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Sustainable Evaluation of Highway Pavement Materials Using Life Cycle Assessment Technique

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Abstract: The pursuit of sustainable pavement construction necessitates careful consideration of selecting appropriate materials due to their significant impact on road investments. Therefore, this study aims to analyze and assess the environmental effects of four distinct pavement materials including A main road, Plain concrete (PC), and three equivalent alternative roads: reinforced concrete (RC), fibrous concrete (FRC), and Hot Mix Asphalt (HMA). The study assesses various pavement alternatives by considering their cumulative energy demand and damages across different categories. The life Cycle Assessment (LCA) tool is used by implementing LCIA ReCiPe 2016 Endpoint (H) V1.07 / World (2010) H/A methodology and Simapro software. A case study of the Cairo-Suez Desert Road in Egypt is selected to apply the study to it. The damages are measured in two categories: human health and ecosystem quality. The results indicate that RC pavement has the highest damage effect in both categories, with values of 94.20 and 36.99 respectively. Both PC and FRC pavements exhibit damage but to a lesser extent. HMA shows a relatively lower damage effect in both categories. These findings can enhance the comprehension of environmental implications associated with various pavement materials, offering valuable insights to decision-makers in the process of selecting sustainable pavement options.

Keywords: Sustainability; Life cycle assessment; flexible pavement; rigid pavement; Simapro.

1. Introduction

Building sustainable and environment-friendly structures and infrastructures has been one of the most important challenges in the construction industry for many years [1]. The development of road infrastructure constitutes a substantial source of greenhouse gas emissions, and this environmental impact continues to expand in tandem with government-led road development initiatives [2]. Concrete roads are experiencing a consistent increase in popularity, primarily due to their extended lifespan and lower maintenance requirements when compared to asphalt roads, making them the preferred choice for handling heavy traffic loads. The adoption of concrete roads is gradually increasing as they exhibit better durability compared to asphalt roads, which tend to deteriorate more rapidly [3]. When considering structural integrity and maintenance expenses, rigid pavement outperforms asphalt roads. [4]. Annually, thousands of miles of roads are constructed using asphalt and steel-reinforced concrete. The research objective is to evaluate the environmental effect of road construction projects by employing the LCA approach. Additionally, the study addresses whether the widespread preference for asphalt over concrete aligns with sustainability considerations. The construction industry is a prominent user of Earth's resources, and the materials it employs have a substantial environmental footprint, spanning. [5], from their production to their utilization, necessitating measures to alleviate their ecological impact. Various strategies have been adopted, including optimizing the production process. [6], optimization of the design process [7], adopting alternative raw materials [8] [9], use of alternative binders [10] [11] use of waste materials [1], reducing waste production [12], use of local products [13].

However, the expansion of road infrastructure frequently gives rise to a multitude of environmental issues that pose risks to both the natural environment and human health. The process of road construction entails the incorporation of various raw materials such as asphalt binders (bitumen), aggregates, and chemical additives. These materials consume significant quantities of natural resources and energy throughout their extraction, production, and processing phases. Thus, road construction leads to energy consumption, dust, and gas emissions, as well as land depletion and degradation, nonrenewable natural resources depletion, and the generation of solid waste. Concrete pavements find widespread use across the globe, owing to their numerous benefits [14], and Numerous approaches have been suggested to enhance the sustainability of concrete pavements, These approaches include the advancement of sustainable design principles [15], reduction of cementitious content, use of supplementary cementitious materials [16], use of recycled materials [17].

The notion of sustainable construction is not only present but has become imperative in the context of global warming and the pressing concern of environmental degradation impacting humanity. As per the 2017 Global

Status Report, the combined energy consumption of buildings and construction amounted to 36% of the overall electricity usage, while they also contributed to 39% of energy-related carbon dioxide (CO2) emissions, inclusive of emissions from upstream power production [18]. The concept of sustainable construction is regarded as a fundamental strategy for addressing environmental degradation and reducing carbon emissions, which constitute a primary driver of global warming within the construction industry.

LCA is a widely accepted and standardized method employed for the comprehensive evaluation of potential environmental impacts associated with a product, service, or process. LCA has the capacity to assess various alternatives throughout the entire lifecycle of a system, encompassing all processes from inception to disposal. This assessment method considers a broad spectrum of environmental aspects throughout the product's lifecycle, including emissions into the air, water, and soil, waste generation, raw material usage, energy consumption, and the impact on natural resources [8]. This approach avoids the misallocation of environmental effects of any product or service and provides an overview for possible impact reduction through the product life cycle.

The research aims to conduct an LCA to assess the environmental impacts of road construction projects by employing the LCA technique, the study aims to contribute to sustainable construction practices. The assessment will encompass the entire life cycle of the road construction, focusing on key stages such as raw material extraction and transportation of materials from extraction sites to the plant, and further to the construction site. The investigation will be restricted to the four specified types of road pavements and adhere to Egyptian code regulations. Notably, the environmental impacts arising from road operation and maintenance will not be within the scope of this study.

2. literature review

In recent LCA studies on road construction, numerous aspects have been explored, but there are still several unresolved issues. [19] conducted a comprehensive LCA study to assess the environmental impacts of asphalt mixture production using different proportions of Recycled Concrete Aggregates, specifically 15%, 30%, and 45% of coarse aggregate weights. The findings indicated that asphalt mixes containing 15% and 30% of RCA are more environmentally friendly compared to ordinary asphalt mixes, as they showed decreases in all impact categories. However, the asphalt mix with 45% of RCA demonstrated a decline in environmental performance across all impact categories when compared to ordinary asphalt mixes.

[20] focuses on evaluating the environmental and economic sustainability of Perpetual Pavements (PPs) in comparison to Conventional Flexible Pavements (CFPs) and Conventional Rigid Pavements (CRPs) for road construction, with a specific case study in Barranquilla, Colombia. Using LCA and Life Cycle Cost Analysis (LCCA) methodologies, it finds that PPs exhibit lower environmental impacts and higher cost-efficiency than CFPs and CRPs, especially in terms of contamination potential. The study emphasizes that PPs offer an advantageous alternative, particularly in the context of developing countries. It highlights the importance of considering initial construction and Maintenance and Rehabilitation (M&R) activities over a 50-year service life. The research suggests potential strategies for reducing environmental impacts, including incorporating waste materials and increasing the use of recycled materials. Furthermore, it underscores the financial benefits of reducing hauling distances in these pavement alternatives, with PPs proving to be a cost-effective choice. This research advocates for the adoption of PPs as a more sustainable approach to road construction, particularly in similar developing country settings.

