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Sustainability Assessments of Hot and Warm Mix Asphalt Paving Technologies

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Abstract

This research provides a comprehensive environmental and economic analysis of both Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) technologies for the purpose of consolidating sustainable pavement solutions. The potential necessity of preventing global warming and minimizing the production cost of standard asphalt production has sparked an urgent need to seek alternatives, leading to WMA as a viable and eco-friendly solution. The temperature in the production process has a great difference between HMA and WMA. The operating temperature of HMA is 150 to 180 °C, whereas WMA works at lower temperatures, like 110 to 140 °C. This drop in temperature has significant environmental advantages, such as reduced levels of greenhouse gas emissions, reduced consumption of fuel, and increased worker safety because of less fume exposure. According to economic evaluations, there are energy savings of between 20% and 75% and reported production cost reductions of at most $1.61 per ton.WMA permits higher recycling materials like Reclaimed Asphalt Pavement (RAP), steel slag, glass fiber, and jute fiber, consistent with the goals of the 4Rs (Reduce, Reuse, Recycle, and Reclaim) of the sustainable philosophy. These composite mixtures have shown improvements in fatigue resistance, moisture susceptibility, and rutting performance. However, WMA technologies present an inferior performance at high traffic levels, particularly concerning early-life durability and moisture sensitivity, because of lower compaction temperature. The application of bio-based WMA additives from waste sources would provide opportunities to overcome these shortcomings. Environmental governance of WMA over HMA is facilitated through Life Cycle Assessment analyses (LCA) that have used commercial (Athena) software, particularly concerning energy utilization and carbon dioxide and greenhouse gas (GHG) emissions. According to this research, WMA is a cost-effective, viable, and performance-responsive alternative to traditional asphalt paving methods.

Keywords
Hot mix asphalt, warm mix asphalt, reclaimed asphalt pavement, gas emission, additives.

1. Introduction

The rising need for sustainable infrastructure, along with the increasing necessity to eliminate GHG emissions and energy usage, propels the development of eco-friendly pavement technology. WMA is a viable alternative to

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traditional HMA, characterized by decreased production temperatures, diminished energy consumption, and reduced environmental effects. This research examines the creation of improved WMA combinations aimed at substantially reducing energy consumption, greenhouse gas emissions, and production costs in comparison to conventional HMA. Table 1 compares various asphalt mixtures (Rubio et al. 2011, Kheradmand et al. 2014, Vaitkus et al. 2016, Jain and Singh 2021, Chowdhury and Button 2008).

Table 1. Advantages and disadvantages of asphalt mixtures

Mix Type	Temperature (°C)	Advantages	Disadvantages
Hot-mix asphalt	150–180	• Superior mixture performance • Lower initial cost	• High production temperature • High emissions • High energy consumption
Warm-mix asphalt	110–140	• Low production temperature • Low emissions • Energy saving • Better working conditions • Longer haul distance	• Low mixture performance • Higher initial cost due to the use of Additives • Poor aggregate coating and bonding

The focus of this research is to design WMA systems that incorporate significant amounts of RAP and bio-based additives and organic materials. These additives are aimed at providing asphalt with increased workability, mechanical strength, and rheological properties while reducing the associated production energy costs. Using a combination of rigorous laboratory analyses and appraisal of environmental and economic factors, the methodical evaluation of the sustainability of the produced asphalt combinations is made through the study. The results are further validated using Life Cycle Assessment (LCA) utilizing Athena software, applying a cradle-to-grave methodology encompassing material extraction, production, consumption, and end-of-life phases. Concurrent economic analysis assesses the costs of WMA-RAP mixes relative to conventional HMA.

