficient mechanisms | | |
| | | | [+1]--if items or construction materials with the potential to pollute the air are kept in a well-sealed and secure manner. | | |
| | | | [+1]--if it is observed that dust control actions are being taken. | | |
| | | | [+1]--In the event that directional dust monitoring is implemented | | |
| | noise control (traffic noise) | see if any type of monitoring of onsite noise level, and the project team is keeping a record of traffic and construction noise | [0]--in the absence of any efforts to reduce noise | | |
| | | | [1]--if amaintend pavement portion intended for reduced noise | | |
| | | | [+1]--if a barrier to reduce noise is established for the section of the pavement that is being maintained | | |
| | noise control (construction noise) | | [1]--the adoption of construction equipment that generates reduced noise levels | | |
| | | | [+1]--establishing a schedule for the utilization of noisy equipment during the construction process | | |
| | | | [+1]--the implementation of temporary noise reduction measures during the construction phase | | |
| | | | [+1]--construction noise levels will be regularly measured and documented to ensure compliance with acceptable standards | | |
| | vibration control | see if any type of monitoring of onsite vibration control, and the project team is keeping a record of vibration | [0]--there is no measures has taken to control vibration during the maintenance project | | |
| | | | [1]--in an effort to minimize disruption, construction equipment with lower vibration output has been integrated | | |
| | | | [2]--a well defined schedule implmented for the utilization of vibration-generating equipment, and construction vibration is rigularlly monitored throughout the duration of the maintenance project. | | |

# Appendix 2: Interview Questions

Thank you for accepting this interview. My name is Sultan Demissie Sheksrij and I'm a master's student at Erasmus University Department of Institute for Housing and Urban Development studying on track urban management and development specializing in Urban Environment, Sustainability and Climate Change. During today's interview, I will attempt to gain a deeper understanding of the Addis Ababa City Road Authority (AACRA) pavement maintenance projects concerning environmental sustainability and to what extent pavement maintenance projects practice environmental sustainability across the two different projects. It focuses on five specific areas of environmentally sustainable pavement maintenance practice indicators: material usage, maintenance techniques, energy and water consumption, maintenance management system, and environmental impacts.

The interview questions have two parts the first part includes the questions about the respondent's background and the second part consists of two to four questions on each specific area of environmental sustainable pavement maintenance indicators mentioned above.

The interview will last about 30-45 minutes. Your privacy is of utmost importance to us. All data collected will be kept anonymous and secured, only accessible by the named interviewer and supervisor when required. Once the research is finalized, all data will be completely eliminated. The results of the study will be disclosed to stakeholders upon its completion. I will ask you to give informed consent to participate in and record the interview.

## I. Interview Questions for AACRA Engineers and Officials

### Background Questions

1) How long have you been working on AACRA pavement maintenance projects?
2) Which one of the following departments are you working for?
   A) Lot-1 own force road maintenance project
   B) Lot-2 own force road maintenance project
   C) Central/North/West region road asset management department
   D) South/East region road asset management department
   E) Other, please specify …
3) Your level of academic

   A) Diploma B) Bachelor's degree C) Master's degree D) Doctoral program

**Opening question**

*In what ways does the Addis Ababa City Road Authority consider sustainability while carrying out regular maintenance projects?*

### Main Questions

**Material Usage**

1) Could you provide a detailed description of the current raw material consumption habits in your current pavement maintenance projects? (For instance, are you

relying solely on raw materials, or are you using a combination of virgin materials and recycling, or is there a preference for utilizing recycling, or are you making an effort to diminish the use of raw materials?)

*Based on your expertise, what specific challenges have you encountered that hinder the adoption of materials?*

2) Are there by-products from other industries (e.g. tires, coal ash, fly ash, slag,) utilized for pavement maintenance projects as alternatives to aggregates or binders?

*Could you provide examples or discuss the evaluation process around their use?*

3) What is the process for making decisions to use locally sourced materials in maintenance projects, specifically those within a 150 km radius of the project site? Are factors such as material availability, transportation energy consumption, and distance advantages taken into consideration?
4) Can you describe the material storage practices in place for pavement maintenance projects?

*Are there specific measures for protecting stored materials to reduce waste and maintain quality?*

Maintenance Techniques

5) What is the typical process for selecting maintenance techniques? Are there explicit environmental sustainability considerations combined with other factors such as cost and condition?
6) How is the surface and side drainage system of pavements managed, particularly during the maintenance project?