[21], offers a comprehensive analysis of the utilization of recycled concrete aggregates (RCA) in pavement construction, comparing them with conventional natural aggregates (NA). It highlights the significant environmental and sustainability advantages of using RCA in pavement construction, including the reduction of health hazards, waste generation, and the burden on landfill sites. The study underscores that while the properties and performance of RCA pavements are influenced by factors like crushing methods, adhered paste content, and extraction techniques, they generally exhibit favorable mechanical and durability properties. The review emphasizes the importance of considering the transport distance of RCA materials, as long delivery distances can impact sustainability negatively. Overall, this paper contributes valuable insights into the sustainable use of RCA in pavement construction, offering a substantial body of knowledge in a field with limited systematic review.

[22]. conducted an assessment was conducted to examine the environmental impacts of asphalt mixtures containing Nano-silica, focusing on emissions associated with material production during LCA. The findings showed that incorporating Nano-silica into the production of asphalt mixture has negligible detrimental impacts on the environmental profile, where the incorporation of Nano-silica into the asphalt mixture results in minimal changes, specifically less than or equal to 1% across all impact categories when compared to the control asphalt mixture [22]. Rosado et al. conducted a comparative LCA study to examine the environmental effects of producing natural aggregate versus Mix RA, which combines recycled coarse aggregate with natural aggregate. The findings showed that Mix RA outperformed other alternatives in terms of environmental benefits across all evaluated impact categories, except for the non-carcinogens category. This exception applies when the distance between the Mix RA manufacturing site and the end user exceeds the distance between the natural aggregate manufacturing site and the end user by approximately 20 kilometers. [23] carried out an extensive LCA study to assess and compare the environmental, societal, and economic impacts between Portland Cement Concrete pavements modified with RCA and standard PCC pavements. The results indicated that incorporating Recycled Concrete Aggregates (RCA) into

Portland Cement Concrete (PCC) offers environmental benefits during the stages of materials manufacturing and construction, nonetheless, it leads to adverse environmental impacts during the utilization phase. Furthermore, the results specifically highlighted the superiority of PCC (pervious concrete pavement) modified with RCA (Recycled Concrete Aggregates) over the basic pavement in impact categories such as "human health cancer," "human health non-cancer," and "ecotoxicity.".

In a comprehensive LCA study conducted by [24], the investigation assessed the environmental effects of bituminous sub-ballast mixtures that incorporated recycled materials, specifically reclaimed asphalt pavements (RAP) and crumb rubber (CRM). The results revealed that CRM mixtures exhibited more significant environmental impacts, primarily due to the rubber treatment process and the higher bitumen content in the mix. Conversely, the inclusion of RAP led to enhancements across all evaluated indicators, as indicated by the LCA findings.

In conclusion, the studies reviewed in this paragraph highlight the importance of LCA in evaluating the environmental impacts of various aspects of road construction. While these studies provide valuable insights, there are still many areas that require further investigation. Further research is needed to compare the environmental and economic performance of various types of flexible and rigid pavement. Determining the optimal alternative in terms of sustainability requires a comprehensive understanding of factors such as energy consumption, raw material usage, greenhouse gas emissions, and life cycle costs. By conducting in-depth comparative studies between these pavement types, researchers can contribute to the selection of the most environmentally and economically viable option for road construction projects. Additionally, investigating the long-term durability and maintenance requirements of these pavements would further enhance decision-making processes in the construction industry. Continued research in these areas will facilitate the development of more sustainable and cost-effective road infrastructure systems.

Overall, both asphalt and concrete have environmental impacts associated with their production, transportation, and construction processes. However, the specific environmental effects can vary depending on factors such as production methods, material composition, and waste management practices. Determining which material is a better choice for sustainable development depends on various factors, including the specific project requirements, local conditions, and available resources. Sustainable road construction often involves considering a combination of factors, such as material performance, LCA analysis, recycling and reuse options, and energy efficiency measures.

The studies mentioned in the literature review section provide valuable insights into the environmental impacts of different road construction materials and techniques. Despite the existing studies on the environmental impacts of road construction materials and techniques, there is still research lacks that need to be addressed. Many of the reviewed studies have primarily focused on the environmental impacts during the production and construction stages. However, the long-term effects of road materials on the environment, including their durability, maintenance requirements, and end-of-life management, require further investigation. The full life cycle of road infrastructure to assess the environmental implications over its entire lifespan should be considered. In addition, regional and contextual considerations: the environmental impacts of road construction can vary significantly depending on the regional context, such as climate, availability of resources, and waste management infrastructure. It is important to conduct studies that consider these regional differences to provide more accurate and context-specific assessments.

The research gap that this paper tries to fill is the lack of emerging materials and technologies because previous researchers were focused on traditional road construction materials. However, there is a need to explore the environmental impacts of alternative materials, and innovative pavement designs. Investigating these novel approaches can provide valuable insights into their potential environmental benefits and drawbacks, helping to identify more sustainable alternatives for road construction. In addition, while some studies have compared the environmental performance of different materials or mixtures, there is a need for more comprehensive and comparative life cycle assessments between different road construction materials, considering a wider range of impact categories and evaluating their performance across the entire life cycle. Addressing this research gap can contribute to a more comprehensive understanding of the environmental implications of road construction and enable the identification of effective strategies for sustainable road infrastructure development.

