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Review Article

A Comprehensive Review of Life Cycle Cost Assessment of Recycled Materials in Asphalt Pavements Rehabilitation

Abbas F. Jasim,[1] **Zahraa K. Ali**,[1] **and Israa F. Al-Saadi**[2]

[1]*Highway and Transportation Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, 10045, Iraq*
[2]*Department of Construction and Projects, University of Baghdad, Baghdad, Iraq*

Correspondence should be addressed to Abbas F. Jasim; abbas.jasim@uomustansiriyah.edu.iq

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This paper provides a comprehensive review of the use of life cycle cost assessment (LCCA) and life cycle assessment (LCA) methods for evaluating the sustainability and costs of using recycled materials in asphalt pavement rehabilitation projects. The review begins with an introduction to pavement rehabilitation strategies and the importance of choosing techniques based on thorough engineering and economic analyses. It then explores the different types of recycled materials that can be utilized, including reclaimed asphalt pavement, recycled concrete aggregate, and recycled asphalt shingles, discussing the key characteristics and properties of these materials based on previous laboratory studies. The review also examines the various rehabilitation methods that employ recycled content, such as cold in-place recycling, hot in-place recycling, and full-depth reclamation, providing a detailed breakdown of the construction, maintenance, and rehabilitation costs considered in LCCA and analyzing the environmental benefits of recycled material usage through a review of LCA techniques and criteria like carbon footprint reduction, impacts on air and water quality, and considerations of technological factors. Software tools for conducting LCA are compared and challenges to advancing the adoption of recycled materials are reviewed along with directions for future research efforts. The unique contribution of this work is its holistic assessment of LCCA and LCA methodologies to inform the sustainable and cost-effective deployment of recycled materials in asphalt pavement rehabilitation, a topic of growing importance for transportation infrastructure management. In summary, this current work provides a valuable review of how LCCA and LCA methodologies can assess the sustainability and costs of employing recycled content in asphalt pavement rehabilitation projects.

1. Introduction

1.1. Overview of Pavement Rehabilitation. The typical four-layer design for asphalt or flexible pavements allows them to withstand heavy traffic for 20 years (i.e., subgrade soils, subbase, granular or asphalt base, and asphalt surface). Heavy truck traffic causes the top asphalt layer of pavement to deteriorate rapidly over time, leading to various asphalt distresses such as rutting, fatigue cracking, thermal cracking, and roughness, if the pavement is not correctly built. Pavement rehabilitation and maintenance should adhere to a plan that allows for the full 20 years of expected service life [1]. Rehabilitating a pavement often involves making structural or functional improvements to the pavement in order to increase its service life and improve its condition [2].

It is now common practice for state and local transportation organizations to perform pavement preservation and restoration treatments. Optimizing budget allocations for infrastructure development projects, increasing pavement service life, and maintaining a safe and reliable quality of service for all users are the ultimate aims. Transportation agencies must determine the appropriate treatment for each pavement type and timing in order to achieve these objectives. Rehabilitation and preservation strategies should not be implemented based on needs alone, but rather on a thorough comprehension of the guiding principles of the field, the type and appropriateness of treatment, strategies for selecting methods at the project and network levels, and the practicality of the proposed construction [3].

Careful consideration and evaluation of available information, along with thorough engineering and cost analyses, are essential steps in the selection of an appropriate treatment. The process involves several key steps, including assessing the existing pavement condition in terms of distress, roughness, skid resistance, and structural capacity. Additionally, obtaining relevant project information such as traffic patterns, accident data, climatic conditions, and as-built design details is crucial. Determining the causes of distress, considering factors like loading, materials, and climate, is a necessary aspect. The development of feasible alternatives is based on project objectives, addressing and preventing distress, ensuring skid resistance, and extending pavement life, with comprehensive engineering evaluations considering factors like traffic, climate, and performance. Life cycle cost analysis, encompassing cost, performance, analysis period, and discount rate, is performed to inform decision-making. Following these steps, the preferred alternative is selected, and subsequent stages involve the construction and ongoing monitoring of performance.

1.2. Choosing Rehabilitation Techniques. The goal of selecting a rehabilitation strategy is to find the one that will fix the pavement's current problems and make it better in terms of its structural capacity, functional adequacy, and drainage adequacy.

1.2.1. Asphalt Treatments. Overlay, patching, cold milling, cold and hot in-place recycling, full-depth or partial-depth repair, and asphalt overlay are some of the treatments used in asphalt pavement rehabilitation. Based on the severity of the damage, repairs can be made to surfaces or subgrade layers; patching is used to alleviate localized distresses. Grinding asphalt surfaces using cold milling improves bond, removes oxidation, and fixes grade concerns. Resurfacing is usually the next step. Through the use of heat, a rejuvenating agent, and either compacting or an overlay, hot in-place recycling can regenerate asphalt on-site, improving bond strength and avoiding reflection cracking. A less rigid material is often required to undergo a surface treatment after cold in-place recycling, which includes grinding the material on-site, combining it with emulsified asphalt and additives, and then recompacting it.

There are a few distinct ways asphalt overlays can be designed; they are structural deficit, deflection-based, and mechanistic models. The goal of each is to enhance either the ride quality, friction, or structural capacity. Factors including mix design, thickness, and the amount of preoverlay repair and surface preparation determine how well an overlay performs. To maximize the performance and longevity of asphalt pavements, the rehabilitation approach is of utmost importance, whether it is improving surface qualities or fixing structural problems.

1.2.2. Structural Evaluation Indicated Techniques (Deflection). Decide if resurfacing or reconstruction are necessary structural improvement techniques for the pavement after completing a structural evaluation. Finding out how badly the pavement is in need of structural repair determines which option is best. Certain overlays, such as bonded concrete or thinner asphalt overlays, are very dependent on the efficacy and economy of the repairs done before the overlay. When structural damage grows, it is time to start thinking about thicker overlays or ones that would not be as affected by preoverlay repair.

A structural asphalt overlay, a normal concrete overlay, or a reconstruction in asphalt or concrete are all viable solutions for improving the structural integrity of asphalt pavements. Methods including cold milling, hot surface recycling, thin asphalt overlay, and ultrathin concrete overlay can be used to improve the road's functionality by lowering its roughness and increasing its wet weather friction. When strategies are used to improve structures, such as overlays or reconstructions, these functional gains take a back seat.

1.2.3. Distress Evaluation Indicated Techniques. In addition to structural and functional improvements, further rehabilitation methods may be needed to heal specific distresses. These treatments may be called "preoverlay repair" or "restoration" depending on whether they are done with an overlay. This step in the rehabilitation strategy selection process identifies rehabilitation strategies that may work for the distress type. Several distress types can be treated using multiple rehabilitation methods. The best asphalt pavement rehabilitation methods for specific distresses. Table 1 shows the rehabilitation techniques suited for pavement distresses.