1.1 Objective

The main goal of this study is to conduct a thorough evaluation of HMA and WMA technologies concerning their environmental impact and economic implications for sustainable pavement construction. This investigation helps to analyze how WMA offers HMA replacement alternatives by comparing its benefits to decreased energy usage, emissions, and health risks to personnel, as well as acknowledging its boundaries and areas needing future study. The project analyzes current literature to discover essential driving factors, together with barriers and developments needed for implementing WMA technologies, which will help make road construction more sustainable with lower costs.

2. Literature review

Vaitkus et al. (2016) presented a comprehensive analysis of several WMA technologies and their impact on asphalt mixture performance. The study delineates four primary WMA manufacturing techniques: water-based foaming procedures, water-bearing additions (such as zeolites), organic additives (such as Sasobit®), and chemical additives (such as Cecabase and Iterlow T). Each of these methods facilitates asphalt manufacturing at temperatures 20–40 °C lower than traditional Hot Mix Asphalt (HMA).

Hetterarachchi et al. (2019) point out a combination of WMA and RAP technologies for the sustainable creation of pavement. WMA's possibilities to manufacture asphalt at 20 to 60 °C lower than the standard level of HMA, due to the use of organic, chemical additives, and foaming, bringing obvious environmental and economic benefits, are illustrated. Although RAP is popular for its economic benefits and virgin material reduction, it brings aged binders that, occasionally, result in increased stiffness of the Mixture and fatigue cold-weather performance.
Cheraghian et al. (2020) offer a comprehensive and current examination of WMA technology, focusing on additive kinds, mechanical performance, environmental advantages, and the incorporation of recycled components. WMA technologies are largely classified into three categories: organic additives (e.g., Sasobit, carnauba wax), chemical additives (e.g., Evotherm, Zycotherm), and foaming technologies (e.g., Aspha-Min, WAM Foam). Each approach decreases production temperatures by 10–90°C relative to HMA, reducing emissions and enhancing workability without significantly affecting performance.

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The assessment of WMA technologies and their applications with RAP was performed by Mohammad et al. (2015) through research in Louisiana. WMA mixtures demonstrated both excellent rutting and moisture resistance regardless of the RAP content percentage used. WMA achieved energy conservation levels of 12–14%, which produced positive effects on environmental sustainability in pavement construction. WMA technologies were designed to be used at a lower level of production temperatures than the HMA. These technologies significantly reduce greenhouse gas (GHG) emissions, particularly CO_2, SO_2, NO_x, and VOCs, and energy consumption of 20 to 75%, depending on the used additives and processes (Milad et al. 2022).

3. Methodology

3.1 Materials Selection and Mix Design Optimization

This research focuses on the sustainable development of the road construction industry. Sustainable development requires fewer natural raw materials, as the extraction cost and energy consumption are very high. It also requires transportation costs. Sustainable development reduces GHG emissions and also encourages the use of recycled materials without deteriorating the standard specification. Figure 1 shows that sustainable development comprises three interrelated areas: social development, economic development, and the surrounding environment.

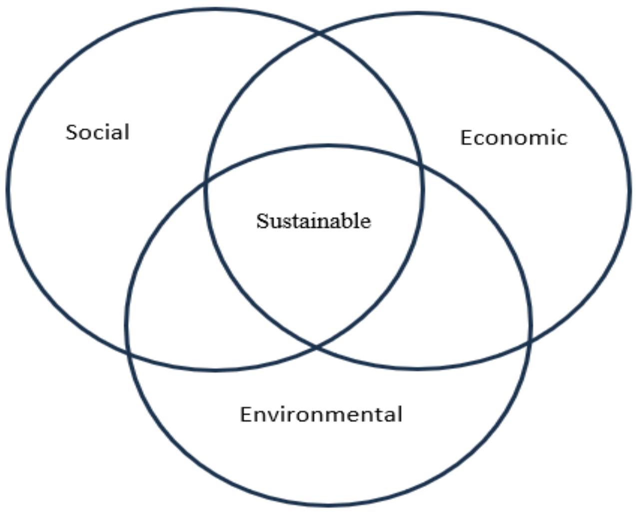

Figure 1. Sustainable development

This research focused on sustainability-based asphalt mix preparation methods in pavement construction through its analysis of WMA advantages. WMA technology facilitates the addition of RAP, Recycled Asphalt Shingles (RAS), and steel and copper slags with no negative impact on pavement performance. Natural jute fibers combined with mineral additives consisting of hydrated and nano-hydrated lime improve asphalt structure reliability against moisture deterioration and cracking.

