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Comparative Life Cycle Assessment of Asphalt Mixtures of road: A review

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A B S T R A C T

To enhance the economic, social development, political, overall performance and social functioning of every society, the degree, and efficiency of road networks play a crucial role. For any community, it is impossible to have overall social growth without a good transport network. In the manufacture and service of road networks, we are constantly looking for solutions to enhance pavement performance, improve construction efficiency and improve environmental protection. The use of additives can effectively improve the quality of asphalt pavement, prevent cracking, enhance water retention, enhance the stability of production and construction suitability, increase strength, and enhance the adhesion of the surface and other good effects. Moreover, different modified asphalt mixtures need to be handled in an environmentally appropriate manner to avoid the negative impacts of their construction, so the approach of LCA was used to evaluate the construction processes. Recently, numerous LCA studies have discussed the environmental implications of road construction activities worldwide, but there are still several issues that need to be further examined. This paper explains an overview of the application of the LCA methodology and its implementation in road construction.

1. Introduction

The road construction industry is constantly pursuing technological changes that improve paving material performance, advance building efficiency, conserve energy, and enhance environmental protection [1]. Building roads may have detrimental environmental impacts and effects on air, water and soil emissions [2]. The LCA approach is commonly recognized and globally agreed approaches for comparing environmental effects of services/processes and determining their sustainability over the life cycle [3, 4]. Both resource use and pollutant emissions related to the system life cycle are considered in life cycle evaluation, for example the processing and extraction of raw materials, chemical manufacturing, recycling, operation, and transportation [5, 6]. The LCA is very well developed and standardized at present. It also contains a process of impact assessment during which all possible environmental effects are collected and quantified that will support and guide decision-makers with regard to road construction.

Moreover, several kinds of raw materials are used by the road industry, such as, aggregates, sand, bitumen, filler, and often selected additives that use a high quantity of natural resources and energy for the extraction, manufacturing, processing, and transport of raw materials. This industry is responsible for the intensive emissions and contamination of air, water, and soil in the surrounding areas [7]. In China, about 290 million tons of CO2 emissions were produced by the highway industry in 2004, the estimated emissions are predicted to hit 1.1 billion tons by 2030 [8]. Also, the asphalt mixture manufacturing and wearing surface construction processes, these emissions also occur through the extraction, manufacture, and transport of raw materials. Recently, the environmental impacts of road construction practices worldwide have been addressed in several LCA reports, but there are still several concerns that need to be studied further [9].

Furthermore, this research aims to contribute significantly to environmental evaluation by comparing the environmental effects of pavement construction, based on a LCA. This contribution will be useful when preparing and managing sustainable road development. These analyses will have a major impact in assisting industry and government decision-makers as a fundamental instrument in the development of road construction management strategies and policies, as well as in estimating investments in new road construction facilities.

2. Thinking of Life Cycle (TLC)

As shown in Figure 1, a products or service life cycle starts with extraction of the raw materials and processing, manufacturing, transport, use, or consumption and this ends with the management of waste. A range of environmental and health impacts of different levels are output from the consumption of non-renewable resources and energy and production of pollutants in each of these life cycle phase [10].

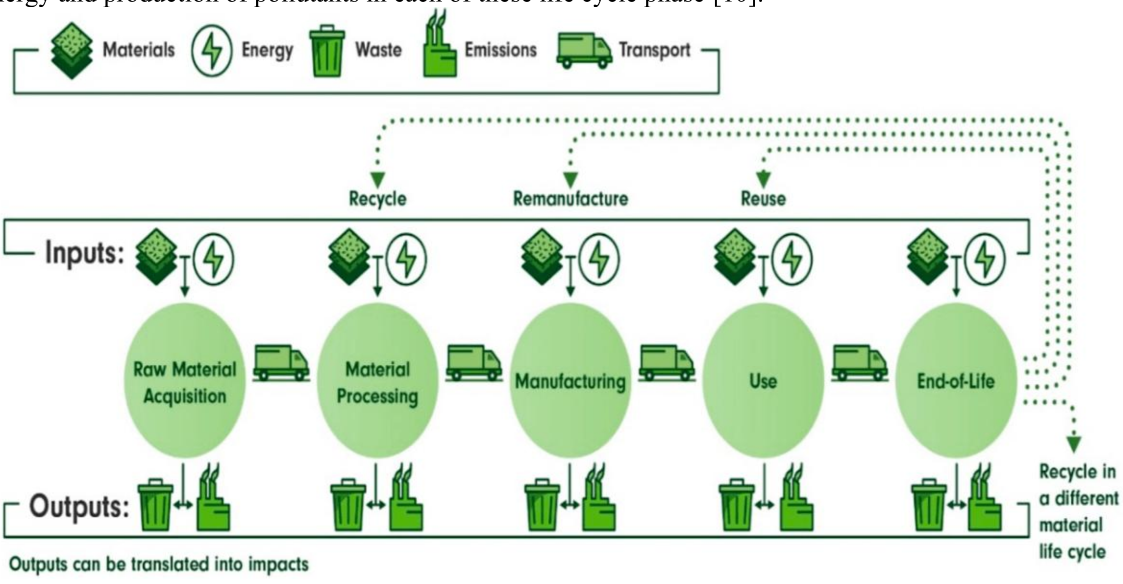

Figure 1. The product's life cycle [10]

Thinking of the life cycle is defined as a systematic methodology to solving environmental problems from the viewpoint of goods or services. This way of thought goes beyond the traditional focus on processes of manufacturing, and sites of production. Over the course of a product's life cycle, it's important to consider economic and environmental factors including consumption and end of use processes. The TLC aims to recognize the future product and service changes in the form of lower potential environmental effects and decreased resource usage in all phases of the life cycle [11]. It also aims to prevent the shifting of the impact that leads to reduced burdens at one point of the life cycle, in a geographical area or a specific category of effects, wanting to raise them at any other location through the product's life cycle.

TLC's key objective is to implement an integrated product strategy to decrease the usage of environmental pollution of the product, in addition, to enhance its socio-economic efficiency over the product's entire life cycle. This will make it easier to link a product's dimensions of economic and environmental across its entire chain of life [12]. LCA applied in current study is one significant approach for applying the life cycle thinking method.

3. Life Cycle Assessment (LCA)

3.1 Definition of LCA and Background in History

Life cycle evaluation is a technique for estimating the environmental characteristics and possible impacts of a product, or activity by gathering the necessary outputs and inputs inventory during its entire Life Cycle (LC) and assessing its possible environmental effects [13]. In its life cycle, LCA explores the environmental effect of a commodity on all processes from cradle to grave. This involves the raw material extraction, the product manufacturing and the components of it, in addition to the maintenance and use of the product as well as final disposal, recycling, or reuse.