1.3. Importance of Sustainability in Pavement Engineering. Sustainability, according to the World Commission on Environment and Development (WCED), is addressing current demands without compromising future needs. Pavement sustainability includes environmental, economic, and social consequences throughout material selection, design, construction, and preservation. Pavement sustainability supports the triple-bottom line: environment, economics, and society. Each city, region, or organization must include sustainability in their goal to balance human demands with finite resources [4].

Sustainable pavements balance environmental awareness, economic adaptability, and social demands. Pavement sustainability depends on energy, emissions, noise, air quality, and stormwater runoff. Public safety, aesthetics, building, and vehicle operation expenses are economic and social factors. Pavement durability is complex, thus these variables are crucial. Sustainability principles improve public health and economic well-being by reducing climate change and emissions [5].

Sustainability influences transportation decision-making from planning and design to implementation and operations. There is no federal sustainability law in the US, but government–industry collaboration promotes sustainable practices. Sustainable pavement engineering has 11 purposes, from safety and accessibility to emissions and air quality. A sustainable pavement system must meet engineering goals, environmental preservation, resource efficiency, and human needs [4].

Sustainable pavements require constant trade-offs, priorities, and strategic alignment. To achieve sustainability, one must embrace new technology and innovations, evaluate the usage phase of pavements within a wider system, recognize context sensitivity, and demonstrate correct leadership,

Table 1: Techniques for repairing damaged asphalt pavements [2].

Asphalt pavement distresses	Asphalt pavement rehabilitation techniques							
	Full-depth asphalt repair	Partial-depth asphalt repair	Cold milling	Hot or cold in-place recycling	Asphalt overlay	Concrete overlay	Subdrainage improvement	Asphalt or concrete
Fatigue cracking	√	√	√	√	√	√	—	√
Block cracking	—	√	√	√	√	√	—	√
Thermal cracking	√	—	√	√	√	√	—	√
Longitudinal cracking	√	—	—	√	√	√	—	√
Slippage cracking	—	√	√	√	√	√	—	—
Bleeding	√	√	√	√	√	√	—	—
Rutting	—	—	√	√	√	√	—	√
Shoving	√	—	√	√	—	√	—	√
Weathering	—	√	√	√	√	√	—	—
Raveling	—	√	√	√	√	—	—	—
Pumping	—	—	—	—	—	—	√	—
Stripping	√	√	√	—	√	—	—	√
Pothole	√	√	—	√	—	—	—	√
Bumps, settlements, and heaves	√	—	√	√	√	√	—	√

Note. This table is reproduced from Hall et al. [2].

partnerships, education, and focused research. Sustainability assessment methods benefit from life cycle assessment (LCA) [6].

Reducing the use of virgin asphalt binder and aggregate by plant recycling, expanding the use of reclaimed asphalt, and utilizing CRM-modified binders from scrap tires are all ways to enhance the sustainability of pavement engineering. Changes in fuel and the use of warm mix asphalt (WMA) technology are two ways that asphalt mixing is being attempted to reduce emissions and energy consumption. Mixture design, high compaction, and application-specific rubber/polymer mixes are the three pillars upon which the durability of asphalt concrete rests.

The use of additives reduces the need for virgin materials and transportation by preventing moisture damage. In-place recycling further enhances this reduction. Investigating less harmful biobinders as potential substitutes for petroleum-based binders is a continuing effort. Unfortunately, these solutions have not been evaluated for their environmental impact or long-term effectiveness. Our future plans include reducing material quantity, increasing the usage of reclaimed construction and demolition waste materials (RCWM), and developing bio-based alternatives as well as local pavement materials [5].

1.4. Role of Recycled Materials in Sustainable Rehabilitation. Rehabilitating severely damaged, defective, or distressed existing pavements through milling and recycling is an environmentally friendly option. Pavement alternatives that are easier on the environment can be created through this process, which includes recycling and reusing structural elements [4]. Both the environment and the economy stand to gain from the use of these recycled materials in road construction.

To keep highly damaged pavements in service, high-maintenance interventions are required to bring them up to functional and structural standards that are in line with sustainability goals. Time, money, and structural reactivity are three areas where preservation procedures fall short. In light of current needs, a full pavement rebuilding might be excessive. With its many advantages, including reduced transportation costs, decreased greenhouse gas emissions, cost-effectiveness, and reduced demand for new materials, in-place recycling becomes a sustainable option in these situations [7].

There have been several efforts to include eco-friendly procedures into sustainable pavement rehabilitation, with recycled materials playing an essential part. When the base layers underneath the asphalt provide enough stability, hot in-place recycling (HIR) is a cost-effective way to repair the pavement. While regenerating aging bitumen, HIR successfully eliminates cracks, rutting, and shove, lowering raw material usage, transport costs, and delays in traffic. Preheating, recycling, remixing, and repaving are the steps used to address imperfections in the top 50 mm of the asphalt's thickness. The milling characteristics and future performance of the asphalt surface are greatly affected by the heating temperature and rejuvenator choice.

Cold in-place recycling (CIR) is another option for rehabilitating asphalt roads that does not involve breaking up the old pavement. Carbon infrared (CIR) is similar to heat injection in that it strengthens recycled materials without rebuilding the pavement structure entirely. Without preheating the surface, CIR mills the existing pavement and reuses the reclaimed material to fix small surface distresses. In order to enhance the mechanical qualities of the recovered mixture, stabilizing additives or rejuvenators are frequently utilized. Compared to traditional pavement reconstruction, CIR is more cost-effective, which improves structural quality, reduces transportation costs, and lessens environmental consequences.

Foamed asphalt, cement, and hydrated lime are examples of stabilizing chemicals used in full-depth reclamation (FDR), a novel rehabilitation procedure that is comparable to CIR but applied at a depth of 300 mm or greater. FDR improves the mechanical qualities of recycled layers while restoring the structural integrity of old or severely worn pavements, fixing specific flaws, and treating severe damage [4]. Reclaimed granular material is stabilized, blended with binding additives, repaved, compacted, and sometimes even covered with a thin asphalt overlay after the previous surface layer and underlying base/subbase layer have been pulverized.

The building and demolition industry when compared to virgin materials, recycled construction and demolition waste (CDW) significantly lowers emissions, preserves natural resources, and uses less energy [7]. Pavements with low to intermediate traffic loads can be supported by CDW aggregates stabilized with cement kiln dust (CKD) and used in the base and subbase layers.

Studies have shown that reclaimed asphalt pavement (RAP), or reclaimed asphalt pavement, is exactly as effective as new pavement, making it a viable alternative. Cold in-place asphalt, cold mix asphalt, hot mix asphalt (HMA), and FDR are some of the many uses for RAP. Not only does this work just like conventional HMA, but it also helps to save money and energy [8]. For a variety of asphalt applications, RAP can double as both an asphalt cement supplement and asphalt concrete. The addition of this material to stabilized base aggregate makes pavement stronger. RAP can save money and energy by reusing materials, but the toxins in the old asphalt are a worry. Nevertheless, this problem can be resolved if the correct procedures are followed while producing recycled HMA. In summary, RAP is an affordable and high-quality alternative to traditional asphalt that shows no signs of cracking, wear and tear, or weathering.