*Are there specific techniques or guidelines followed?*

Maintenance Management

7) In maintenance projects, is sustainability integrated into the planning of maintenance schedules? (Yes or No)

*If yes, could you detail the specific ways in which sustainability is integrated into the planning of maintenance schedules, including the particular methods and practices used?*

8) How do you track sustainability-related data (e.g., energy use, material type) at the individual project level?
9) How are work zones managed during pavement maintenance to balance worker safety, traffic needs, and minimizing disruption to residents?

*Are there examples of innovative practices?*

Energy & Water Consumption

10) Does your agency use strategies to reduce energy consumption related to lighting, transportation, or equipment use during individual projects? (Yes. Or No.)

*If yes, how is the practice done?*

11) Are there on-site practices or innovations used to optimize water use and conservation during pavement maintenance?

Environmental Impact

12) Can you discuss specific measures taken to manage and reduce waste during a pavement maintenance project?
13) What techniques do you use to mitigate air quality issues (e.g., dust, emissions) during a project?
14) How are noise concerns managed during pavement maintenance? Are there monitoring efforts and strategies used to address any noise disruptions for residents or nearby businesses?

Do you have anything else to add about your experience with the AARA pavement maintenance project?

Thank you very much for the interview and precious time, also I promise to keep it private.

**II. Questionnaire for Consultant Staff**

**Background Questions**

1) How long have you been working with AACRA pavement maintenance projects?
2) Which one of the following pavement maintenance projects are you working with?
   A) Lot-1 own force road maintenance project
   B) Lot-2 own force road maintenance project
3) Your level of academic
   B) Diploma B) Bachelor's degree C) Master’s degree D) Doctoral program

**Opening question**

*In what ways does the Addis Ababa City Road Authority consider sustainability while carrying out regular maintenance projects?*

**Main Questions**

Material Usage

1) Based on your experience, to what extent does AACRA prioritize the use of recycled or alternative materials in pavement maintenance projects?
   *Are there examples of successful implementation?*
2) How could AACRA improve practices for sourcing materials locally, while balancing the environmental benefits with transportation energy consumption and distance advantages considerations?
3) As a consultant, do you have adequate guidance in recommending innovative and sustainable material alternatives within AACRA projects?
   *What are the barriers, if any?*

Maintenance Techniques

4) From your experience, are long-term sustainability impacts adequately included in AACRA's current maintenance technique selection process?
5) To what extent is preventive maintenance emphasized in AACRA projects you've been involved with?
   *Could you describe successful preventive maintenance strategies that delivered environmental benefits?*
6) How is the surface and side drainage system of pavements managed, particularly during the maintenance project?

Maintenance Management System

7) From an environmental sustainability standpoint, how would you assess AACRA's current pavement maintenance scheduling practices?

   *Are there opportunities to better integrate sustainability factors into scheduling decisions*?

8) Does AACRA have a strong system for collecting and analyzing pavement maintenance data?

   *Do you see any areas where improved data management could directly benefit environmental sustainability*?

9) Could the role of consultants be expanded to provide more focused sustainability training and knowledge transfer to AACRA maintenance crews?

   *If so, in what specific areas?*

Energy & Water Consumption

10) In AACRA maintenance projects you've consulted on, how actively are energy-efficient solutions for lighting, transportation, and equipment use considered?

    *Are there barriers to enhancing the implementation?*

11) Are water conservation strategies routinely discussed during the planning and execution of AACRA pavement maintenance projects?

    *Could you suggest potential areas for improvement in this regard?*

Environmental Impact

12) In your experience with AACRA projects, how strictly are waste management protocols implemented, especially regarding the potential for recycling or reuse of materials?

    *Do you see the potential for improvement?*

13) Beyond regulatory compliance, does AACRA demonstrate a proactive approach to monitoring and mitigating air quality impact (e.g., dust, emissions) during pavement maintenance activities?

    *Please share examples or areas where they could enhance their practices.*

14) How effectively does AACRA address noise pollution concerns during pavement maintenance?

    *Do you think consultants could play a more active role in noise reduction strategies?*

Do you have anything else to add about your experience with the AARA pavement maintenance project?

Thank you very much for the interview and precious time, also I promise to keep it private.