The fundamental goal of WMA design optimization involves decreasing mixing and compaction temperatures by 20 to 40°C from those of HMA. Various recycled materials used in WMA are shown in Table 2. Table 2 provides a detailed overview of several WMA additives and their combined impact with RAP, slag, fibers, oils, and rejuvenators on the performance of asphalt mixtures. The additions comprise chemical agents and materials such as steel slag, furnace slag, hydrated lime, and nano additives that enhance essential pavement characteristics, including fatigue resistance, stiffness modulus, fracture resistance, and moisture susceptibility. RAP, when mixed with additives like Sasobit® and steel slag, substantially lessened rutting and enhanced resilience modulus, whereas glass fibers and crumb rubber improved fatigue resistance and moisture tolerance.

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Table 2. Uses of recycled materials in WMA

WMA Additive	Effect	References
Glass (10%) + ZycoTherm™ (0.05, 0.10, 0.15 and 0.20% **)	Minimize creep and moisture susceptibility	Sanji et al. (2019)
Furnace slag (30% *) + Sasobit® (4% **) or Rediset™ (2% **)	Optimize fatigue resistance and stiffness modulus	Martinho et al. (2018)
Steel slag (40% *) + Surfactant-based chemical additive (0.5% **)	Enhance the fatigue resistance and mechanical properties of asphalt mixtures	Pasett et al. (2017)
RAP (0, 20 and 40% *) + Steel slag (0 and 40% *) + Sasobit® (1.5% **)	RAP increases moisture sensitivity and resilient modulus; steel slag supplements the resilient modulus	Fakhri and Ahmadi (2017)
RAP (20, 30, 40, 50, and 60% *) + Mobile engine oil (10, 12.5, 15, 17.5 and 20% **) + Evotherm™ (0.5% **)	The tensile strength ratio (TSR) decreased with higher RAP; higher rejuvenator dosage also reduced the TSR.	Farooq et al. (2018)
RAP	The use of WMA increases permanent deformation, but adding RAP reduces rutting	Vargas and Timm (2012)
RAP	50% of RAP WMA has good fatigue performance	Padula et al. (2019)
Jute fibre (0, 0.3, 0.5 and 0.7% ***) + Sasobit® (3% **)	Increased fracture resistance	Mansourian et al. (2016)
Hydrated Lime (1% ***) + Advera (0.25%**), Sasobit (3.0%**), and Cecabase RT (0.35% **)	Improve moisture susceptibility	Hasan et al. (2015)
Nano hydrated lime (1% ***) + Aspha-Min (0.3% **), Evotherm (0.5% **), and Sasobit (1.5% **)	Increase the indirect tensile strength (ITS) and TSR	Cheng et al. (2011)

*By aggregate weight, **By binder weight, ***By mixture weight

3.2 Production Process Analysis and Laboratory Evaluation

The production process of WMA stands unique from HMA manufacturing through its lower operating temperatures, ranging from 110°C to 140°C, while HMA operates at production temperatures between 150°C and 180°C. Specific additives make temperature reduction possible and include organic components such as wax product Sasobit®, together with chemical surfactants Rediset and Evotherm®, and foaming technologies WAM Foam and Aspha-Min®. Table 3 lists some of the WMA additives and their optimum dosages segregated into three main categories, i.e., organic additives, chemical additives, and foaming methods (Ma et al. 2020, Rubio et al. 2012, Silva et al. 2010, Capitão et al. 2012, Aurilio et al. 2022, Pouranian and Shishehbor 2019, Chowdhury and Button 2008, Peng et al. 2015, Sharma and Lee 2017, Firmansyah and Tamalkhani 2019). Such additives are provided by different companies in the world, and they can be used in diverse parts of the planet. The WMA production process consists of two main stages: (1) Plant Operations – including the heating and mixing of aggregate and binder, and (2) Paving Operations – involving transportation, laying, and compaction on-site.