The LCA technique was developed in a variety of countries, including the USA, Sweden, the UK, and Switzerland, starting in the late 1960s [14, 15]. In terms of the restrictions on energy supplies and material resources have generated attention in seeking methods to cumulative account for the use of energy and the provision and use of resources for potential projects. At the conference of World Energy in 1963, Harold Smith offered the first publications on this topic [16]. Initial studies were basic and usually limited to the measurement of waste of solid and energy needs, but the evaluation of possible environmental impacts did not pay much attention.

The Institute of Midwest Research (MRI) launched research for the company of Coca-Cola in 1969 that laid the groundwork for the existing life cycle inventory analysis methods in the USA [17]. To decide which had minimal emissions to the environment and the lowest impact on the natural resource supplies, the aim was to compare various types of containers. This study calculated for each container the fuels and raw materials used as well as the loadings of environments from the production phases. There was no clear measurement of the impact on the health of the human, although the amounts of different emissions and the quantities of natural resources used were recorded. The outcome was an inventory of activities that cause an environmental burden without ever specifically measuring those impacts [18].

Several studies in extensive energy associated with a life cycle evaluation methodology were carried out for a big variety of industrial systems through the oil crisis in 1970 [19]. And in 1980, without a standard theoretical structure, various studies were conducted using different approaches. Therefore, while the subjects of the experiments were mostly identical, the findings varied significantly, thereby avoiding LCA from being a more widely practiced analytical method.

From 1989, under the management of the SETAC, efforts have been done to harmonize the LCA methodology. With its origins in government, industry, and academia, SETAC is a research association that can provide a forum based on science as a medium for the coherent production of LCA. The CML partnered with the Netherlands Organization for TNO in 1992 to create a guide and history paper on the LCA environmental approach [20]. SETAC issued a practice code in 1993 that sets out public basics and a structure for the use of LCA results, conduct, presentation, and analysis [21]. In 1994, activities were introduced by the International Organization for Standardization (ISO) to create the first full set of LCA specifications. In the 14040 series, the following public specifications have been created:

- ISO 14040 (1997 edition): A specification on values and structure [13].
- ISO 14041 (1998 edition): A specification on analysis of inventory, as well as the definition of goal and scope [22].
- ISO 14042 (2000 edition): A specification on impact assessment of life cycle [23].
- ISO 14043 (2000 edition): A specification on interpretation of life cycle [24].

While each one of SETAC and ISO has its independent work, there is a public agreement between the two organizations on the methodological structure, the variance being only in terms of detail [25]. Four methodological mechanisms via the LCA were defined by the SETAC practice code: the goal definition, analysis of LCI, assessment of the improvement and the effect of life cycle. Moreover, the interpretation of the life cycle process has been presented [26].

3.2 LCA's Methodological System

Definition of goal, inventory analysis, impact evaluation, and interpretation are the four stages of the LCA approach's technical framework as shown in Figure 2.

These stages are followed not necessarily in a single arrangement, but in a repeated process in which the next stages can afford more detail levels (from LCA screening to complete LCA or lead to adjustments in the first process followed by the last process outcomes [12].

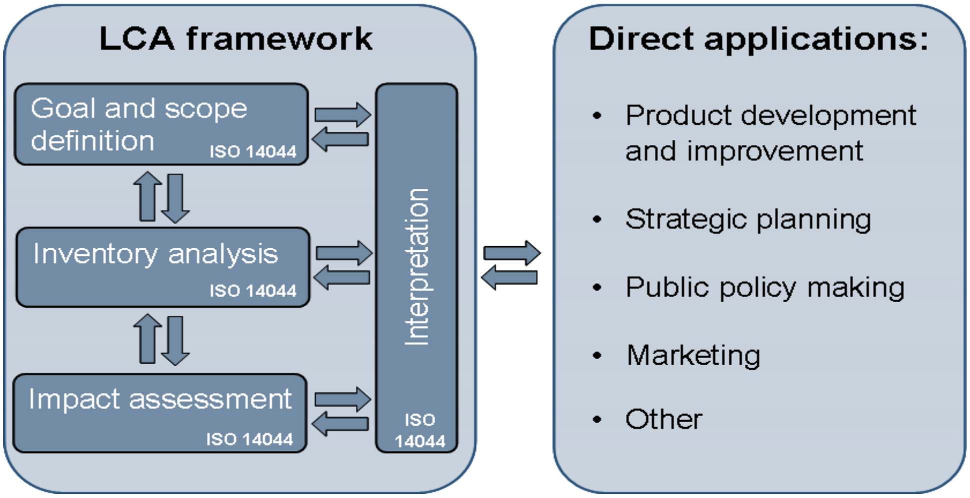

Figure 2. LCA stages and implementations [13]

3.2.1 Definition of Goal and Scope

The purpose is designed to provide the necessary LCA study standards. The resources and time required will be calculated and the whole process will be directed to ensure that the most important results are getting. Each decision taken during this phase affects either how the analysis will be carried out or the validity of the final results [27]. The practitioner must follow such protocols to carry out the purpose and scope of an LCA report [28]:

- Identify the unit of function and the purpose of the LCA analysis that is the study quantitative guide.
- Defining the study scope by defining the spatial bounds between the system of a product under study and its environment in the neighborhood and describing this system by drawing up a flow chart of its unit processes (define system boundary).
- Defining the necessary data, quality, and sources.

☒ **Goal of the LCA**

The causes for conducting the research, the purposed application, and the purposed audience to whom the study's outcomes are purposed to be connected must all be stated clearly in the study's purpose [22]. The LCA is a flexible instrument from cradle to grave for quantifying the cumulative environmental consequences of a process, or service during the life cycle. The major objective is to select the best service, system, or product that has the lowest impact on the health of the human and the environment. To significantly reduce emissions and resource requirements, the conduct of the LCA study may also help guide the production of new products, technologies, or activities. In the beginning, the key objective of the analysis and the justification for the creation of an LCA must be established because it has a strong impact on the additional steps that will identify the applied study type and the data type needed.

☒ The Functional Unit (FU)

It is the base of an analysis by the LCA. It serves as the connecting point for all inputs and outputs and allows the effects of the LCA to be clearly compared. This unit is applied as a reference for calculations and generally also as a reference for comparing the relationship between the various systems that perform the same purpose [28]. All raw data of emissions, resources, energy, and wastes for a system or a product are standardized to this unit, placing all the data on a normalized base [29]. In addition, the functional unit describes product function quantification and should be explicit and suitable with the study's purpose and scope [22].

Studies of life cycle inventory have usually been connected to products, and their FU has been described based on product quantity, such as per liter or kg. The functional unit is thus stated according to the output of the system [30]. In contrast, the waste management system unit is not specifically related to the product production, but with the disposal of waste in a certain area or causing by a specific service. Therefore, this unit can be described as the input of a certain system according to (kg or tone of waste managed) [30]. The usage of the conventional functional unit creates associated energy, emissions, and material analysis and does not evaluate the exact mass (quantity) that may be necessary to deal with particular environmental burdens [29]. The waste amount that can be created by exchanging the functional unit (a ton of waste) to the annual amount of waste produced in the geographical area or service area may also be linked [31].