Rubberized asphalt (RA) and recycled asphalt shingles (RAS) are two more environmentally friendly alternatives to traditional asphalt. In asphalt mixtures, RAS can serve as a binder or fine aggregate fraction [6], whereas RA, made from recycled tires, helps with the asphalt's viscosity–temperature susceptibility and the degree of noise caused by vehicle interaction. All things considered, there are environmental, financial, and practical advantages to using recycled materials in pavement rehabilitation.

2. Recycled Materials in Asphalt Pavements

2.1. Types of Recycled Materials (RAP, RAS, and RCA). The use of a variety of recycled materials has increased in recent years due to the desire to actively adopt the concepts of material reuse and recycling and to preserve the remaining natural resources. Not only does this method help preserve the environment but it also makes profit. Some common examples of recycled materials are given below.

2.1.1. Reclaimed Asphalt Pavement (RAP). The aggregate and asphalt binder that make-up RAP are recycled from HMA and used in new asphalt mixes. Reduced material needs are achieved by reusing milled materials into virgin HMA when HMA nears the end of its service life; these materials maintain great value. Addressing rising asphalt prices, aggregate shortages, and the environmental imperative, RAP is quickly becoming a preferable alternative to virgin materials, demonstrating the technical, economic, and environmental instrumentality of this recycling approach [9]. Furthermore, RAP helps to reduce waste and solves disposal issues with highway construction materials, which is especially important in densely populated urban areas like Baghdad. Al-Qadi et al. [9] mentioned that RAP was introduced in 1973 but not widely used since its effects on asphalt mix performance were not well understood. Now, in order to save money, recycle asphalt pavements, and lessen environmental impact, modern methods use larger percentages (e.g., >50%). Because of its potential impact on asphalt mix performance, resistance to fatigue cracks, thermal cracks, and permanent deformation is the principal issue when adding RAP to new asphalt mixes.

2.1.2. Recycle Asphalt Shingle (RAS). About two-thirds of the housing roofing market in the US is made up of RAS, making them an important component of the roofing industry. Organic and fiberglass are the two main varieties. On one hand, you have organic shingles, which are made up of 30%–35% asphalt, 5%–15% mineral fiber, and 30%–50% mineral and ceramic-coated granules [10]. In contrast, fiberglass shingles are composed of 15%–20% asphalt, 5%–15% felt, and 15%–20% mineral filler, and they have a fiberglass reinforcing backing that is coated with asphalt and mineral fillers. Asphalt shingles have a lifespan of 14–21 years depending on the region; in hotter areas, degradation happens faster [11]. In major cities, the cost to dispose of old shingles can be rather high, going as high as $90 to $100 per ton. Surveys show that tested shingles had a low asbestos content of 1.5%, in line with EPA standards that forbid materials with more than 1% asbestos from being used in roadway construction [12]. However, asbestos was occasionally utilized in early fiberglass asphalt shingle manufacture [13]. Ongoing study is being conducted to assess the effect of abandoned shingles on polycyclic aromatic hydrocarbon (PAH) emissions during the manufacturing of HMA due to concerns about the emission of PAH. Recycled and processed tear-off asphalt shingles can be tested for asbestos at 1% using the polarized light microscopy (PLM) technique on a periodic basis [14].

2.1.3. Recycle Concrete Aggregate (RCA). Everyone agrees that concrete is the mainstay of civil engineering projects around the world. The majority of the concrete structures that are used to make RCA come from buildings that were either built, demolished, or repaired as part of civil construction projects [15]. The versatility of recycled concrete as a foundational material for structures and roadways is a major benefit. In addition to reducing the negative effects associated with mining and shipping virgin aggregate, using recycled concrete instead demonstrates environmental responsibility. According to research [16], using just 1% recycled aggregate instead of virgin aggregate can cut construction waste by 8 tons. By minimizing the need for natural aggregate (NA) extraction, cleaning up abandoned areas, and encouraging the incorporation of alternative materials in construction, this trend toward recycled materials actively contributes to environmental preservation [17].

Al-Bayati et al. [18] conducted an extensive analysis and found that RCA particles made from CDW have a composition with 65%–70% NA and 30%–35% cement. Consequently, RCA obtained from CDW stands out as a worthwhile and environmentally friendly substitute for traditional building materials [19]. The adaptability of CDW and RCA in civil engineering construction has been demonstrated in a plethora of studies. These studies cover a wide range of applications, including but not limited to sub-base layers and pavement bases [20, 21, 22], structural concretes [23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34], mortars, rigid pavements [35, 36], and asphalt mixtures [17, 18, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69]. Recycled concrete has the ability to promote sustainable practices in the building industry and reduce environmental impact through its wide range of applications.

2.2. Characteristics and Properties of Recycled Materials. RAP is a game changer in the road construction industry. It is a sustainable solution that repurposes milled material from old asphalt pavements, reducing the need for new resources. Since Oman's regulations only allow for a 10% RAP content in road infrastructure, researchers there have conducted extensive experimental studies to compare and contrast the physical properties of RAP with those of virgin materials. Incorporating RAP into asphalt mixes has great promise for increasing the pavements' profit/cost ratio and extending their useful life. Extensive research with RAP blends has shown complex dynamics at work, with some cases suggesting an increase in material stiffness and others showing no effect at all. The complex relationship between temperature and material characteristics is clearly shown when RAP shows traction frequency and tensile strength that are on par with, or even higher than, virgin blends. Careful consideration of the materials used is essential, particularly when working with aggregates such as steel slag, which, although useful in high-friction contexts, can swell when exposed to water. Incorporating RAP into recycled blends with low RAP rates reduces the environmental impact and increases resilience to moisture damage, making it an important technique for sustainable road construction. Investigating bio-modified binders using stringent testing protocols like ASTM D4792 also paves the way for better fatigue resistance and cracking qualities, especially at higher RAP levels. As this survey's complete results show, a promising and acceptable way to developing sustainable road construction practices is the synergistic inclusion of bio-modified binders with virgin and RAP binders [70].