Laboratory assessment of WMA concentrates on mechanical comparisons with HMA, including ambient condition assessments to analyze four essential properties: rutting resistance, fatigue life, moisture susceptibility, and stiffness modulus. This study indicates that WMA combinations containing RAP, crumb rubber, and steel slag have almost equal characteristics to HMA. Table 4 shows the heating energy and CO_2 emissions for different fuels (Ore 2021, Peng et al. 2015).

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Table 3. Optimum dosages of additives for WMA

Type of Additive	WMA Process	Product	Company	Dosage
Organic Additive	FT Wax	Sasobit®	Sasol	1.0–2.5% *
Organic Additive	Montan Wax	Asphaltan B	Romonta GmbH	2.0–4.0% *
Organic Additive	Fatty Acid Amide	Licomont BS	Clariant	3.0% *
Organic Additive	Wax	3E LT or Ecoflex	Colas	Not specified
Chemical Additive	Emulsion	Evotherm®	MeadWestvaco	0.5–0.7% *
Chemical Additive	Surfactant	Rediset	Akzo Nobel	1.5–2.0% *
Chemical Additive	Surfactant	Cecabase RT	CECA	0.2–0.4% **
Chemical Additive	Liquid Chemical	Iterlow	IterChimica	0.3–0.5% *
Foaming Technique	Water-based	Low Energy Asphalt (LEA®)	LEA-CO	3% water with fine sand
Foaming Technique	Water-based	Low-Emission Asphalt	McConaughey Technologies	3% water with fine sand
Foaming Technique	Water-based	LT Asphalt	Nynas	0.5–1.0% *
Foaming Technique	Water-based	LEAB®	Royal Bam Group	0.1% *
Foaming Technique	Water-based	Double Barrel Green	Astec	2.0% water *

*By aggregate weight, **By mixture weight

Table 4. Energy and CO_2 emissions for different fuels

Fuel	Heating Energy for Aggregate		CO_2 Emission	
	Value	Unit	Value	Unit
Diesel	42,791,000	J/kg	2.6390	kg/L
Heating oil	42,612,000	J/kg	-	-
Fuel oil (N°1/2)	42,686,000	J/kg	3.2160	kg/t
Natural gas	47,141,000	J/kg	0.1836	kg/kWh
Propane gas	46,296,000	J/kg	-	-
Electricity	3,600,000	J/kWh	0.5410	kg/kWh

3.3 Sankey diagram

Sankey diagrams were created to visually represent the flow and distribution of materials and energy throughout the life cycle of both alternatives, like HMA and WMA. These diagrams illustrate the resource and energy usage, as well as the environmental implications of each option at every stage of its lifespan. The Sankey diagram for both alternatives has been drawn with the help of Sankematic. From the Sankey diagram, it is shown that carbon dioxide emissions are higher in HMA for the same amount of asphalt production. Figure 2 and Figure 3 show the Sankey diagram of WMA and HMA, respectively. From both Sankey diagrams, it is observed that for the same quantity of asphalt production, in WMA, 0.9 tons of CO_2 is produced, whereas in HMA, 1.5 tons of CO_2 is emitted into the environment.