☒ System Boundaries

The limits of any study should be set once the general aim and intent of the LCA study are understood. A key move in any LCA analysis is to pick the system limits. The system limits describe the phases and activities of the unit that will be part of the system under the analysis. LCA is described as a thorough examination of the potential environmental consequences of a product system's inputs and outputs over its entire life cycle. Consequently, the product system should also be designed to contain all environmental inputs and outputs at their limits [20]. LCA limitations for a product include the production of the key product, the procurement of raw materials, and the usage of the product, the product final disposal, and the product reuse or recycling.

Essentially, the method limits should cover all phases related to the system of the product. This will result in system limits that are too broad and complicated to define and assess. As a result of several data, cost limitations, and the complexity of various intended applications, this is also neither feasible nor realistic. Thus, after identification of all stages that exist in the system limits of the study, it can be simplified by ignoring all phases and activities that have slight effects on the results. All similar processes can be excluded in the case of comparable alternatives [32]. In general, ignoring any stage of the study, must not affect its results. The main goal and scope of the analysis should decide how much information will be used in each step of a system or the product's life cycle. It is a significant factor in removing a particular operation from the limits of the system [33].

Generally, a process, product, or activity's life cycle is described as a system enclosed by the environment. All activities which share in this system life cycle should exist at the limits of the system. Natural resources, like resources of energy, are the inputs to this system and the outputs are the series of emissions to the environment (soil, water, or air)[33]. In Figure 3, this definition is listed.

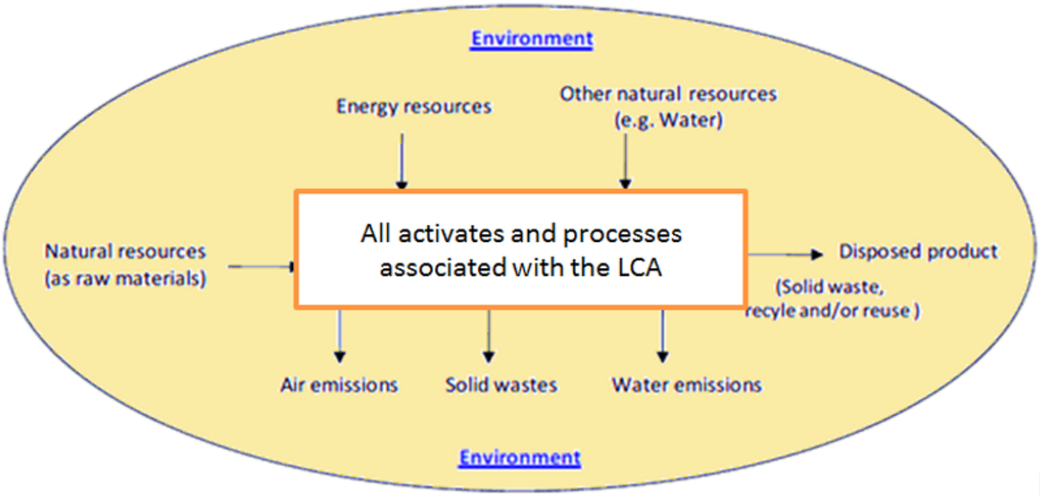

Figure 3. Definition of system boundaries [33]

The limits of a system should be defined in several dimensions based on the study scope. Consideration should be given to the following aspects [32]:

- The system's and the environment's boundaries, as the life cycle starts with the point at which energy and raw materials carriers are extracted from nature. It should involve all the stages necessary to get resources and raw materials into the system. The last step of a product's LC usually contains air or water, the heat into the soil, or the release of waste.
- In the majority of LCA studies, the geographical region plays an important role. Infrastructures, such as systems of transport and power generation, change from region to region. In addition, the sensitivity of the ecosystem to environmental effects varies also regionally.
- The limits must be determined not only within space but also within the horizon of time. The LCA is used to estimate the actual and future environmental effect of a product. The period of system limits is typically constrained by the lifespan of the technologies included and the lifetime of the contaminants.

3.2.2 Life Cycle Inventory (LCI)

Analysis of LCI is a scientific method of measuring the energy and raw materials needed, and the environmental effects emitted during a system’s life cycle in the soil, water, and atmosphere [34]. The definition of environmental loads is the number of ingredients, radiation, emissions, or sounds released or removed from the environment that resulting possible or actual negative effects [28]. At the LCI process, all related input and output data are gathered or measured and arranged for each unit operation over this system’s life cycle, as clarified in Figure 4. The LCI stage provides a list including the magnitudes of pollutants emitted into the atmosphere and the quantity of materials used from cradle to grave throughout the life cycle of the system studied. During the remaining LCA procedures, the level of precision and information on the gathered data is reflected.

To identify the intent of the analysis of the inventory, the inventory phase starts with the definition of the scope stage [35]. Throughout its life cycle to achieve emissions and resource consumption reduction, it’s important to clearly identify phases within the scope of the framework being studied. Next, an LCI data gathering strategy confirms that the accuracy and consistency of the data gathered to meet the study's scope and limits. It is suitable to create a flow diagram for the major system that includes a sequence of phases or subsystems over its entire life cycle, for data collection goals. All subsystems include energy inputs, material, and has product outputs, solid waste, waste stored in water, and other emissions. The inventory data for each subsystem should identify its energy sources and materials used and its environmental emissions.

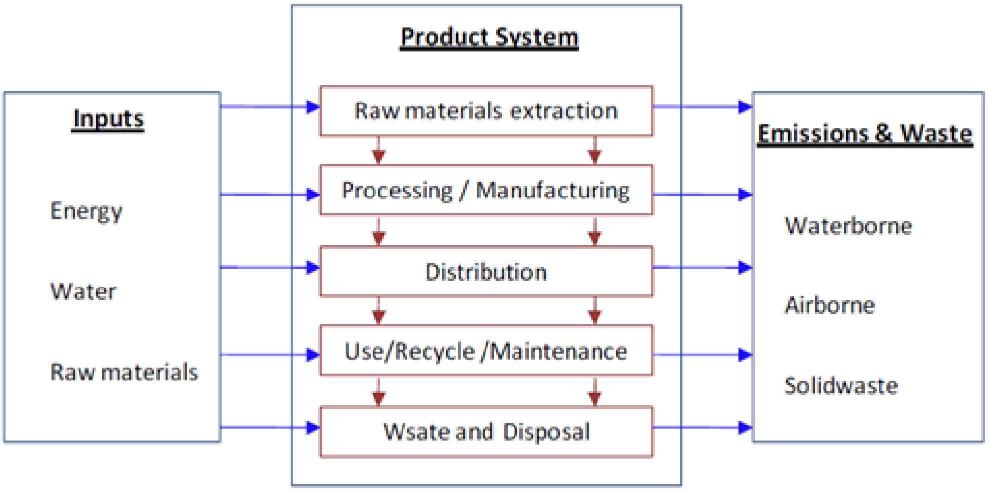

Figure 4. Life cycle inventory logical diagram [29]

The collection of data starts with a mixture of site visits, literature, direct communication with experts, and LCA software packages for commercial purposes. After data is gathered in the system being evaluated for each phase, some calculations are required to place the data in a particular format and express it according to a specific functional unit [33]. Then, in the LCI phase, a computer model for each stage of the system is created to integrate and collect the data for inputs and outputs.