2.2.1. RAS Characteristic and Properties. By using RAS into hot-mix asphalt, highway agencies and the asphalt industry stand to gain significantly by using less virgin asphalt binder. The organic or fiberglass fibrous shingle base has beneficial fibers that can improve the asphalt mixture's overall performance [13]. The effect of adding this recycled material to asphalt mixes on their mechanical performance has been the subject of much research since the early 1990s. The viscosity of air-blown asphalt, which is typically used to make asphalt shingles, is greater than that of the conventional asphalt binder in HMA [71]. Research by Button et al. [72] and Gardiner et al. [73] shows that adding RAS to asphalt mixtures can lower creep stiffness and tensile strength, but it also makes the mixture more resistant to moisture damage, uses less virgin binder, and is less likely to permanently deform. On the other hand, several researchers have seen a trend toward using asphalt shingles, which raises concerns about the mixture's reduced resilience to low-temperature cracking [74, 75, 76]. Foo et al. [71] looked into HMA mixes with fiberglass shingles in particular, and they found that they were better at preventing rutting, but they were worse at preventing fatigue and low-temperature cracking. Increased moisture resistance is a notable benefit of WMA that contains RAS at a concentration of 3%–5% [77]. While field trials have shown that HMA made with 5% shingle waste performs adequately, there are still some important considerations to make, such as how to deal with stockpiling problems caused by the high asphalt concentration in RAS while the plant is hot [78].

2.2.2. RCA Characteristic and Properties. Crushing and fracturing concrete or reinforced concrete components produces RCAs, which are particles with a highly angular and heterogeneous structure made of NA, cement mortar, or a mix of the two. Environmental factors, the water/cement ratio, the type and amount of additives, the origin, and the aggregate percentage are some of the quality indicators of the source concrete that significantly impact the attributes of RCAs. The reduced water absorption values and increased density of RCAs produced from high-strength concrete with a low water/cement ratio are results of the material's less porous structure. The cement mortar phase is strongly associated with the RCAs' quality, which improves with decreasing particle size. Past research indicates that, irrespective of particle size, RCAs typically consist of around 65%–70% aggregate and 30%–35% cement mortar. The water content in RCAs increases as the cement phase composition rises due to the greater porosity of the cement mortar phase compared to the aggregate phase. In spite of having less abrasion resistance than NAs, X-ray diffraction experiments have shown that fine RCAs (5 mm) contain C_2S and $C_3S_2H_3$ (C—S—H), which give them a self-cementing quality. The self-cementing capability of concrete is enhanced by C_2S, which is less reactive and implies that there will be limited hydration during the concrete's service life. The strength properties of RCA grains, notably the California Bearing Ratio (CBR) and resilience modulus values, are positively affected by the adhering cement mortar. This is probably because the nonhydrated cement particles in the mortar react positively with water. But mechanical qualities including water absorption, sulfate resistance, and Los Angeles (LA) abrasion resistance are negatively affected by these traits [79].

3. Life Cycle Cost Assessment (LCCA)

3.1. Principles and Importance of LCCA. When comparing alternative investment strategies over the long term, life cycle cost assessment (LCCA) is a crucial tool that uses well-established economic analysis principles. The procedure is adding up the discounted monetary equivalent of all anticipated expenses and benefits for each choice. Finding the investment option that boosts society the most yields the best return. To make well-informed judgments about infrastructure management, LCCA's analytical framework is a great asset. But there are a lot of unknowns when it comes to LCCA input factors including the analysis period, details of future rehabilitation efforts, and the discount rate for converting expenses over time. Accurate and trustworthy LCCA results require a thorough understanding of the theoretical background in economics and engineering [80].

In order to make well-informed investment decisions, it is essential to use LCCA to assess project expenses. Using this method, we can compare alternatives side by side, taking into account all important expenditures over the whole life cycle. This includes not only the direct charges for transportation agencies but also the effects of highway treatment projects on road users. The LCCA often includes agency expenses, road user costs (including fuel, safety, and travel time), and other pertinent social costs (materials, labor, equipment ownership and operation, transportation, and so on) (economic fairness and background noise) [81]. It is worth mentioning that a significant amount of road user expenses are linked to delays in travel. While most of the research on LCCA in highways has concentrated on rehabilitation and maintenance, there has been little investigation into other highway treatment methods, and social factors like user safety have been neglected [82, 83, 84, 85]. Resolving these restrictions can greatly improve the evaluation of the social and economic benefits of various roadway treatment initiatives during their lifetimes [86].

Consideration of all costs incurred during the investment's acquisition, ownership, and disposal is a key component of LCCA, which is used to assess the total ownership or operational expenses of a facility or project. Figure 1 shows the main cost considered in LCCA.

3.2. LCCA Procedure. In order to follow the guidelines for LCCA, users must choose an analysis period that accurately records the changes in long-term costs caused by different design techniques. An analysis period of 30–40 years is considered reasonable, while the FHWA recommends a minimum of 35 years for pavement projects. Net present value (NPV) is the standard method for economic efficiency indicators, while uniform equivalent annual cost (UEAC) is a

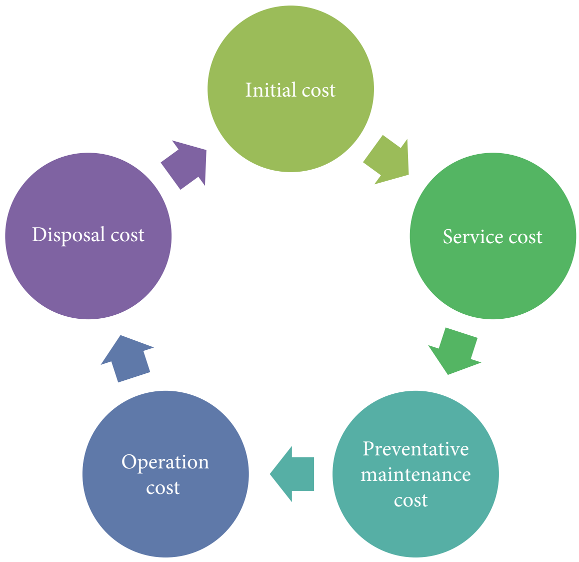

FIGURE 1: LCCA approach.

respectable substitute that may be obtained from NPV. Due to the complexity of separating costs and benefits, it is generally discouraged to compute benefit/cost (B/C) ratios.

To maintain parity among different currency types, all projected costs and benefits must be expressed in constant dollars and discounted to the present using a real rate. To make sure that all expenses are in line with the selected discount rate type, it is absolutely forbidden to mix real and nominal dollars. Additionally, actual discount rates should be selected such that they represent patterns over long periods of time; an acceptable range for these rates is usually 3%–5%. All of these factors, together with the fact that performance periods are carefully evaluated and routine maintenance expenses have a small effect on NPV, make for a solid and trustworthy LCCA [87].

3.3. Components of LCCA (Construction, Maintenance, and Rehabilitation)

3.3.1. Construction (Initial Cost). A variety of procedures and types of equipment are required to begin off-road development during the building phase, which accounts for the first component of the budget. Transportation of equipment and unbound materials to the site is the first step in the construction process. Other tasks include clearing the site, excavating, treating the foundation or base with cement or lime, compacting it, building and compacting road layers, and incorporating supplementary facilities like lighting and signs. Labor, gasoline, mobilization, demobilization, insurance, taxes, interest depreciation, and permits are all part of the associated costs, as are safety measures, on-site storage, and construction machinery or equipment. Road users also have to pay more to avoid construction-related hazards such volatile organic compounds (VOCs), an increase in the probability of accidents (AC), and the costs associated with work zone delays.