# Appendix 3: Project Assessment Result

Table 1 Tewodros Roundabout to Mahamud Musicabet pavement maintenance project

| Category | Indicators | Maximum points | actual points | Explanation |
|---|---|---|---|---|
| Material usage | recycle material | 5 | 0 | raw materials or virgin material is used in projects to maintain the asphalt roads section such as aggregate and sand. The trend of using a combination of virgin and recycled material is not practiced |
| | local material | 2 | 2 | material within reasonable distances was used within a radius of 150km from the project site |
| | material production | 4 | 0 | Information not available |
| Maintenance Technique | technique selection | 2 | 1 | they selected the maintenance technique by considering aspects of the financial and longevity |
| | preventive maintenance | 2 | 0 | overall, no preventive maintenance is included in the project |
| | distress reason | 4 | 2 | analyzing and inspecting distress was made by asset management teams and included as problem-solving for decision-making |
| | uneven surface | 2 | 1 | around the edges of the maintenance area, some slops are provided |
| | standard procedure | 8 | 6 | clearing the site, patching and overlay was following the standards of AACRA manual |
| | drainage | 10 | 4 | some drainage issue was subsequently addressed, but still, the capacity of the drainage system along that street is not adequate enough |
| Maintenance Management | maintenance schedule | 3 | 2 | the starting and finishing times of the projects were published through the Telegram platform |
| | project record | 4 | 2 | the project data was recorded on contractors database like weekly, monthly |
| | emergencies | 3 | 1 | emergency addressing strategies available |
| | work zone management | 3 | 0 | the equipment parking was not well organized, parking on the streets and blockage of traffic flow |
| | project team | 2 | 2 | the project has a designated team leader, and the team is aware of their specific duties. |
| Energy & water consumption | Efficient lighting | 3 | 1 | energy-saving renewable solar lights are used in the project |
| | Transport energy usage | 2 | 1 | data on energy usage for transportation has been compiled |
| | Equipment energy usage | 3 | 2 | more than half of the construction equipment in use utilizes fuel-efficient, new equipment used |
| | Water consumption | 2 | 1 | total consumed water was non-potable water |
| Environmental impact | wastes | 6 | 4 | wastes are disposed of in a responsible manner, and no hazardous wastes are observed |
| | air quality | 4 | 1 | there is a dust control mechanism when cleaning debris by the air compressor |
| Total points | | 74 | 33 | |

Table 2 Kagnew Roundabout to Egypt Embassy pavement maintenance project

| Category | Indicators | Maximum points | actual points | Explanation |
|---|---|---|---|---|
| Material usage | recycle material | 5 | 3 | Onsite recycling base course material is observed. during maintenance, the percentage of usage of recycled material is greater than the raw material usage |
| | local material | 2 | 2 | material within reasonable distances was used within a radius of 150km from the project site |
| | material storage | 2 | 2 | on the project site, the materials are stored and well-located |
| | alternative material | 2 | 0 | there are no alternative materials used at all |
| | material production | 4 | 0 | Information not available |
| Maintenance Technique | technique selection | 2 | 2 | the maintenance technique selection is fully considering the financial, and environmental aspects |
| | preventive maintenance | 2 | 0 | preventive maintenance isn't included in this project |
| | distress reason | 4 | 4 | analyzing and inspecting distress was made by asset management teams and included as problem-solving for decision-making (like cement stabilization of base course) |
| | uneven surface | 2 | 1 | around the edges of the maintenance area, some slops are provided |
| | standard procedure | 8 | 6 | clearing the site, base course placing, and maintaining damaged surface was following the standards of AACRA manual |
| | drainage | 10 | 7 | the drainage system along that street was improved but not adequate |
| Maintenance Management | maintenance schedule | 3 | 2 | the starting and finishing times of the projects were published through Telegram |
| | project record | 4 | 3 | the project data was recorded by a data collector and feed into the database system |
| | emergencies | 3 | 1 | emergency addressing strategies available |
| | work zone management | 3 | 0 | Poor management in the workplace, no traffic signs |
| | project team | 2 | 2 | the project has a designated team leader and the team is aware of their specific duties. |
| Energy & water consumption | Efficient lighting | 3 | 2 | energy-saving, hydropower electric lights were used at the project |
| | Transport energy usage | 2 | 1 | data on energy usage for transportation has been compiled |
| | Equipment energy usage | 3 | 2 | more than half of the construction equipment in use utilizes fuel-efficient and is tracked by GPS |
| | Water consumption | 2 | 1 | total consumed water was non-potable water |
| Environmental impact | wastes | 6 | 5 | wastes were reused and leftovers were disposed of in a responsible manner, no hazardous wastes were observed |
| | air quality | 4 | 2 | there is a dust control mechanism when cleaning debris by the compressor and showering with water to minimize dust |
| Total points | | 78 | 48 | |