The SimaPro 9.1.0 program was selected in the current study to model phases or systems and analyze their environmental influences. SimaPro is a commercial technique to quantify and imagine flow systems of energy and materials. It is applied to assess the process streams. Using environmental and economic success metrics, outcomes can be evaluated.

3.2.3 Limitations of the LCA

LCA considers a full instrument for calculating the environmental burdens of a system associated with a functional unit. This phase presents its strength and weakness aspects, while the extensive purpose of the study of a system's entire life cycle can only be accomplished at the cost of simplifying other sides [36]. Concerning the strength aspects present in the fact that it is a method that approaches a system's entire life cycle about all specific forms of environmental burdens, helping to expand the reach of responsibility in environmental management. On the contrary, its drawback is that the temporal and spatial accuracy of the findings is poor, and economic and social factors are not considered [15].

For the relative analysis of emissions, materials, and energy, the results of using functional unit do not evaluate the exact mass (quantities) that should be necessary to resolve particular environmental effects. The identification and evaluation of serious problems caused by the repetitions of long-term and short-term patterns of rising waste flows are insufficient. For instance, with emissions measured at 100, 1000, or 1000000 tons of waste, the relative mass of environmental impacts will not be adjusted. Whereas, there will be radically various changes of relevance to the environment [29, 31].

Although the LCA is the only instrument that contains all the environmental influences associated with the system's life cycle and connects these burdens to a functional unit, it is not capable of evaluating the real effects of the system on the environment. The ISO [1998] warns that LCA does not forecast or determine protection, risks or whether limits are exceeded for actual impacts. How, where and when they are emitted into the atmosphere will affect the real environmental impacts of wastes and/or emissions. Therefore, if a particular emission from a single event is emitted at a point source, it can have a somewhat dissimilar environmental effect than the continuous emission from many common sources over the years.

While LCA seeks to be based on science, there are various technological assumptions and value choices included. Moreover, to prevent disagreements and to make these decisions more coherent and clear, the ISO standardization phase presents a major role. Data availability where databases are established in different countries and are often ancient, inimitable, or of unknown efficiency is an additional restriction [30]. Even considering all these restrictions, LCA is a method used to compare between different systems over its life cycle from cradle to grave. It is difficult to be changed by another instrument for the same reason [37].

3.2.4 Life Cycle Impact Assessment (LCIA)

It is a phase of evaluation of life cycle that uses a methodological basis during its life cycle to measure the environmental burdens related to a specified activity, phase, or product. The results of the inventory study of the effect valuation process are converted into their contributions to related effect categories like acidification, climate change, abiotic resource depletion, etc. The LCIA aims to create a link between the activity, process or product and its possible effects on the environment. No clear, exact effects related to a process or product are quantified [17]. LCIA is useful for a relative comparison of the possibilities for environmental harm or human, although is not an absolute risk or real harm measure [38]. Resource scarcity and public health effects, ecological and even social services should be treated in the impact evaluation [17]. The LCIA includes optional and mandatory constituents in compliance with ISO 14042 [2000], as shown in Figure 5, and should continue through the stages that follow:

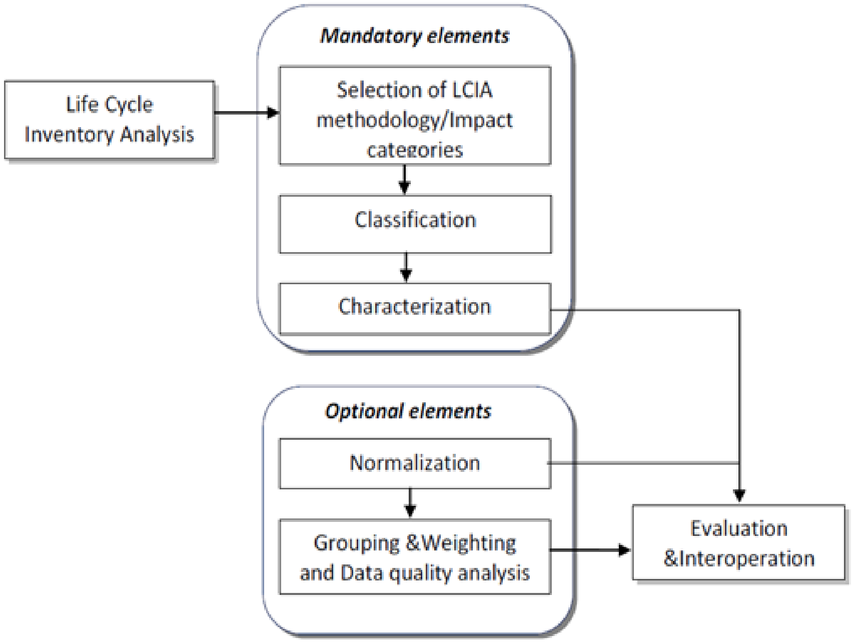

Figure 5. Elements of life cycle 's impact evaluation [23]

☒ **Mandatory Steps:**

- Choosing of LCIA approaches, the selection of associated categories of environmental effect, and the indicators for all effect categories.
- Classification of environmental burdens for different environmental effect categories through the LCI data.
- Characterization of environmental burdens of all related LCI flows.

☒ **Optional Steps:**

- Normalization: Measuring the value of the effects of the category indicator compared to reference values, such as overall emissions or resource consumption.
- The results of weighting and Grouping: The indicators can be sorted and possibly ranked concerning their importance. The indicator results could be also aggregated into a final score across the impact categories.
- Analysis of data efficiency helps to understand the reliability of the findings of the LCIA.
- Consequently, to get the final recommendations and conclusion of the study, the findings of LCI and LCIA are examined, assessed and explained according to the purpose concept of the research.

3.3 Selection of LCIA Methodology/Impact Categories

The goal of the LCIA techniques is to link resource extraction, pollution and other life cycle inventory interventions according to impact ways to their related environmental harm [39]. The impact way or analysis of cause and effect chain aims to explain the chain of fundamental relations to their effect on different receptors such as ecosystems or humans for the emissions of a load by chemical transformation and transportation into the environment [40]. The results of the LCI are first categorized in terms of ISO 14042 [23] into effect categories, every category has an indicator to reflect the quantity of its possible effect on the environment. The indicator of each category should be placed between the results of the LCI and the endpoint of the category in the impact path at any point. The endpoint category is often referred to as the degree of harm and reflects changes that are directly linked to societal problems, such as disease occurrence, natural resources, human age and important habitats, etc. [41]. Figure 6 explains the overall LCIA structure, illustrating through the cause and effect chain of the environmental process the relationship between LCI outcomes, indicators of each category, effect categories and endpoint of each category. It explains these principles according to the acidification effect category.