3.4 Economic Feasibility Study

WMA production requires less fuel because studies demonstrate a maximum reduction of up to 32% in fuel usage (Oliveira et al. 2011). The state of Louisiana recorded average energy cost efficiencies of $1.61 for every ton of asphalt paving mix that is produced (Mohammad et al. 2015). The usage of WMA technology makes it possible to incorporate reclaimed asphalt pavement (RAP) to reduce the required quantity of fresh binder significantly. The use of 100% RAP enables contractors to save around 80% of their construction costs when compared to asphalt mixes containing no RAP (Khan et al. 2021). The cost savings from WMA production become more significant when zeolites or chemical agents such as Evotherm are utilized because they improve workability without affecting financial efficiency.

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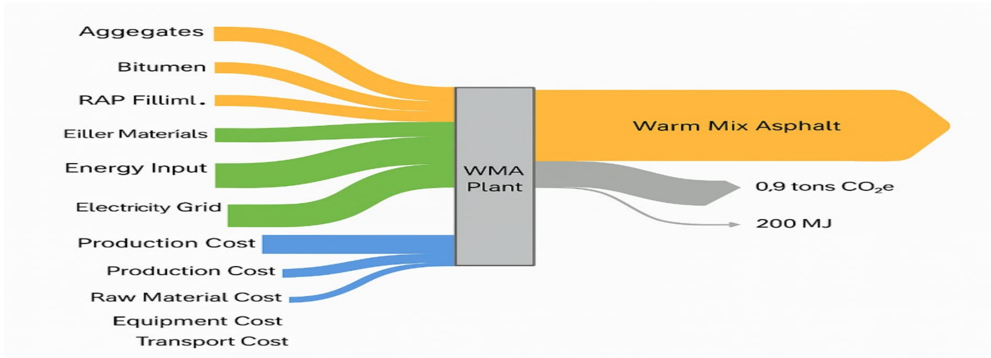

Figure 2. Sankey diagram of WMA

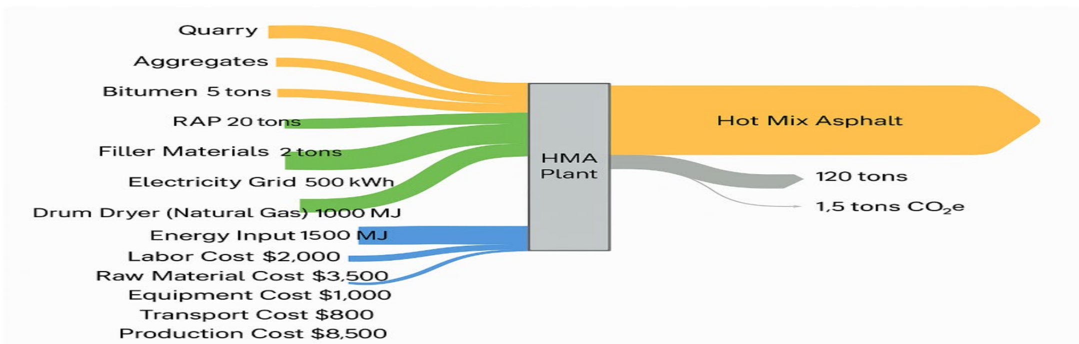

Figure 3. Sankey diagram of HMA

3.5 Health and safety impact assessment

The integration of WMA results in better industrial health and improved safety conditions through operational advantages. The modern paving method enables the process to occur at lower temperatures to allow for quicker pavement cooling, thus aiding in earlier road lane re-openings, particularly crucial for busy urban streets and airport facilities. The short exposure period for workers prevents them from encountering roadside dangers that include both traffic movements and adverse climatic conditions.

4. Data Collection:

4.1 Life Cycle Assessment (LCA)

The LCA evaluation of asphalt pavement across the complete development sequence starts with material extraction and finishes with waste disposal activities. The LCA framework is divided into six main stages (Milad et al. 2022), including the extraction of materials, transportation needs, the construction phase, usage duration, and service maintenance before final disposal. Figure 4 shows the main stages of LCA. In this research, Athena pavement software is used for the LCA of both WMA and HMA.