3.3.2. Maintenance Cost. Addressing the effects of weather and human-induced activities on road performance and durability, which lead to the deterioration, is a crucial part of the maintenance phase. To slow the rate of degradation brought on by these variables, maintenance is crucial. Roads undergo maintenance and rehabilitation (M&R) at various intervals throughout their service lives to improve overall performance and keep them in serviceable condition. When applied to a road that is already in good shape, preservation is a straightforward and inexpensive way to prolong the road's useful life without drastically boosting its structural capacity. To prevent deterioration, preservation treatments such as microsurfacing, diamond grinding, slurry seals, chip seals, crack filling, and patching need to be done more often. Without significantly increasing the road's structural capacity, maintenance successfully delays future degradation and improves the road's condition [88].

3.3.3. Rehabilitation Cost. Rehabilitation is necessary to extend the service life when there is a high risk of failure due to the pavement condition and structural capacity. Because it requires milling or removing the old road and building a new one, rehabilitation is the most expensive option. Materials, construction machinery or equipment, labor, and transportation are some of the associated cost components for restoration activities, just as they are for the construction phase. Repair methods are used to fix damaged pavement and inadequate structural support, including HIR, CIR, and FDR [88].

4. Methodologies for Assessing Recycled Materials

4.1. Data Collection and Analysis Methods. Information obtained from the DOTs of six national governments of the Recycled Materials Resource Center (RMRC) were used to evaluate the environmental and economic benefits of employing recycled materials. An upgraded version of the LCA instrument called PaLATE was used to measure the environmental benefits in this study. In order to calculate the economic benefits, we compared the average prices of virgin and recycled materials, factoring in the cost structures of each state [89].

Researchers complemented this study with a number of research projects. To examine the environmental implications of using recycled materials in asphalt pavement repair, Chiu et al. [90] used the eco-indicator 99 database to complete a life cycle inventory that included proposed recycled material formulations and service records. Focusing on highway repair utilizing RAP materials, Rafiq et al. [91] analyzed costs using both LCA and LCCA techniques, with the aim of improving project performance over the next decade. Without taking raw material extraction procedures into account, Riekstins et al. [92] compared pavement construction and restoration practices using LCCA and LCA. In their assessment of the environmental advantages of several recycled materials, including RAP, RAS, RCA, fly ash, blast furnace slag, rubber, and more, Bloom et al. [93] utilized the PaLATE LCA tool.

4.2. Laboratory Testing for Recycled Materials. The use of recycled materials in engineering projects has been the subject of extensive study, with many studies focusing on road construction in particular. Pervious concrete mixes containing normal Portland cement (PC-Regular), fly ash (PC-FA), and blast furnace slag (PC-BS) were tested in a controlled environment to determine their hydraulic conductivity, mechanical strength, and freezing–thaw resistance [94] (PCeBFS). Their research focused on the performance qualities of these mixes, which can guide environmentally conscious decisions about concrete formulation for a range of technical uses. Compared with this, Kashesh et al. [95] concentrated on incorporating crumb rubber into bitumen pen 40/50, making up 15% of the mixture. They investigated the mechanical, rheological, and physical properties of the RA that was created by mechanical mixing at 180°C for half an hour. The behavior of the modified bitumen was thoroughly examined in the study, which included tests measuring penetration, softening point, ductility, and viscosity. The material's applicability for road building applications was further strengthened by empirical tests of temperature susceptibility and bitumen stiffness.

Concrete aggregates made from recycled building and demolition debris have been the subject of research by several researchers, such as Rao et al. [96]. Important factors such as size distribution, absorption, and abrasion resistance were also their primary attention. This study contributes to sustainable practices in the building sector by illuminating the feasibility and viability of using recycled materials from construction and demolition waste in concrete mixes.

The use of recycled materials in the construction of road bases and sub-bases has also been the subject of various research. In order to assess the practicability of using varying percentages of RAP with virgin aggregates, Taha et al. [97] performed tests that included dry density and CBR. By bringing together environmental concerns with engineering performance requirements, these efforts help fill in the gaps in current knowledge about how to successfully use recycled materials in components of important infrastructure.

Lee et al. [98] investigated on the rheological and mechanical characteristics of RAP-binder blended asphalts, using PG 64-22 and PG 58-28 binders in particular. In order to determine if CDW might be used as sub-base materials in road construction, Mehrjardi et al. [99] conducted a series of studies, including soil grading, Atterberg limits, modified compaction, the CBR, and direct shear testing. They also tested the bearing capability of CDW materials with cyclic plate loads to see how geocell reinforcement affected it. Focused on their effort to highlight the consequences caused by the interaction between rubber and these components, Rigotti and Dorigato [100] concentrated on the physical qualities of building materials when using recycled rubber. Proposed technical techniques were also thoroughly examined from a material science point of view.

5. Factors Influencing Recycled Material Performance

5.1. Climate and Environmental Conditions. Direct and indirect effects are the two primary ways in which climate change expresses itself. Environment factors such as temperature, humidity, precipitation, and wind speed and direction cause direct affects [101]. Researchers Mogawer et al. [102] discovered that asphalt mixtures including RAS, RAP, or both were more resistant to moisture failure. In terms of skid resistance at different temperatures and simulated surface conditions, another study by Pomoni and Plati [103] showed that recycled mixtures performed as well as, or even better than, traditional ones. In their study, Wen et al. [104] looked at how various weather factors, including moisture and temperature, affected the resilient modulus of base materials with varying percentages of RAP. They found that when the RAP content was higher, the frozen moduli were lower. Researchers Ma et al. [105] looked at how different temperatures affected the performance of 100% recycled asphalt mixes after HIR. They found that higher mixing temperatures activate a larger proportion of RAP binders, which could make the mixture more rutting-prone. Warm mix asphalt with recovered asphalt pavement (WMA-RAP) mixes performed worse in laboratory tests for rutting resistance and moisture and low-temperature cracking than WMA mixtures without RAP, according to an evaluation by Guo et al. [106]. Combinations of recycled asphalt pavements, used motor oil, and additional binder enhanced with crumb rubber outperformed traditional combinations in mechanical characteristics and performance, according to research by Jahanbakhsh et al. [107]. Although mixtures with RAP and RAS exhibited relatively lower cracking resistance in the overlay tester, Zhang et al. [108] demonstrated that RAM, such as RAP and RAS, improved rutting resistance in HMA, particularly in regions with high pavement temperatures and heavy traffic. Recycled aggregates with a percentage of 30% were found to have the best rutting resistance and raise the optimal binder content (OBC), according to research by Fatemi and Imaninasab [44]. Increasing the amount of C&D waste materials also improves the resistance to moisture damage.