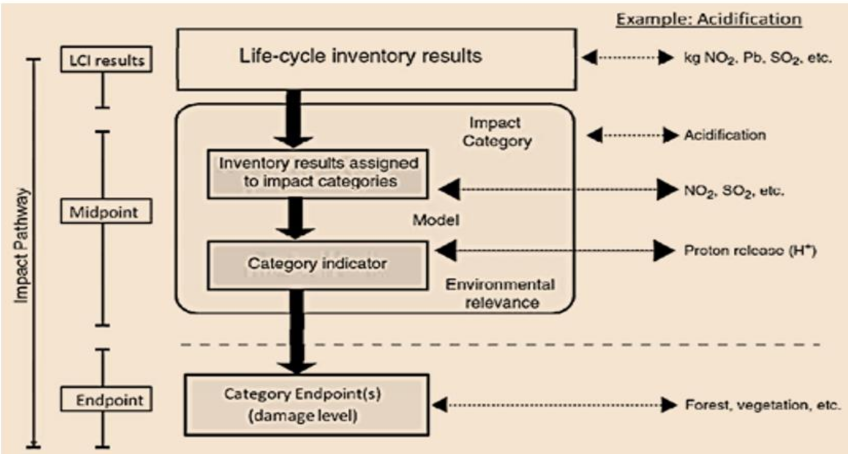

Figure 6. The mechanism of environmental based on the LCIA systems [23]

3.3.1 LCIA Methodology

LCA users have an available range of different impact evaluation procedures and most of them are incorporated in software that is currently accessible on the market [42]. The LCIA approaches can be divided into two major schools [43]:

- **Approaches of classical impact assessment** or midpoint methods that prevent numerical modeling and divide LCI outcomes to categories of the midpoint [44]. EDIP97, CML2001 [20], and its additional modifications TRACI [38] and (EDIP2003) [45, 46] are the developed procedures by this method.

- **Approaches of harm oriented** or end-point method like EPS [47] and Eco-indicator 99 [48, 49] that aim to model the chain of cause and effect to the environmental harms to human health and natural resources.

The accessibility of accurate data and adequately strong models to enhance the modeling of endpoint continues to be very limited at the moment. The indicators of the midpoint are more informative as they are significant for a broader range of outcomes, while the models of endpoint concentrate on a smaller number of routes. Beyond the indicators of the midpoint, doubts may be very high, so a false sense of precision and progress can be gotten. Nonetheless, the midpoint effects are hard to interpret, particularly in the decision making phase. They are not specifically associated with the protected area exercised by the effects of endpoint, such as loss of resources, the efficiency of the ecosystem, and human health damage. The modeling of endpoints can promote the creation of more organized and knowledgeable weighting based on common parameters, especially science related to the collection through categories [20, 28, 50].

At the Brighton workshop, the experts of the LCIA demonstrated the agreement that both the midpoint and endpoint approach affords the decision-maker with valuable knowledge. The call for fresh instruments that contain midpoint and endpoint in a coherent context is welcomed [51]. Some methods of this sort have recently been advanced, such as the Japanese LIME approach, which covers 11 categories of midpoints and 16 categories of damage and exists in the Japan region [52], as well as IMPACT 2002+ that exists in European countries and covers 14 categories of midpoints and 4 categories of damage [43]. Figure 7 demonstrates the LCIA approach's overall planner whereas all forms of LCI outcomes are related to the harm categories through the conventional categories of the midpoint. The dashed arrows show that only specific or uncertain relations are established and the solid arrows show that there is a measurable model [53]. The common LCIA approach to damage and midpoints is only at the start, many effect categories have not been taken into account and much of the details now presented between the midpoint and level of damage are highly inexact.

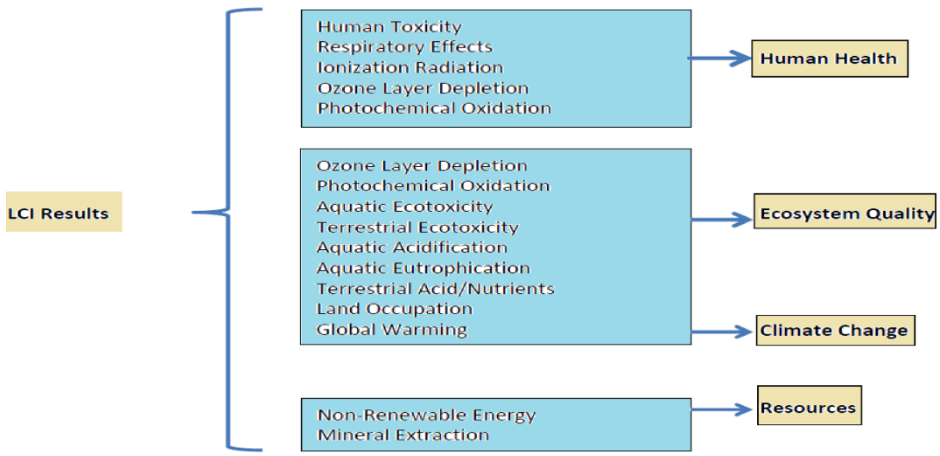

Figure 7. Structure of the shared midpoint/damage LCIA outline [53]

3.3.2. Impact Categories of the Life Cycle

The definition of the category is a group showing important environmental matters that can be allocated to the results of LCI. The effects are described as the implications that a system's output and input streams could have on the natural environment or human health [27]. ISO 14042 does not have a specific list of effect categories for attaching it in LCIA but provides three large sets of effect categories. These sets are usually denoted to in the protected area that contains the environmental impact, human health and use of resources [54]. Generally, the applied categories of effect should be suitable for the LCA study's purpose and scope.

Depending on the environmental significance of the LCA and the availability of suitable description tools, as shown in Table 1-, three groups of effect categories are featured [20]. The SETAC-Europe effect evaluation working group's list of effect categories and best existing models has been developed as the base for effect categories standard and indicators of the category [55].

- Group A: 'Effect categories standard' includes the effect categories standard defined and addressed by Udo et al [55] and are involved in nearly all LCA analyses.
- Group B: 'Categories of study-specific effects' contains categories which, depending on the LCA analyses' purpose and scope, can worth attaching if suitable data is existing.
- Group C: 'Other effect categories' includes numerous categories for which no technique of standard characterization is available and before being used in LCA analyses requires additional study and explanation.