3. RESEARCH METHODOLOGY

The research methodology involves a systematic series of steps to assess and compare flexible and rigid pavement construction materials and their alternative counterparts for environmental sustainability. Initially, the materials are identified and classified into their respective categories. Once the selection of study alternatives is made, criteria for sustainable evaluation are defined, setting the foundation for data gathering. Subsequently, equivalent sections for these alternatives are designed in accordance with the guidelines provided by the AASHTO Guide for pavement structure design. A critical examination of life cycle assessment methods is conducted to ensure a comprehensive understanding of the assessment process. Following this, a life cycle assessment is applied to a case study of the Cairo-Suez Desert Road in Egypt and its alternatives using the Simapro software, employing the LCIA ReCiPe 2016 Endpoint (H) V1.07 / World (2010) H/A methodology. The final step entails the environmental evaluation of the selected alternatives, wherein the impacts are analyzed to provide valuable insights into their sustainability, all through the utilization of Simapro software. These integrated steps are shown in Fig. 1.

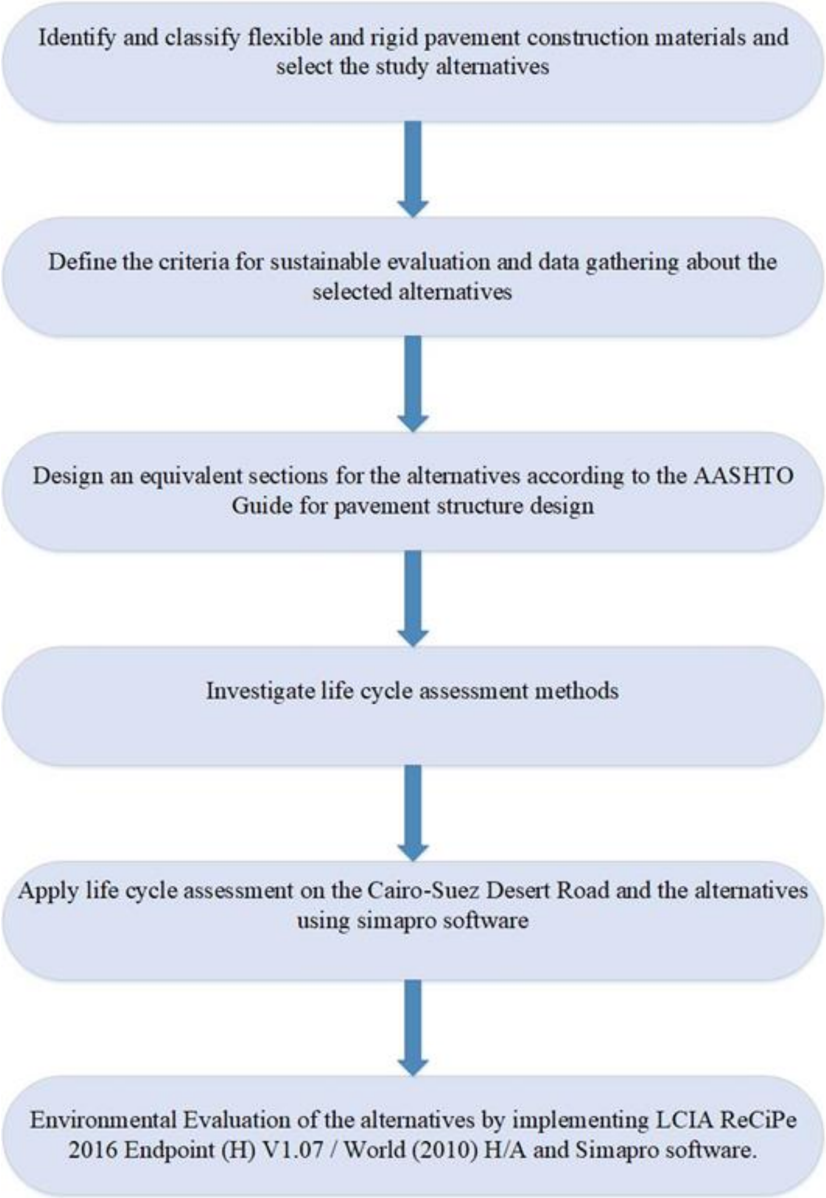

FIGURE 1. Methodology flow diagram

4. Materials and methods

This research aims to assess and appraise the environmental effects of four types of pavement materials: PC, RC, FRC, and HMA. Asphalt mixes are composed of natural aggregates and binder constituents, with the possibility of other materials present to a lesser extent. Coarse aggregates are sourced from stones, while fine aggregates utilize sand, and bitumen serves as the binder constituent. Additionally, filler products from cement and lime may also be utilized. Similarly, concrete mixes primarily consist of binder constituents and natural aggregates, with other materials potentially present to a lesser extent. Fine aggregates are obtained from sand, coarse aggregates from gravel, and the binder constituents comprise cement, water, and additives.

Fig. 2 illustrates how RC utilizes contraction joints and reinforcing steel to manage cracking. The spacing of transverse joints typically ranges from about 7.5 m to 15 m. Cracking between joints is expected due to temperature and moisture stresses, and to mitigate this, reinforcing steel or a steel mesh is employed to tightly hold these cracks together. Dowel bars are commonly used at transverse joints to facilitate load transfer, while the reinforcing steel/wire mesh aids in load transfer across cracks. The estimation of material quantities is derived from the dimensions of the design cross-sections, which are determined according to the AASHTO Guide for pavement structure design. Fig. 3 illustrates the cross-section dimensions. The LCA methodology is chosen to assess and compare the environmental effects of four pavement materials throughout their entire life cycle. LCA is a flexible tool used to examine the environmental aspects of a process, product, or activity. It achieves this by identifying and quantifying the input and output flows associated with the system, as well as evaluating its delivered functional output, all from a life cycle perspective. All the processes associated with a product is ideally covered from cradle to grave. When various design options are available, LCA can also suggest various alternatives for different stages of the system's life cycle. In order to enhance the efficiency of the development of the study, SimaPro software application was used with LCIA ReCiPe 2016 Endpoint (H) V1.07 / World (2010) H/A.