5.2. Traffic Load and Volume. Concerns over performance and sustainability in high-risk areas under heavy loads have historically made airports cautious to include RAP on runway surfaces [109]. Nevertheless, Celauro et al. [110] have shown that it is possible to achieve the "high-performance" classification for bituminous mixtures in common Italian Specifications and Standards, even when using extremely high recycled material percentages (up to 50%). Mixtures intended for use in the top layers of roadways in areas with hot weather and high traffic volumes are designated with this name. Research by Zaumanis et al. [111] confirmed the mechanical, traffic safety, and environmental performance of a wearing course mixture of 100% recycled asphalt through the use of a performance-based design approach. Their findings suggest that this kind of combination design can effectively create asphalt mixtures made entirely of recycled materials that are just as safe for traffic and the environment as conventional asphalt mixtures, if not safer.

In addition, in roads with a T2 traffic intensity (200–799 heavy vehicles/day and lane), Tavira et al. [112] discovered that C&D, after being treated in a mobile plant, can be used as a new raw material for unbound base and subbase layers. In their study, Mills-Beale and You [113] examined the mechanical properties of asphalt mixtures that included recycled concrete aggregates. They concluded that a specific proportion of RCA in HMA would be acceptable for low-volume highways, taking into account performance parameters. Incorporating crumb rubber modified (CRM) into asphalt binder can improve resilience modulus, increase resistance to moisture damage, and prevent permanent deformation under increased traffic loading, as pointed out by Khaled et al. [114]. The addition of crumb rubber from used tires to asphalt binder increases viscosity, which in turn increases durability against traffic loads, decreases fatigue cracking, and improves rutting resistance and permanent deformation [115].

5.3. Material Quality and Processing Techniques. The use of RCA in many aspects of road construction was investigated by Nwakaire et al. [116] by examining information from multiple sources. The researchers compared RCA's mechanical and physical characteristics, such as its strength, to those of NA. Methods to improve the performance of RCA in asphalt and concrete mixes were also discussed by the researchers.

An examination of the recycling of asphalt was the primary topic of Karlsson and Isacsson [117]. Both the quality of recycled binders and the binder's mixing performance in various asphalt mixtures were examined in detail. The chemical composition of the old binder and rejuvenator determines the recycled binder's quality in terms of its consistency, aging characteristics, and structural stability.

RAP combinations, according to Zaumanis and Mallick [118], are more difficult to design and manufacture than conventional asphalt and necessitate the expertise of a pavement engineer. Mix design without understanding the exact blending quantity between RAP and virgin binder, evaluating RAP aggregate and binder qualities, choosing the optimal RAP processing method, coping with increased dust content, and so on are all part of the process. High RAP combinations that have been well-designed have performed admirably in the field, avoiding problems like fatigue cracking and low-temperature stress.

The importance of using high-quality input material was highlighted by Zaumanis et al. [119] as a significant obstacle to producing 100% recycled combinations. They proposed that RAP aggregate standards should be the same as those for virgin materials. Improving the quality of the end result could be as simple as taking control of the supply chain at the outset, beginning with the milling of old pavement. Their main points were to keep contamination to a minimum, make sure the RAP was homogeneous, segregate components with different values, and decrease the amount of particles and moisture. It was suggested that quality control processes be put in place to examine RAP stocks for characteristics such as aggregate gradation, specific gravity, and binder concentration.

According to the research reviewed by Shaban et al. [120], there are various methods for treating RCA. Each method was carefully evaluated for its merits, shortcomings, practicality, and constraints. They emphasized the importance of improving the attached mortar's quality and characteristics to optimize RCA as concrete aggregate.

With an emphasis on their application in concrete production, Silva et al. [33] investigated the factors impacting the compositional, physical, chemical, mechanical, and permeation properties of recycled aggregates from building and demolition waste. The purpose of the research was to provide a feasible metric for evaluating recycled aggregates, which would allow for more predictable concrete performance.

6. Sustainability and Environmental Impact

6.1. Assessment of Environmental Benefits and Drawbacks. To fully comprehend the significance of sustainability programs, it is essential to weigh their environmental advantages and disadvantages. The results of these evaluations put a spotlight on the environmental impact and efficacy of different sustainability strategies. These evaluations aid in determining the strengths and weaknesses of sustainable practices by taking into account aspects like resource conservation, carbon emissions reduction, waste management, and biodiversity preservation. They aid in the formulation of all-encompassing plans to ensure a more sustainable future and direct decision-making toward eco-friendly solutions [121, 122].

6.2. Reduction of Carbon Footprint through Recycled Materials. The negative impacts of greenhouse gases like carbon dioxide on the globe have brought the problem of global warming to the forefront of public consciousness. Concrete and asphalt, two materials regularly utilized for roads, are frequently used in the massive undertaking of pavement building. Greenhouse gas emissions and pollution are two environmental challenges that these materials exacerbate [123]. Furthermore, environmental considerations, excessive traffic, and cracking/rutting/deformation in standard asphalt pavement make repairs and maintenance necessary for the pavement to last [124]. Transportation costs rise and environmental implications worsen in some regions due to a lack of readily available natural resources, such as high-quality asphalt aggregates, which include things like natural sand and gravel [125]. Recycling and reusing materials and technologies can help overcome these challenges and advance a sustainable transportation system.

The construction of continuous asphalt pavement uses a lot of fuel, technology, and materials, which means it produces a lot of carbon dioxide. Asphalt pavement's carbon footprint must be reduced in order to meet the critical goal of reducing CO_2 emissions. To minimize the environmental effect of building and maintaining asphalt pavement, it is necessary to employ materials and technologies that effectively reduce emissions; this is in line with sustainable development goals. In addition, the LCA method has been introduced as a systematic strategy to reduce the environmental impact of the road sector, which is a pressing concern everywhere. LCA enables the evaluation and measurement of a product, system, or process's effect on the environment [126]. The results of studies on

Table 2: Studies on low-carbon asphalt pavement using recycled waste materials.