Table 1. The default list of categories and subcategories of impact

Group A Baseline impact categories	Group B Study-specific impact categories	Group C Other impact categories
Depletion of abiotic resources	Impacts of land use: loss of life support function loss of biodiversity	Depletion of biotic resources
Impacts of land use		
Climate change		Desiccation
Stratospheric ozone depletion	Ecotoxicity: Freshwater sediment ecotoxicity Marine sediment ecotoxicity	Odor: Malodorous water
Human toxicity		
Ecotoxicity: Freshwater aquatic ecotoxicity Marine aquatic ecotoxicity Terrestrial ecotoxicity	Impacts of ionizing radiation Odor: Malodorous air	
Photo-oxidant formation	Noise	
Acidification	Waste heat	
Eutrophication	Casualties	

The effects of dissimilar categories on different spatial scales have penalties for human well-being and the environment, as shown in Figure 8. The influences of ozone layer depletion and change of climate are global. This also holds for natural resource mining, but not all parts of the world have the same requirement for all resources. Other groups, such as nitrification, acidification and the creation of photochemical oxidants, are normally resulted from contaminants that remain in the atmosphere and allow continental dispersion. The ecotoxicity categories may be deemed to have a regional dimension in which the effects of photo-oxidant creation are based entirely on the local condition [12].

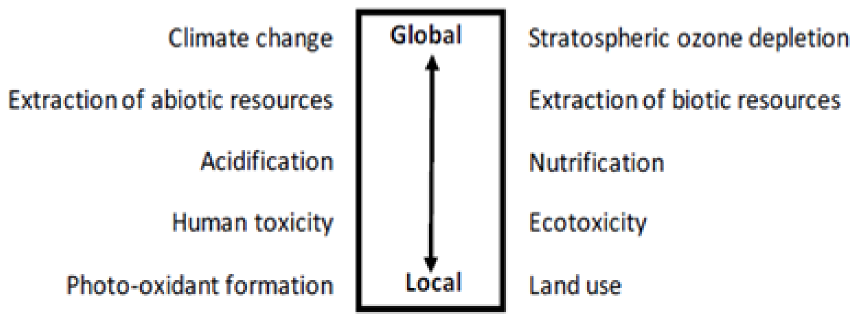

Figure 8. The need for spatial differentiation in different impact categories [12]

3.3 Classification

The classification stage aims to arrange and allocate the resources and emissions in the results of the LCI to the effect categories that are applied in the study, according to their capability to share various environmental difficulties [56]. A direct task is the allocation of LCI objects, which relate to only one category of effect. The results of the LCI that lead to more than one category of effect should be defined as follows [23]:

- Parallel effects: acidification and human health were assigned to emissions of pollutants that could result in different effects, such as SO2. The amount of LCI results is usually suggested to be allocated in proportion to their share of each category of effects. Although, there are no available instructions for how this activity should be carried out. It is recommended that they be allocated to all applicable effect categories in their entirety or split evenly between categories [20]. Lee et al [57] claimed that it is usual for all forms of effect categories to allocate the total sum of LCI outcomes, although double-counting is not a big problem in LCA that tries to study the worst potential scenario.
- Serial effects: emissions of pollutants that may have significant effects on human health, such as heavy metals that have initial toxic impacts on ecosystems and eventually effects on human health through food chains. Such releases are usually suggested to be distributed in their entirety to all associated categories [20, 57].
- Indirect effects: effects are caused by an inventory emission, which does not produce the effect by itself, such as NOx, which serves as a catalyst in the photo-oxidant ozone creation. Though, the effect of this group is primarily due to carbon monoxide and VOCs emissions. All associated effect categories should be allocated to these emissions in their entirety [20].

3.4 Characterization

All resources of extraction or associated emissions in the LCI results that are allocated in the classification process to a specific effect category are categorized and computed as a common unit by scientifically derived factors (characterization factors). The effects can be gathered into a single score until the share of all measures in an effect category has been quantified.

Characterization factors are often generally referred to as equivalence factors that are derived from the related emitted elements in terms of the equivalence standard applied in chemistry. Within every effect category, these factors may help to compare the results of the LCI directly, thus converting the various inventory inputs into directly comparable effect indicators. For instance, the characterization will afford an estimation of the global warming potential between methane, nitrogen dioxide and carbon dioxide.

3.5 Normalization

Normalization is a phase of computing the value of the outcomes of the characterization indicator according to related data, it is considered an optional stage in the LCA method [23]. The major purpose of the results of the normalizing indicator is to obtain well understanding of the relative significance and value of these findings by putting them in a wider sense and changing the results to have common dimensions [54]. Reference information can apply over a given period to a given culture (such as China, Egypt, or the world), individual or other systems. For instance, the total interventions in the specific year for a certain area (local, international, national, and global). The results of the normalization can assist in assessing the relative significance of various effect categories through an LCA analysis and affording input into grouping or weighting stages.

3.6 Weighting and Grouping

Weighting is considered an optional impact evaluation stage that assigns the results of the (normalized) indicator to relative magnitudes or weights according to their relative significance for each effect category. To simplify comparison through indicators of the effect category, weighting can contain a collection of the weighted outcomes into a final score.

The LCA weighting process is usually a debatable subject, while important ideological, political, and ethical valuations affect the assessment weighting factors, the methodology of assessment, and the choice of weighting technique. Therefore, there is no social agreement on these core principles. Since, it may be predicted that some assessment approaches, including some different weighting groups, will be created [58]. ISO 14042 [23] mentions that "the usage and implementation of weighting approaches should be transparent and suitable with the objective and scope of the LCA analysis". Because of different people, communities, and organizations which have different values, it is likely that, depending on the identical indicator results, different parties can be able to obtain different weighting outcomes. Also, it has been revealed that different assessment strategies can provide different results in case studies [59]. Weighting is commonly applied, although these changes [60]. The main weighting approaches in LCIA can be categorized into three main categories as follows [56, 61]:

- Approaches depend on monetary values: The important side of the approaches of monetization is that the weighting factors include a monetary measure. There are broad ranges of environmental effect monetization methods that can also be divided into strategies that are depending on willingness to pay and that are not. The desire to pay approaches are generally connected to the desire to pay an exact sum of money to prevent danger or harm from occurring. Also, there is a range of approaches of monetization that are not dependent on the desire to pay but are depend on a cost estimate without suggesting that any individual will be ready to pay this cost [61].
- Approaches depend on approved (Distance-to-target) targets/standards: Based on the gap between the current environmental emission norm and the future environmental target value, these approaches compare various environmental effect categories [62]. Weights in these approaches are extracted from the degree to which real environmental output deviates from such targets or criteria [63]. The usage of emission standards that might be dependent on what is politically feasible, instead of what is technically desirable. Furthermore, they differ according to technical constraints and other political issues between countries [64].
- Approaches depend on the judgment of an authoritative panel: In these approaches, a set of individuals are requested, according to their professional experience to provide weighting factors. This can be achieved within a set with Committee members of experts, laypeople, or concerned people through group discussions, interviews, or questionnaires. In a one-round method or a multi-round method with findings, the panel may be carried out.

There can also be a difference between the midpoint and endpoint techniques. This is dependent on environmental problems of environmental methodology or cause and effect chain. In addition to damage or endpoint approaches that depend on modifications later in the cause and effect methodology, approaches that are dependent on modifications early in the cause are named the midpoint approaches.