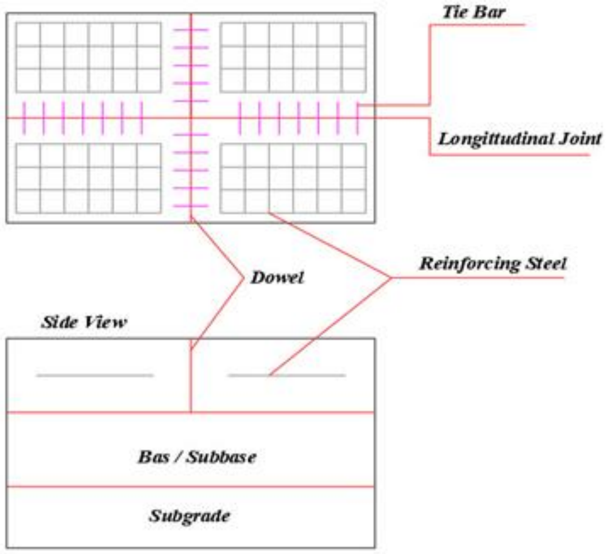

FIGURE 2. Typical cross section in rigid pavement

5. APPLICATION OF LCA IN A CASE STUDY

The main inventory data was collected through on-site investigations conducted during the construction of a major highway in Egypt, known as the Cairo-Suez Desert Road, which spans approximately 106 kilometers. The lane width on this road is 3.76 meters, with six traffic lanes dedicated to cars and three traffic lanes for heavy transport until it intersects with the regional ring road. Beyond this point, there are four lanes for cars and two lanes for transport, leading to the entrance of the Suez governorate.

5.1 Goal and Scope Definition

5.1.1 Purpose of the Study

The primary objective of this study is to assess and compare the environmental impacts of various flexible and rigid pavement alternatives in Egypt. It employs LCA following Egyptian codes to establish a comprehensive and sustainable approach to managing road construction in Egypt.

5.1.2 Function Unit

The functional unit serves as a measure of the function performed by the system under study, providing a reference against which the inputs and outputs are evaluated. The study defines the functional unit as a 1-kilometer-long road section with a width of 1 meter. All calculations for emissions, materials, costs, and energy consumption are based on this functional unit.

5.1.3 System Description and Boundaries

The life cycle of road construction comprises four primary subsystems: material production, construction, utilization, and end-of-life. The system boundaries are shown in Fig. 4 and Fig. 5. The study comprises several phases: firstly, the raw material extraction phase encompasses the extraction and processing of essential materials like aggregates, cement, asphalt, and other construction components. Secondly, it includes the transportation of these materials from their extraction sites to the plant and subsequently to the construction site, taking into account the associated energy consumption and emissions from transportation activities. Thirdly, the construction phase involves all road-related activities, such as pavement laying, grading, compaction, and any other construction processes involved. However, the study does not account for the environmental impacts associated with road operation, maintenance, and the end-of-life phase, which involves assessing scenarios such as recycling, reuse, or disposal of demolished materials.

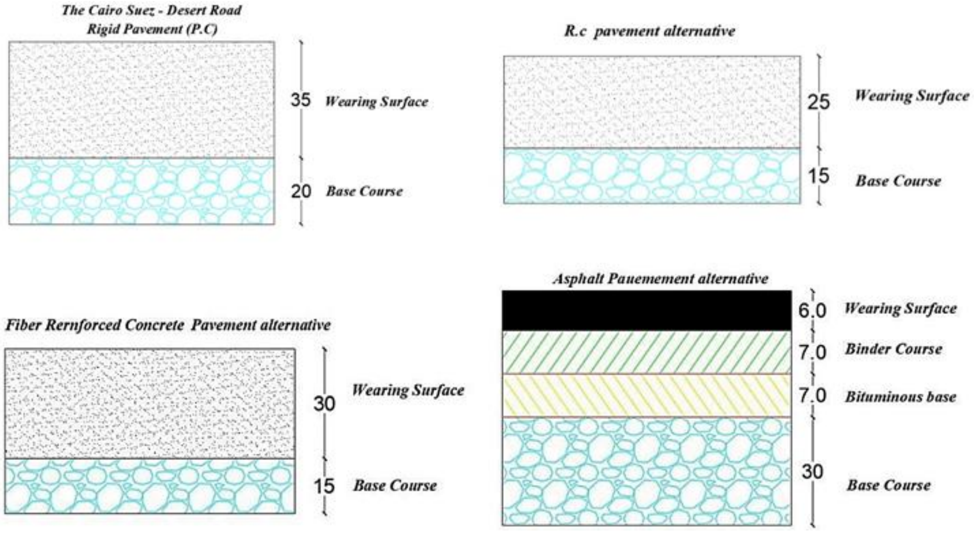

FIGURE 3. Cross-section alternatives in the Cairo-Suez Desert Road (dimensions are in "cm")