Materials or technologies	Usage	Finding	References
RAP	Replacing aggregates (30%, 40%, and 50%)	Researchers reduced greenhouse gas emissions by 12.4% by adding more RAP to asphalt binder	[127]
	Aggregate replacement (10% and 30%)	When hot asphalt mixtures were mixed with RAP, carbon emissions were 6.8% lower	[128]
Crumb rubber	Asphalt binder modifier (18%)	Wet-technology asphalt binder with 18% crumb rubber reduced carbon emissions by 36%–44%	[129]
	Asphalt binder modifier (1.6%)	Asphalt rubber has a lower carbon footprint than Portland cement mixes	[130]
Recycled aggregate	Aggregate substitution (100%)	Compared to Portland cement mixtures, asphalt rubber has a lower carbon impact	[131]
RCA	Instead of natural aggregate	Decrease in emissions from the production of natural aggregates ranging from 22% to 65%	[132]
	Instead of natural aggregate	Using RCA instead of natural aggregates to construct highway pavement can reduce greenhouse gas emissions by up to 65% and save nonrenewable energy use by up to 58%	[133]
	Instead of natural aggregate	Energy reductions of 24% and decreases in greenhouse gas emissions of 35% are possible	[134]
Technology	Cold recycling	Cold in-place recycling reduces CO_2 emissions by reducing aggregate, transportation, and plant usage (a decrease of 9% throughout the entire lifespan and 54% when only the recycling phase is included)	[128]
	Cold recycling	Cold in-place recycling could reduce CO_2 emissions by as much as 75% compared to traditional building methods because it makes use of preexisting materials and uses less energy	[135]
	WMA	As a more environmentally friendly alternative to traditional asphalt, WMA can cut CO_2 emissions by 10%–40% in asphalt plants	[136]
	WMA	According to the research, asphalt binder facilities might see a 35% drop in CO_2 emissions using WMA instead of the old way	[137]

low-carbon asphalt pavement using recycled waste materials are listed in Table 2.

6.3. Impact on Air and Water Quality. An important venue for recognizing and encouraging environmental excellence in the effective provision of transportation services is the Center for Environmental Excellence (CEE) of the American Association of State Highway and Transportation Officials (AASHTO). To evaluate sustainability factors, the CEE focuses on specific areas of interest, such as preservation and maintenance procedures for pavement. Air quality/emissions is one of these metrics; it is an analysis of the six main air pollutants (CO, LEAD, NO_2, ozone, PM, and SO_2) that it covers. Air quality and material and equipment emissions are computed as part of the evaluation.

Water quality is another important area of concentration for the CEE. This field involves assessing the impacts of transportation-related methods and materials for maintenance [138].

Using recycled materials is a must for environmentally friendly pavement designs. Reduced energy use, fewer greenhouse gas emissions, and cost savings are the goals of this strategy. From an economic and environmental standpoint, many studies highlight the advantages of using recycled materials. Reduced greenhouse gas emissions, energy use, and water use are some of the benefits of increasing the proportion of recycled materials, as pointed out by Zhao et al. [139].

Using RAP in pavements has the ability to have positive effects on the environment and the economy. However, there are certain disadvantages to consider as well, as discussed in [89]. Hossain et al. [133] show that compared to conventional aggregate production, making recycled aggregates from C&D waste can significantly reduce net environmental impacts by 49%–51%. In addition, we may significantly reduce our use of nonrenewable energy sources (185 MJ) and our emissions of greenhouse gases (14 kg CO_2 eq.).

According to Townsend et al. [140], recycling asphalt shingles, particularly when used in HMA, is both technically possible and expected to have positive economic and environmental impacts. This article addresses the issue of asbestos in residential reroofing tear-off shingles, specifically focusing on the possibility of hazardous emissions of asbestos minerals during the production of asphalt shingles, which is a major worry. Known to have harmful effects on human health at high exposure levels, PAH chemical emission is another secondary concern.

According to Lee et al. [141], using recycled materials in the subbase and base layers of a highway pavement can decrease water usage by 11%, hazardous waste output by zero, and greenhouse gas emissions (GHG) (6%). Based on their narrow focus and comparison with water quality parameters, Vashisth et al. [142] came to the conclusion that including crumb rubber into HMA had no negative impact on water quality under any of the tested environmental circumstances.

Based on their possible effects on surface and underground water quality, Edil [143] determined that recycled materials and industrial by-products are environmentally suitable for adoption. The use of recycled materials has many advantages, including less energy use, less waste, less depletion of natural resources, and lower total prices.

7. Challenges and Future Directions

To better understand the complex barriers to encouraging and using recycled construction materials, Geng et al. [144] conducted a qualitative political, economic, social, and technological (PEST) study (RCMs). All of the PEST categories have major obstacles that the study finds, and the treatments that are suggested are directly related to those obstacles. In light of the rapid progress in construction technology, this highlights the study's practical usefulness and importance in directing future research and policy development.

The difficulties that prevent the implementation of RAP in Greece were found in a study conducted by Marantzidis and Gidado [145]. Environmental elements mentioned in the literature were the focus of this research, which tried to investigate their impact on these barriers. A review of the relevant literature and organized interviews with influential Greeks were used to compile the data. The research concludes that the Greek construction industry might benefit from more asphalt planning recycling.

In their study, Batista et al. [146] proposed a framework that aims to promote the sustainability and integration of municipal solid waste (MSW). The authors considered the current obstacles and key success factors (CSFs) needed for developing country municipalities to achieve S-ISWM.

Recent advances in using waste tire rubber in asphalt and Portland cement concrete were described by Shu and Huang [147]. Several approaches were suggested in the review to improve the performance of rubberized Portland cement concrete and remove obstacles; some of these approaches showed promise.

8. Available Software

When analyzing the effects of a product or process on the environment, LCA takes a "cradle-to-grave" approach, examining at everything from the extraction of raw materials through production, operation, and disposal [148]. As part of the Environmental Management Standards (EMS) set out by ISO14000, this method offers a thorough framework for determining environmental impacts across a range of indicators [149]. Objectives and scope definition, inventory analysis, impact assessment, and interpretation are the four interconnected steps of LCA defined by the methodological framework of ISO 14040 and ISO 14044 [150].

Alternatively, LCA is defined as a method for evaluating the effects of a product on the environment. The process includes making a list of all the important things that go into a system, making sure that everything gets out, checking to see if there are any negative effects on the environment that could be caused by those things, and then finding out how all of that fits into the study's goals. LCA investigates the environmental factors and possible effects at each stage of a product's existence, from the procurement of raw materials through its final disposal (i.e., cradle-to-grave). Use of resources, effects on human health, and ecological outcomes are the broad classes of environmental impacts [151]. Table 3 presents the most common LCA software and their advantages and disadvantages.

9. Successful Projects

Several successful projects have effectively utilized recycled materials in asphalt pavement rehabilitation, showcasing the potential benefits in terms of cost savings, environmental impact, and overall sustainability. For instance, the I-15 Freeway Rehabilitation Project in California incorporated reclaimed asphalt pavement (RAP) and RAS, resulting in significant cost reductions and reduced reliance on virgin materials. Similarly, the Greenroads Initiative in Washington State focuses on sustainable transportation infrastructure and has implemented various projects that emphasize LCCA, highlighting the economic and environmental advantages of incorporating recycled materials. Moreover, Texas's Recycled Asphalt Pavement (RAP) Program promotes the use of recycled materials, providing guidelines and specifications that ensure high-quality performance while reducing costs and environmental impact. Additionally, the Florida Department of Transportation (FDOT) has implemented a Recycled Materials Policy, encouraging the incorporation of reclaimed asphalt pavement and recycled concrete in pavement rehabilitation projects, yielding successful outcomes in terms of cost savings and sustainability. These examples serve as illustrations of how recycled materials can be effectively employed in asphalt pavement rehabilitation, showcasing the potential for cost savings, environmental benefits, and improved sustainability through LCCA.