3.7 Interpretation

The major objective of the interpretation process is to reach decision making, recommendations and conclusions that can be taken from an LCA analysis in terms of its objective and definition of scope. At this stage, concerning different characteristics such as consistency, sensitivity, and completeness, the inventory of life cycle study results and the assessment of the life cycle effect are studied. Moreover, main subjects such as materials, phases, activities, elements, or processes of the life cycle are also recognized that have an important influence on the overall effects [24]. It is essential to ask during the interpretation stage whether the findings essentially address the questions presented in the study objective and alike the responses are within the stated goal. Figure 9 shows the life cycle steps interpretation phase, in comparison to other processes of the LCA phase.

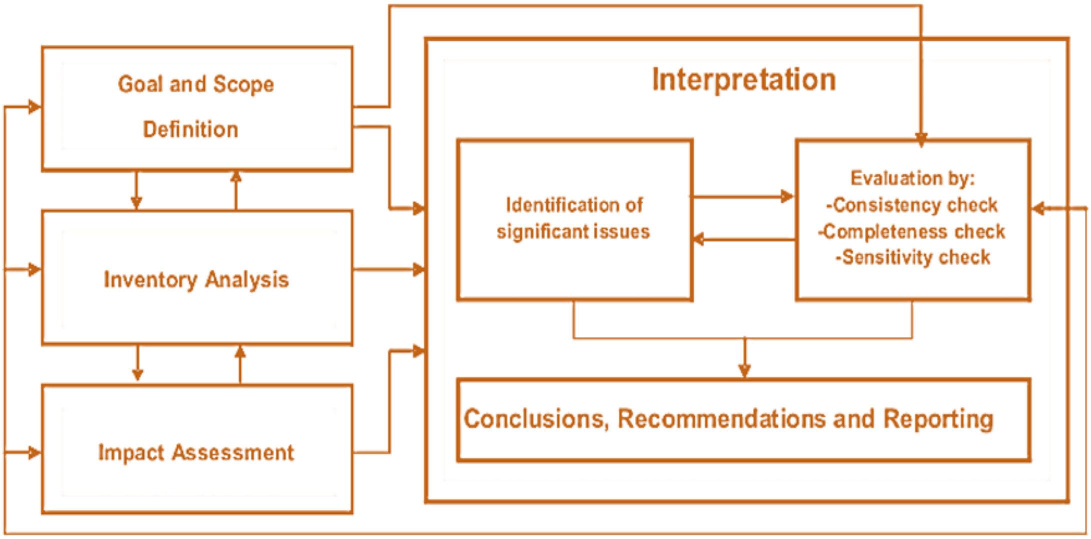

Figure 9. Relationship of steps of interpretation with other LCA processes [24]

4. Review of LCA Application in Road Construction

Discovering all advantages of modifiers and additives for the long-term efficiency of bitumen pavements is considered very significant. Keeping in mind sustainability, as well as embracing the international effort to decrease the environmental effects related to these recently modified compounds, it has become significant to have the ability to make decisions and assess the environmental friendliness and advantages and related to the long-term efficiency of the asphalt mixes. Therefore, applying an LCA instrument to evaluate modified bitumen mixtures on a life cycle base is required. By affording a better comprehension of the processes, LCA analyses can be beneficial for limiting and decrease energy use, resource consumption, and environmental releases [65]. Also, when the environmental behavior of a specific compound or material is not suitable, LCA analyses may support providing various replacements. Several researches have been applied on the additive that used to modify bitumen binders, and numerous studies have been applied to estimate the environmental influence of bitumen materials. The industry of pavement has been supported to expand the application of eco-friendly materials and tools in road infrastructure construction [66-69]. Furthermore, the LCA method was conducted to estimate the building materials sustainability such as steel, concrete, cement, and rigid pavement [70-72]. Nevertheless, there are no available published studies to evaluate the LCA for the manufacturing process of lignin (and/or) glass fiber that's used in modifying asphalt mixtures.

The next section reviews some applications of LCA in road construction selected from previous studies and its analysis. The summary of the data applied in these studies is presented in Table 2.

Table 2. A outline of the major properties of the LCA-related studies in road construction [67, 69, 73-83]

Ref.	Location	Impact assessment methodology	Data sources	Function unit	Software
[74]	China	CML baseline method	Databases, i.e Chinese Life Cycle Database (CLCD) and European Bitumen Association and US Environmental Protection Agency (EPA)	Section of road pavement there are six lanes with a total length of one kilometer and a width of 33 meres.	LCA-based

[75]	China	IMPACT 2002+	Databases, i.e. Chinese Light and Power (CLP), CLCD and European Life Cycle Database (ELCD)	One ton of aggregates, i.e. fine/coarse natural or fine/coarse recycled aggregate	SimaPro
[76]	France	ILCD 1.0.8 2016 method	Ecoinvent database version 3.2, but modified by using French energy inputs/mixes.	A 1 km long highway section, composed of Two separate roadways of 2 lanes each with an individual width of 3.5 m each.	Open LCA version 1.5.0
[77]	Portugal	Eco-indicator 99, CML Baseline	Real-time data from the area	One ton of coarse aggregates	SimaPro
[78]	China	------	CLCD and EBA	The section of road pavement with six lanes with a total length of one kilometer and a width of 33 meres.	-------
[67]	Brazil	IMPACT 2002+	.Ecoinvent v.3 and (USLCI)	1000 Kg of aggregates, i.e. Natural Aggregates (NA) or combination of NA and RCA (MixRA)	SimaPro
[69]	Colombia	TRACI v.2.1.	USLCI and Ecoinvent databases, literature and survey	Highway section, with 1 km in length and 1 lane 3.5 m wide.	SimaPro 8.4.0
[79]	Korea	TRACI v.2.1.	Ecoinvent v.2.2 database	1 ton of nano-silica adjusted bituminous mixes produced	Open LCA
[73]	Colombia	TRACI v.2.1.	USLCI and Ecoinvent v.3 databases, literature and survey	The highway segment is 1 kilometer long and has one lane that is 3.5 meters wide.	SimaPro 8.4.0
[80]	Colombia	IMPACT 2002+	Ecoinvent v.3 Real-time data from the region	1000 Kg of aggregates, Recycled Concrete Aggregate	SimaPro
[81]	France	CML 2001 method	Database of Ecoinvent and Existing publicly available reports.	A 1 km long highway section, consisting of two different roadways, each with two lanes and a width of 3.5 meres	Open LCA version 1.5.0
[82]	United States	TRACI	RSMeans database; Oklahoma DOT Annual Average Daily Traffic (AADT) Traffic Counts database	Pavement section 12.8-km long and A width of 14.4m the same Portland Cement Concrete (PCC) layer thickness (25 cm)	(EIO-LCA) (CMU)
[83]	China	CML 2001 method	Ecoinvent database (V 3.6, 2019)	The section of the wearing surface layer of typical pavement with a length of 1 km and 1 m width	SimaPro 9.1.0

According to the outcomes made by Ma et al [74] conducting the LCA method, the environmental influences of HMA and WMA asphalt mixes were evaluated. The outcomes indicated that WMA and HMA asphalt pavements used nearly the identical quantity of resources over their lifetimes, while the environmental influences of $PM_{2.5}$ emissions and greenhouse gas-related HMA pavement were little greater than those of the WMA, except in the case where HMA asphalt pavement outperformed WMA asphalt pavement in the long run.