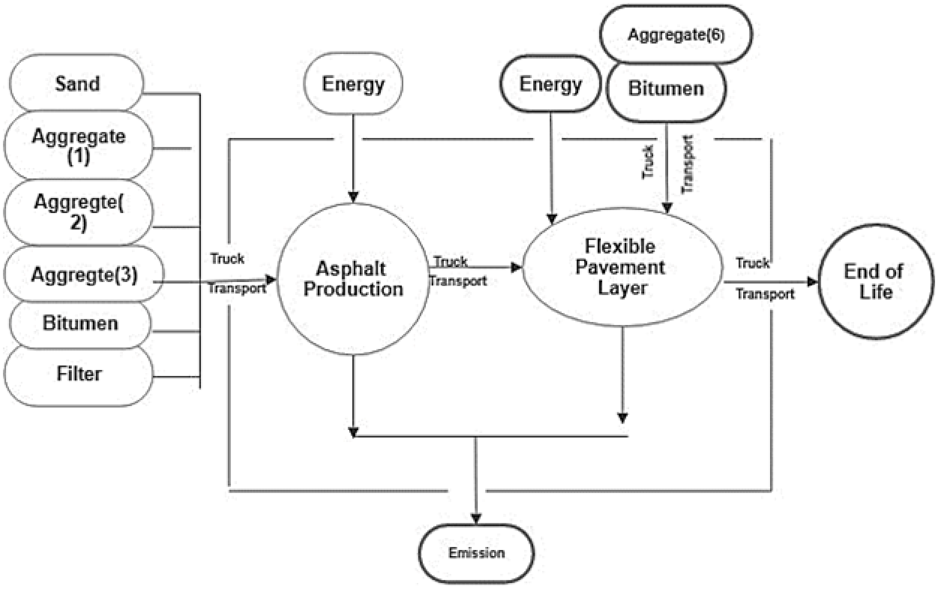

FIGURE 4. System boundaries of flexible pavement construction method

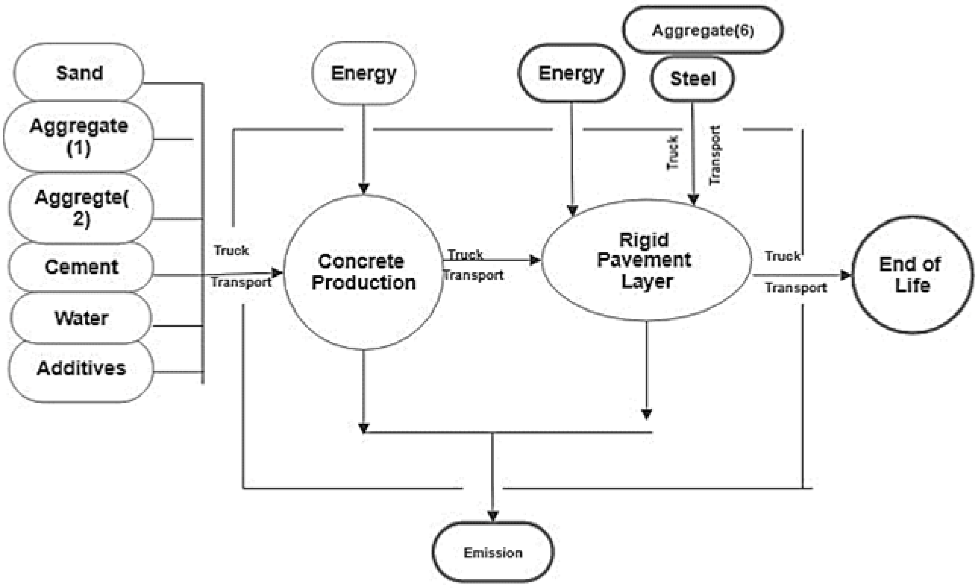

FIGURE 5. System boundaries of rigid pavement construction method

5.2 Life Cycle Inventory (LCI)

The inventory analysis encompasses the material and energy flows associated with the four alternatives (PC, RC, FRC, and HMA), considering various sub-steps such as raw materials extraction, production, transportation, consumption, and waste disposal. To establish the boundaries of the main system, sub-components originating from various sub-systems, the inventory data is obtained by tracing the inflows from the cradle to the grave within the defined system boundaries. Information regarding input materials for each sub-component is collected using field data supplied by construction companies. When field data is not accessible, data is obtained from LCA databases and relevant literature sources. Following the data collection phase, each sub-component is modeled using the SimaPro software application.

5.2.1 Asphalt Production

Besides the production process of HMA, the asphalt plant was also inventoried separately. The LCI was established using field data gathered from the production of HMA on three major highways in Egypt, as well as data from the asphalt plant operated by the General Nile Company Mix Plant. The inventory data pertaining to the asphalt plant are extrapolated from estimations rooted in the General Nile Company Plant. The plant's anticipated lifespan is approximately 50 years, with an average annual asphalt production of roughly 204,400 tons. The asphalt plant employs a range of machinery, as illustrated in Fig. 6, outlining the overall layout of the General Nile Company Mix Plant.

5.2.2 Concrete production

In addition to assessing the concrete production process, a separate inventory was conducted for the concrete plant. The LCI was constructed using on-site data covering concrete production, taking into account fluctuations in energy consumption and air emissions resulting from variations in composition and manufacturing methods. The concrete plant encompasses considerations for land usage, infrastructure, and the machinery employed in concrete production. The anticipated operational lifespan of the plant is approximately 50 years, with an average annual concrete production output of around 262,800 cubic meters. The concrete plant utilizes various machinery components. The concrete plant's general layout is shown in Fig. 7.

5.2.3 Transportation

The LCI data for the transportation process primarily rely on factors such as vehicle types and the distances traveled. Raw materials are transported from extraction and processing sites to the asphalt and concrete plants, while the asphalt and concrete mixes are subsequently transported to the construction site. The specific travel distances are contingent on local conditions and requirements. The significant volume of transported materials and the extended travel distances can significantly impact the overall energy balance of the system. Detailed transportation process inventory data are documented using pertinent truck transport datasets from the SimaPro database. Table 1 provides insights into the distances covered for all transported materials based on field study data.