10. Conclusion

The LCCA of recycled materials used to rehabilitate asphalt pavements is thoroughly examined in this research paper. It emphasizes the importance of making thoughtful technique choices that improve pavement condition and ride quality, as well as the value of implementing sustainable practices during pavement repair. Examining the current pavement condition, gathering project details, determining the sources of distress, coming up with workable alternatives, doing a life cycle cost analysis, and finally choosing the best rehabilitation method

TABLE 3: Common software used for LCA.

Characteristics	Open LCA	SIMA pro	BEES	GaBi	References
Software tool and developer	LCA and LCCA tool developed by GreenDelta since 2006	LCA tool developed by PRé Consultants in 1990	NIST created the LCA and LCCA tool (National Institute of Standards and Technology)	The LCA and LCCA tool was created by sustainability-focused PE Europe GmbH. IKP University of Stuttgart developed the program over 10 years	[151]
Assessment categories	Multiple, mainly manufacturing	Multiple, mainly manufacturing	Construction	Multiple, mainly manufacturing	[152]
Database	Ecoinvent and GaBi databases, ProBas, USDA, Ökobaudat, Social Hotspots, LC-Inventories.ch, NEEDS, ELCD, bioenergiedat	Ecoinvent, US LCI, ELCD, US Input Output (EU) and Danish Input Output, Swiss Input Output, LCA Food, Industry data v.2	LLC and First Environment, Inc., using the SimaPro LCA software	Gabi LCA databases, ecoinvent, US LCI, energy, renewable raw materials	[153]
Use	This tool used for the materials extraction and manufacturing stage of a pavement LCA. It is freely available, without license costs	This tool extracts and manufactures pavement LCA materials. Downloading software requires a license	This tool was inspired by an environmental and economic material selection strategy. The user can use the software online without downloading it	Pavement LCA material extraction and manufacture. Downloading and upgrading the software require a license and an internet connection	[152, 154]
Advantage	Automatic and manual process networks and graphical modeling are open LCA's advantages. Another benefit of this application is that users can work with GaBi and other databases	Advantages include being adaptable, attached to various databases, quickly connecting with other tools, user-friendly, transparent results, etc.	Weighing economic and environmental criteria is a strong feature of the tool	GaBi's definition function, LCIA approaches, user ability to change databases, and extensive information and results presentation are its best characteristics	[155, 156]
Presentation of LCA results	Presents LCA findings using a Sankey diagram (bar) charts, and tables for inventory management	Presents LCA findings using a Sankey diagram and bar charts, and analyzes inventories using tables	Only results in columnar charts are graphed. No further graphs or tabular presentations of those results are available (flexibility in presentation limitation)	Makes use of bar charts and Sankey diagrams to display LCA outcomes. Inventory analysis makes use of tables and automated flow balances. GaBi provides the best graphical user interface (GUI) for modeling since it is both easy to use and understand	[157, 158]

are all essential steps in the selection process that are highlighted in the paper.

The analysis covers a wide range of asphalt pavement rehabilitation procedures, including cold milling, hot in-place recycling, cold in-place recycling, asphalt overlays, and full-depth or partial-depth restoration. The selection of these procedures is influenced by factors such as structural evaluation, functional evaluation (taking roughness and skid resistance into account), distress evaluation, and drainage assessment. This review highlights the use of recycled materials in pavement rehabilitation as a means to reduce environmental impact and promote sustainability. This study provides valuable insights that can help transportation authorities, researchers, and engineers make informed decisions and execute cost-effective techniques for asphalt pavement rehabilitation.

Finally, by providing useful insights into rehabilitation technique selection, life cycle cost evaluation, and recycled material integration, this review considerably advances our understanding of pavement repair. Encouraging improved infrastructure performance and long-term sustainability, it becomes an essential resource for professionals involved in asphalt pavement design, maintenance, and management.

In conclusion, this extensive research sheds light on how to evaluate the long-term viability and financial impact of using recycled materials in asphalt pavement repair projects by applying LCCA and LCA approaches. Additional research is necessary to determine the best way to utilize recycled materials and to measure their complete life-cycle impacts, since the building industry is always looking for greener and cheaper alternatives. If we want to see sustainable pavement repair approaches adopted more widely, we need further research into novel recycling methods, stronger decision-support systems, and how well they hold up over time. The advantages of recycled materials and the advancement of transportation infrastructure sustainability can only be realized if there is a clear path from academic research to industry application.

The review paper highlights the potential environmental benefits of utilizing recycled materials in asphalt pavement rehabilitation, such as reduced carbon footprint, improved air and water quality, and diversion of waste from landfills. However, the review also notes that challenges remain in fully realizing these environmental advantages. To address this, the review could further explore mitigation strategies to minimize any negative environmental impacts associated with recycled materials. For example, measures like emissions controls, wastewater treatment, and responsible waste management practices during the recycling and rehabilitation processes could help maximize the sustainability gains. Additionally, LCA methodologies can be leveraged to quantify and optimize the environmental performance of recycled material usage compared to traditional approaches. By delving deeper into these mitigation tactics, the review could provide a more comprehensive perspective on how the environmental benefits of recycled materials can be reliably achieved in asphalt pavement rehabilitation projects.

Nomenclature

ASTM: American Society for Testing and Materials
B/C: Benefit/cost
CBR: California bearing ratio
CDW: Construction and demolition waste
CEE: Center for Environmental Excellence
CIR: Cold in-place recycling
CKD: Cement kiln dust
CRM: Crumb rubber modified
EMS: Environmental Management Standards
FDR: Full-depth reclamation
HIR: Hot in-place recycling
HMA: Hot mix asphalt
LCA: Life cycle assessment
LCCA: Life cycle cost assessment
M&R: Maintenance and rehabilitation
MSW: Municipal solid waste
NA: Natural aggregate
NPV: Net present value
OBC: Optimal binder content
RA: Rubberized asphalt
RAP: Reclaimed asphalt pavement
RAS: Recycled asphalt shingles
RCA: Recycle concrete aggregate
RCWMs: Reclaimed construction and demolition waste materials
RMRC: Recycled materials resource center
UEAC: Uniform equivalent annual cost
VOCs: Volatile organic compounds
WCED: World Commission on Environment and Development
WMA: Warm mix asphalt
WMA-RAP: Warm mix asphalt with recovered asphalt pavement.

Data Availability

The datasets presented in this review are already available within the manuscript, as they were obtained from other research that has been published previously.

Conflicts of Interest

The authors declare that there are no competing interests.

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