In the study obtained by Hossain et al [75], a comparison of environmental implications of the manufacturing of natural and recycled aggregates was made. It showed that the recycled coarse aggregates produced from CDW decrease the emissions of Greenhouse Gas (GHG) by 65% compared to coarse NA and decrease the consumption of non-renewable energy by 58%. Compared to those related to the manufacture and import of aggregates from initial bases, substantial decreases in climate change, health, energy, and the processing of recycled aggregates from waste resources will realize environmental danger degrees.

According to the outcomes made by Santos et al [76], compare the potential environmental consequences based on using polymer adjusted asphalt surface mixes to a control asphalt surface mix. In comparison to base bitumen, the use of EVA polymer clearly degrades life cycle environmental profile of the pavement. This result is different from when the NBR is employed as an asphalt modification because it has been shown to enhance the environmental quality of the life cycle of pavement section.

As reported by Estanqueiro et al [77], a comparison of the environmental effects of three choices for the providing of coarse aggregates for the manufacturing of concrete mixtures was conducted: NA; RCA manufactured in a fixed facility; and RCA manufactured in a moveable facility. Results detected that the usage of RCA in the manufacture of concrete is superior according to inorganic respiratory substances and land use to the usage of NA. Moreover, when good recycled aggregates are applied in concrete manufacturing rather than sent to a landfill, NA can have worse environmental behavior than that of RCA.

In research done by Zhu et al [78], the assessment method for energy protection of the pavement of asphalt rubber was provided depend on LCA. Results showed that the mixing method uses the most energy in the pavement building stage, but compaction and paving phases use far less energy. The energy usage of the FBAR mix is 5.75% less than the asphalt mixture improved with SBS, and the mixture of Trans Polyoctenamer (TOR) and the Terminal Blended Asphalt Rubber (TBAR) are lower by 13.61% and 13.66%, respectively.

As reported by Rosado et al [67], conduct a relative LCA analysis on environmental effects associated with the MixRA (the mixture of RCA and NA) and NA manufacturing. And indicated that for all effect categories evaluated (excluding 'non-carcinogens'), MixRA is the better choice when the distance between the site of manufacturing and the client site is more than 20 km the distance between the NA site of manufacturing and the client site.

Based on the results made by Vega-Araujo et al [69], the potential environmental influences based on the use of RCA in the production of WMA as a fractional substitution of NA with traditional HMA was compared. The usage of WMA with RCA content as a substitute for coarse NA degrades the environmental profile of pavement compared to the equivalent usage of traditional mixtures (i.e., HMA0). This can be clarified by WMA's less behavior compared to that of the base mixture that increases the layer thickness got from the construction of the asphalt pavement.

In research done by Sackey et al [79], a NMAM over the Life Cycle Assessment approach (LCA) based on material output releases was evaluated, and to know the significant participation of nano-silica in bituminous mixes, in comparison with base bituminous mix outcomes. It revealed that the global warming potential of NMAM was 7.45×10^3 kg CO_2-equivalent per unit of function as opposed to 7.42×10^3 kg CO_2-equivalent per traditional bituminous mix unit of function.

In another effort by L. Vega A. et al [73], the potential environmental consequences of using RCA as a fractional exchange of coarse aggregates in the manufacturing of HMA were assessed. It is clear that mixes containing 30 and 15% of RCA may be considered as eco-friendly choices to the standard mix, as two contents enable reductions in every influence category ratings. In the other hand, the mix containing 45% of RCA denoted a lower environmental quality than that of the standard mix.

As reported by Martinez et al [80], the environmental influences of coarse NA manufacturing and merging the RCA by coarse NA (RCA-NA) were compared. The outcomes indicated that the transport distance from the limestone to the plant was the most significant factor for the RCA-NA combination in the LCA; the raw materials should not be transported more than 200 kilometers.

In research done by Santos et al [81], presented a detailed method-based comparative LCA to consider the environmental effects of mixing temperature decrease by the usage of hot mixed technologies, including chemical and additives that based on foam and various degrees of recycling (0% and 50% RAP). Results showed that the best environmentally friendly option of all different solutions is the construction of paving and an M&R phase that includes WMA mixture based on foam with a 50% RAP content is used in the wearing course during life cycle of the pavement. Furthermore, the outcomes of a scenario study indicated that if the natural gas is used to fuel the plant of asphalt, or if the system of the pavement was eliminated at the end of its lifespan and recycling the debris, the environmental effects of life cycle could be minimized.

As reported by Shi et al [82], a comparison of the economic, and environmental burdens of Portland Cement Concrete (PCC) pavements associated with RCA and an ordinary PCC pavement was made. And indicated that in the manufacturing and construction processes of products, the application of RCA in PCC provides environmental advantages but leads to greater negative environmental effects throughout the usage process. Precisely, in the effect categories human health cancer, human health non-cancer, and ecotoxicity, the RCA-PCC has been shown to be more environmentally friendly than plain asphalt.

In the study obtained by Khater et al [83], examined three modified asphalt mixtures: lignin-modified, glass-modified, and composite of lignin with glass fibers-modified. The life cycle of the road pavement manufacture process was divided into four phases: (1) raw materials manufacturing; (2) asphalt mixtures production; (3) transportation; and (4) construction of wearing surface. Results demonstrated that the negative effect caused by the composite mix and other modified mixes is minimal related to their overall environmental effects. Therefore, the composite asphalt mix can be used depending on its overall enhanced performance advantages for the asphalt mixtures.

5. Conclusions and recommendations

LCA has been used to assess the environmental implications of roads in order to implement sustainable processes at all phases of the road's life cycle from materials extraction to end-of-life treatment. A great number of LCA studies have been done in a road's projects, and these studies have been thoroughly reviewed. Conclusions are difficult to translate beyond regional boundaries. Depending on the place under consideration, differing electricity blends, manufacturing processes, designs of pavement, local maintenance procedures, available materials, and other region-specific components will produce varying results. Because of these differences, results from different countries may not be directly comparable. To fully comprehend the impact of regional variances on outcomes and conclusions, more research is required. As a result, it is suggested that future research makes more efforts to analysis of network-level and standardize and customize LCA approaches to match the properties of roadways. The importance of including dynamic variations in the environmental implications of emissions in road LCA has also been recommended for further research. Improvements in these fields can help to close the gap of knowledge and produce more accurate results, which will help to better inform policymakers and decision-making in the area of road sustainability.

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