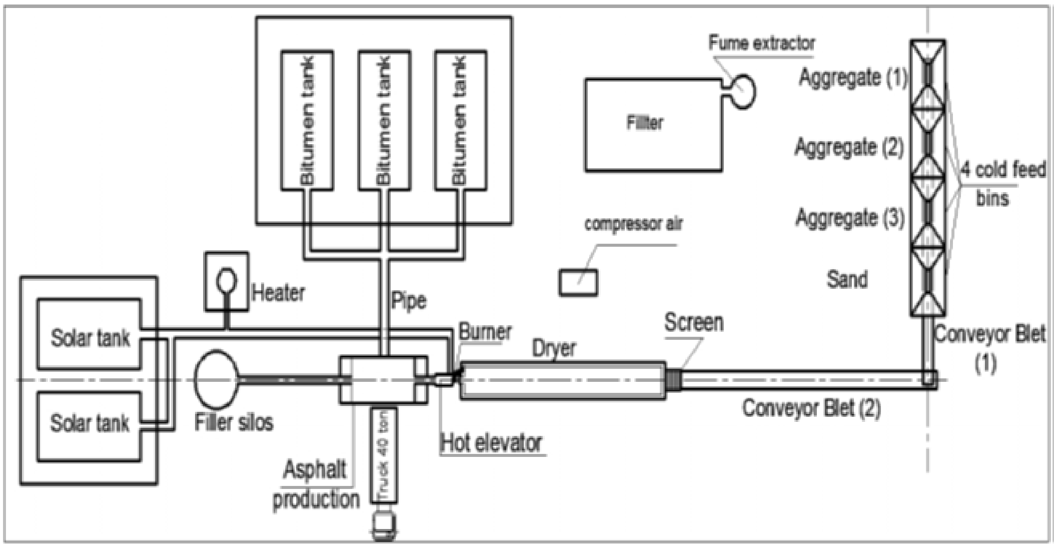

FIGURE 6. Asphalt plant general layout

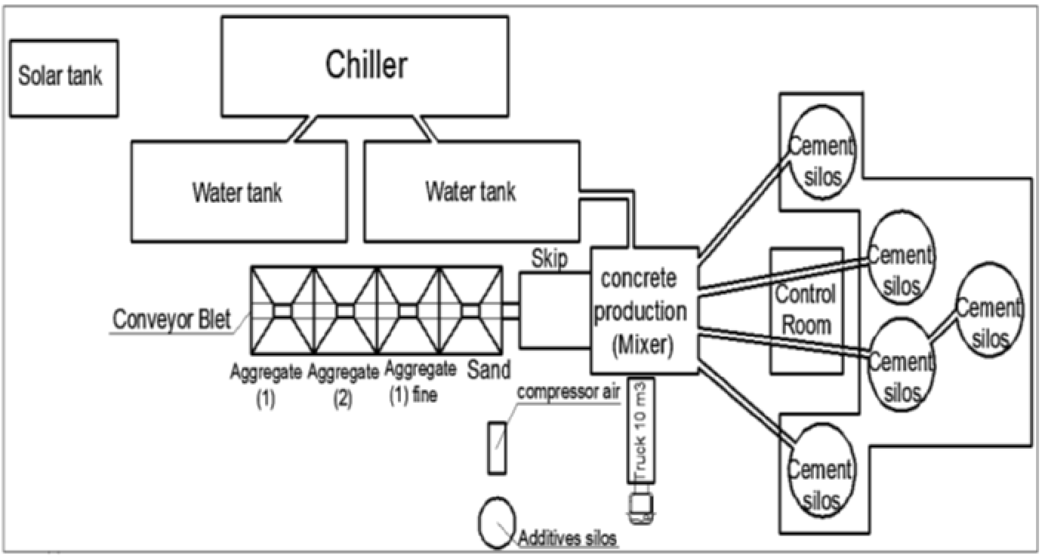

FIGURE 7. Concrete plant general layout

TABLE 1. Materials transportation

Component	From	To	Distance (km)
Sand	Extraction and processing sites	Plant	80
Aggregate (1)	Extraction and processing sites	Plant	90
Aggregate (2)	Extraction and processing sites	Plant	90
Aggregate (3)	Extraction and processing sites	Plant	90
Aggregate (6)	Extraction and processing sites	Site	105
Bitumen	Extraction and processing sites	Plant	90
cement	Extraction and processing sites	Plant	90
Filler	Extraction and processing sites	Plant	90
Bitumen to spray	Extraction and processing sites	Site	105
asphalt mixes	Plant	Site	30
Steel	Extraction and processing sites	Site	95
Additives	Extraction and processing sites	Site	95
Concrete mixes	Plant	Site	30

5.2.4 Construction

Environmental impacts associated with the construction phase arise from various sources, including fuel consumption, air emissions from paving machinery, emissions and leachate from the road pavement, as well as alterations to the land.

a) Machinery

The company typically employs a range of machinery for spreading and compacting both the asphalt and base layers, including an asphalt paver, a heavy vibratory roller, a rubber tire roller, and a grader. As well as the concrete and base layer: concrete mixing pump, mechanical vibrator, helicopter, rubber tire roller, and grader. Basic data on the operating phase of these machines are shown in Table 2.

TABLE 2. Machinery's energy consumption

Machine	Energy Consumption
Grader	80 liter / 1 km^2 (Diesel)
Rubber tire roller	20 liter / 1 km^2 (Diesel)
Heavy vibratory	20 liter / 1 km^2 (Diesel)
Asphalt paver	240 liter / 1 km^2 (Diesel)
Concrete mixing	0.85 liter / 1 m^3 (Diesel)
Mechanical	0.07 liter / 1 m^3 (Benzene)
Helicopter	0.1 liter / 1 m^3 (Benzene)

b) Electricity generation mix

Electricity plays a crucial role in LCA studies, as it is essential for modeling and evaluating resource utilization and pollutant emissions during generation and distribution activities. In Egypt, the electricity sector had a total generation capacity of 22,583 MW in 2008, with a generation mix consisting of 58.3% natural gas, 28.9% petroleum products, and 12.8% hydroelectric power. Considering the specific conditions in Egypt, the cumulative energy demand for electricity production is estimated to be 9.29 MJ/kWh. This estimation encompasses the pre-chains associated with energy sources, auxiliary materials, primary source processing, and transportation, the transportation of electricity to consumers is not considered in the assessment.

c) Diesel fuel

The LCI for energy consumption and related emissions during the extraction, transportation, and refining of diesel fuel is computed using Simapro datasets.

5.2.5 Mass balance for the main road and different alternatives

The materials and energy mass balance of rigid pavement construction alternatives for the Cairo-Suez Desert Road are estimated as shown in Table 3.

5.3 Life cycle impact assessment (LCIA)

The environmental impact assessments for the different scenarios under examination will be carried out using the LCA methodology, which adheres to ISO 14040/14044 standards, particularly ISO 14044 [25]. The LCI for each treatment process include factors like energy consumption, raw materials, air emissions, and water emissions. These LCI data are sourced from pilot studies, databases, and literature references, and will be adjusted to suit the specific conditions of the present study. Fig. 8 depicts the origin and structure of the LCA tool in alignment with ISO 14040, while Fig. 9 outlines the components of the Life Cycle Impact Assessment (LCIA) based on ISO 14042. The chosen impact assessment method is ReCiPe 2016 Endpoint (H) V1.07 / World (2010) H/A.