Table 3 Mexico Roundabout to Sarbet Pavement Maintenance Project

| Category | Indicators | Maximum points | Actual points | Explanation |
|---|---|---|---|---|
| Material usage | local material | 2 | 2 | all materials were used from a reasonable distance from the project site in a radius of 150km |
| | material storage | 2 | 0 | materials are not properly handled, wastage of materials observed |
| | material production | 4 | 0 | Information not available |
| Maintenance Technique | technique selection | 2 | 2 | the selection of maintenance methods is being made with careful consideration of financial and environmental impacts. |
| | distress reason | 4 | 2 | Distress was examined and investigated as part of their problem-solving approach to decision-making. |
| | uneven surface | 2 | 1 | around the manholes of the maintenance area, slops were provided |
| | drainage | 10 | 7 | improved drainage system, a newly designed type of drainage structure is set in place |
| Maintenance Management | maintenance schedule | 3 | 2 | the project's timeline, including the start and end times, was officially communicated |
| | project record | 4 | 2 | the project data was collected and recorded daily |
| | crew training | 4 | 2 | the crew members are experienced, but the training isn't common |
| | emergencies | 3 | 0 | no provision for an emergency response strategy |
| | work zone management | 3 | 2 | the management of the workplace is consistently proactive in addressing traffic control, work zone safety management |
| | project team | 2 | 2 | the project has a designated team leader, and the team is aware of their specific duties. |
| Energy & water consumption | Equipment energy usage | 3 | 1 | the project had an equipment energy usage track format |
| | Water consumption | 2 | 0 | Throughout the project, the presence of water waste was noted |
| Environmental impact | wastes | 6 | 2 | wastes were managed appropriately but after completion of the project it has been noted |
| | noise control | 4 | 0 | Information not available |
| Total points | | 60 | 27 | |

- The number of indicators involved in this project=17
- Total maximum points = 60
- The actual points the project earned = 27
- Earned points in percentage = (27/60) x 100= 45.00%

Table 4 Hana Mariyam to Kality Mesaltegna pavement maintenance project

| Category | Indicators | Maximum points | Actual points | Explanation |
|---|---|---|---|---|
| Material usage | recycle material | 5 | 0 | recycled materials utilization is not practiced |
| | local material | 2 | 2 | all materials were used from a reasonable distance from the project site in a radius of 150km |
| | material storage | 2 | 1 | proper handling of material was observed, but a material follow-up format was not available |
| Maintenance Technique | technique selection | 2 | 0 | the selection of maintenance methods is being made with consideration of only financial impacts. |
| | distress reason | 4 | 2 | Distress was examined and investigated before the start of maintenance of the road section |
| | drainage | 10 | 0 | the drainage issue was not addressed, some wastes and debris were observed that blockage of the drainage line |
| Maintenance Management | maintenance schedule | 3 | 2 | the project's timeline, including the start and end times, was officially communicated |
| | project record | 4 | 2 | the project data was collected and recorded daily |
| | work zone management | 3 | 2 | the management of the workplace is consistently proactive in addressing traffic control, work zone safety management |
| | project team | 2 | 2 | the project has a designated team leader and the team is aware of their specific duties. |
| Energy & water consumption | Efficient lighting | 3 | 2 | energy-saving, hydropower electric lights were used at the project |
| | Transport energy usage | 2 | 1 | route design is implemented for material transportation, and truck hauling at the project duration |
| | Water consumption | 2 | 2 | It has been observed that there is less waste of water during the execution of the project; the total consumed is non potable |
| Environmental impact | wastes | 6 | 2 | wastes were managed appropriately but after completion of the project it has been some waste noted |
| | air quality | 4 | 0 | during the brooming process, dust production was high. |
| | noise control | 4 | 0 | Information not available |
| Total points | | 58 | 20 | |

- The number of indicators involved in this project=16
- Total maximum points = 58
- The actual points the project earned = 20
- Earned points in percentage = (20/58) x 100= 34.48%

# Appendix 4: IHS copyright form

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