TABLE 3. Mass balance for the main road and different alternatives

Roads	PC “Main Road”	RC	FRC	HMA
Materials	**(625 ton)**	**(450 ton)**	**(550 ton)**	**(447 ton)**
Sand	188.5 ton	143.3 ton	165.9 ton	131.8 ton
Aggregate	628.5 ton	552.5 ton	596 ton	1011 ton
Cement	100 ton	72 ton	88 ton	x
Bitumen	x	x	x	23.1 ton
Water	49.5 ton	35.6 ton	43.5 ton	x
Filler	x	x	x	4.4 ton
Additives	1.8 ton	1.3 ton	1.6 ton	x
Fiber	x	x	13.75 ton	x
Elec. energy	939 Kwh	678.5 Kwh	822 Kwh	2264 Kwh
Diesel Fuel	1764 liter	1364 liter	1649.2 liter	4069.5 liter
Benzene	113 liter	110 liter	111 liter	x
Steel	14.35 ton	35.875 ton	14.5 ton	x

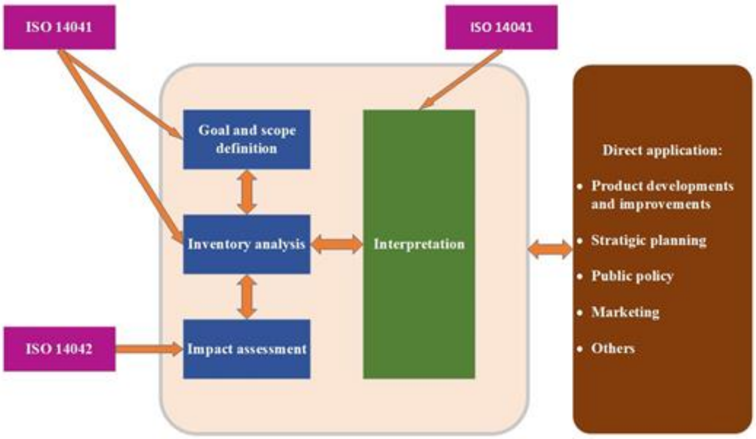

FIGURE 8. LCA tool origin and structure based on ISO 14040

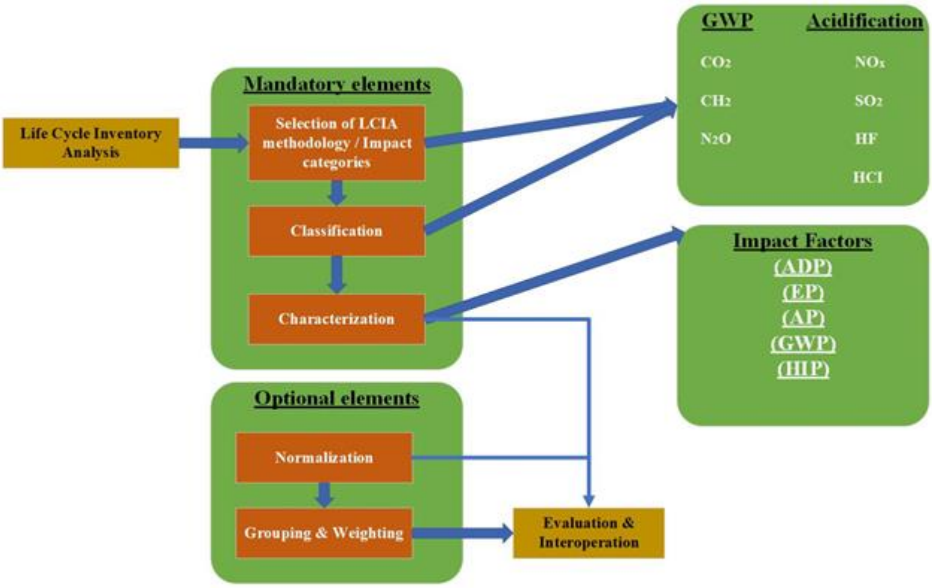

FIGURE 9. The elements of the life cycle impact assessment (LCIA) based on ISO 14042

6. Results and discussion

The LCI results for different impact categories associated with the four pavement alternatives are presented in Table 4. They represent the categorized as well as the total impacts for each pavement type. In terms of the total impacts, asphalt pavement has the lowest value of 1.310 kPt. Then the other three alternatives FRC, PC, and RC with total impacts 11.295, 12.044, and 12.635 kPt respectively from low to high. This indicates that asphalt pavement generally has the least overall environmental impact among the four alternatives. Looking at specific impact categories, asphalt pavement generally performs well in terms of human health, global warming, global warming on terrestrial ecosystems, and global warming on freshwater ecosystems. It also has low impacts on stratospheric ozone depletion, ozone formation on human health, ionizing radiation and terrestrial acidification. On the other hand, FRC, PC, and RC tend to have higher impacts in these categories compared to asphalt pavement. They also have higher impacts in categories such as fine particulate matter formation, ozone formation on terrestrial ecosystems, freshwater and marine eutrophication, terrestrial and freshwater ecotoxicity, mineral and fossil resource scarcity, human carcinogenic and non-carcinogenic toxicity, and water consumption for human health and terrestrial ecosystems as shown in Fig. 10.

Overall, the results suggest that asphalt pavement has the lowest environmental impact across various categories, while FRC, PC, and RC have higher impacts in several categories. These findings can be valuable for decision-makers and stakeholders in selecting pavement alternatives that prioritize environmental considerations. However, it is important to note that these results are based on the specific LCI numbers provided and may vary depending on specific contexts and regional factors.

TABLE 4. LCI numbers for different impact categories

Impact category	**Unit**	**PC**	**RC**	**FRC**	**HMA**
Total	**kPt**	**12.04438709**	**12.63515082**	**11.29541327**	**1.310722241**
Global warming, Human health	kPt	5.813235359	5.98132984	5.461854377	0.340044067
Global warming, Terrestrial ecosystems	kPt	0.284445443	0.292667198	0.267256629	0.016640774
Global warming, Freshwater ecosystems	kPt	7.76694E-06	7.99157E-06	7.2974E-06	4.54296E-07
Stratospheric ozone depletion	kPt	0.000492037	0.00052033	0.00043751	1.23275E-05
Ionizing radiation	kPt	9.71779E-06	1.66288E-05	8.11581E-06	0
Ozone formation, Human health	kPt	0.012841972	0.013192333	0.01206185	0.002024986
Fine particulate matter formation	kPt	5.014958724	5.22566231	4.708152395	0.677959779
Ozone formation, Terrestrial ecosystems	kPt	0.031584641	0.032377472	0.029840441	0.005341317
Terrestrial acidification	kPt	0.072935728	0.074111958	0.068088024	0.012655705
Freshwater eutrophication	kPt	0.000978554	0.001132844	0.000929476	0.000237382
Marine eutrophication	kPt	2.37848E-07	3.47018E-07	2.0846E-07	2.37606E-07
Terrestrial ecotoxicity	kPt	0.00059384	0.00074096	0.000547316	6.87769E-06
Freshwater ecotoxicity	kPt	2.35418E-05	3.44233E-05	2.00638E-05	0.000101169
Marine ecotoxicity	kPt	7.78318E-06	1.08791E-05	6.83553E-06	2.05813E-05
Human carcinogenic toxicity	kPt	0.143589454	0.341457968	0.094489386	0.004555603
Human non-carcinogenic toxicity	kPt	0.038903526	0.052532233	0.03412712	0.110581732
Land use	kPt	0.001273069	0.001617874	0.001182108	0
Mineral resource scarcity	kPt	0.020297136	0.017391046	0.017665139	0.038170097
Fossil resource scarcity	kPt	0.466894694	0.458117546	0.460328807	0.102369153
Water consumption, Human health	kPt	0.128602148	0.12939189	0.125969217	0
Water consumption, Terrestrial ecosystem	kPt	0.012711079	0.012836086	0.012440337	0

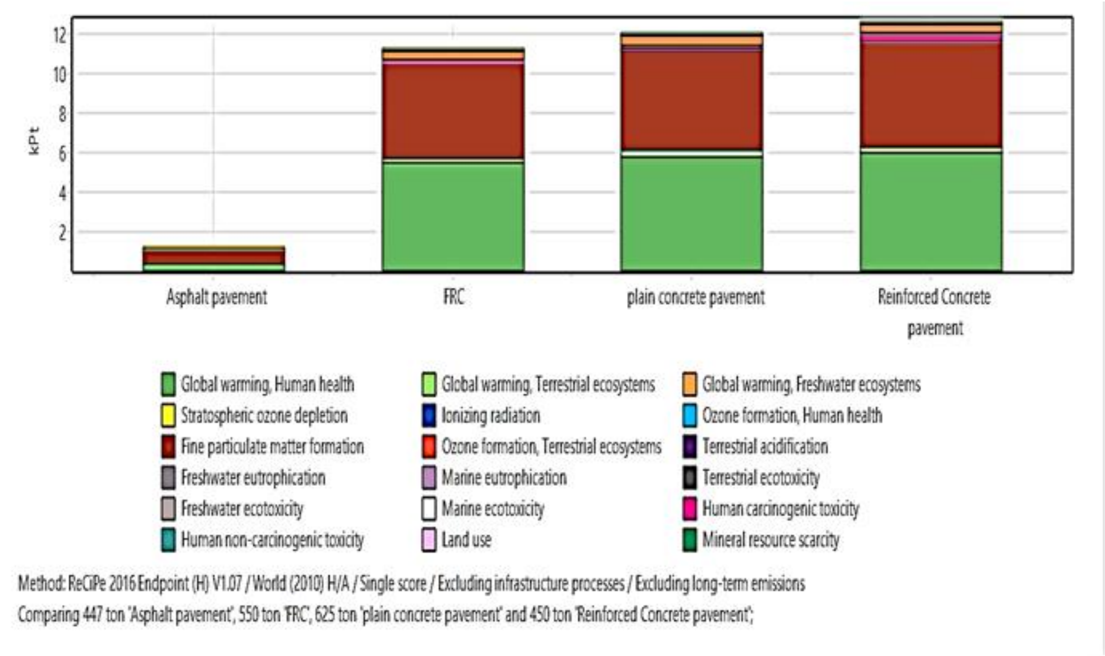

FIGURE 10. Single score for the alternatives

7. Conclusions and recommendations

Given the pressing demand for road network development and the adverse environmental impacts of road construction, sustainable construction practices hold the key to addressing this issue. Therefore, this research studied the environmental impacts of flexible and rigid pavement materials for road construction projects. The assessment of environmental impacts linked to road projects is conducted using the LCA tool. The goal and scope of the study were defined, with a focus on the Egyptian condition and the aim to contribute to sustainable road construction management in Egypt. The functional unit, system boundaries, and LCI were also outlined. Based on the LCI analysis for HMA, FRC, PC, and RC, the results revealed that asphalt pavement generally has the lowest environmental impact among the alternatives. It exhibits lower impacts in categories such as global warming, human health, terrestrial ecosystems, freshwater ecosystems, ionizing radiation, stratospheric ozone depletion, ozone formation on human health, and terrestrial acidification. On the other hand, FRC, PC, and RC tend to have higher impacts in these categories and others such as fine particulate matter formation, eutrophication, ecotoxicity, resource scarcity, and water consumption. These findings highlight the environmental advantages of asphalt pavement and can guide decision-makers and stakeholders in choosing sustainable and eco-friendly pavement alternatives. Overall, this study contributes to the understanding of the environmental impacts of road construction and highlights the importance of adopting sustainable practices in the industry. By considering the life cycle perspective and conducting LCA analyses, stakeholders can make more informed decisions to minimize the environmental footprint of road projects and work towards sustainable development.

In future research, it is highly recommended to expand the scope of investigation to include an in-depth analysis of the cost implications associated with each pavement material alternative. This entails a thorough examination of not only the initial construction costs but also the long-term maintenance and operational expenses. Evaluating the economic aspects by calculating the benefit-cost ratio for each alternative will provide valuable insights into the financial feasibility and sustainability of the chosen pavement materials. Additionally, it is advisable to consider the synergy between environmental and economic factors, as this can offer a more holistic perspective for sustainable decision-making in road infrastructure projects. Furthermore, future research endeavors should encompass all the aforementioned recommendations to foster a comprehensive understanding of the environmental and economic dimensions, ultimately guiding the selection of the most sustainable and cost-effective pavement materials for highway construction.

8. References

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