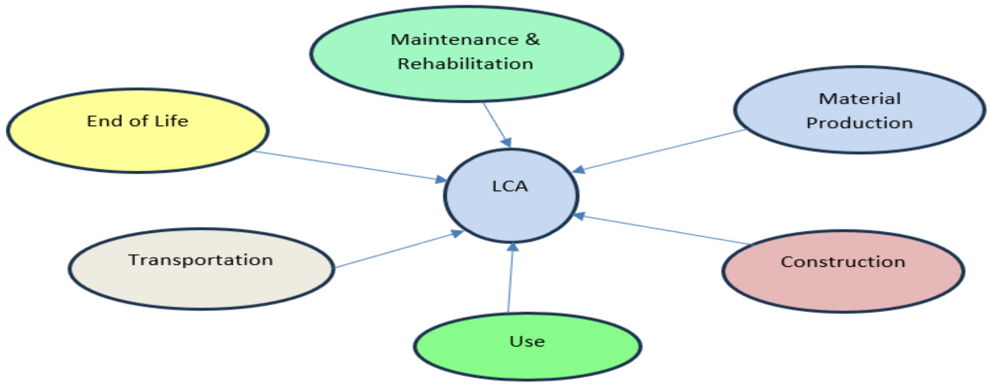

Figure 4. Stages of LCA

5. Results and discussion

The substitution of HMA with less environmentally harmful WMA offers asphalt producers multiple sustainability advantages because WMA requires manufacturing temperatures between 110–140°C, which is lower than the 150–180°C of HMA. This temperature difference results in diminished energy requirements and reduced greenhouse gas emissions.

Tables 5 and 6 provide a thorough LCA assessment of HMA throughout three life cycle phases: manufacturing, construction, and embodied impact. The Global Warming Potential (GWP) is the primary contribution, which is roughly 13.24 million kg CO_2 equivalent, with 2.99 million kg CO_2 eq resulting from calcination in the manufacturing process. Additional essential environmental impacts are acidification potential (37,563.19 kg SO_2 equivalent), eutrophication potential (6,949.45 kg nitrogen equivalent), and human health particulate matter (10,973.60 kg PM2.5 equivalent). The ozone depletion potential is negligible at 0.34 kg CFC-11 equivalent. The overall primary energy demand is roughly 590.43 million MJ, which is mostly derived from non-renewable energy sources and fossil fuel usage.

Table 5. LCA output of HMA (Manufacturing)

Name	Unit	Manufacturing		
		Material	Transport	Total
Global Warming Potential	kg CO2 eq	11,828,938.39	1,412,515.02	13,241,453.40
Global Warming Potential - Calcination	kg CO2 eq	2,987,047.36	0.00	2,987,047.36
Acidification Potential	kg SO2 eq	23,934.61	13,628.58	37,563.19
HH Particulate	kg PM2.5 eq	10,221.28	752.32	10,973.60
Eutrophication Potential	kg N eq	6,102.05	847.39	6,949.45
Ozone Depletion Potential	kg CFC-11 eq	0.34	0.00	0.34
Smog Potential	kg O3 eq	494,261.24	430,412.82	924,674.06
Total Primary Energy	MJ	569,836,618.66	20,594,954.96	590,431,573.62
Non-Renewable Energy	MJ	564,342,515.27	20,586,450.84	584,928,966.11
Fossil Fuel Consumption	MJ	541,106,458.49	20,555,136.92	561,661,595.40

Table 6 shows the environmental impacts of construction activities and embodied effects across multiple sectors, including global warming potential, acidification, and energy use. Embodied consequences are dominant, indicating significantly higher emissions and energy consumption compared to on-site construction.

Table 6. LCA output of HMA (Construction and embodied effect)

Name	Unit	Construction			Embodied Effects		
		Equipment	Transport	Total	Materials and Equipment	Transport	Total
Global Warming Potential	kg CO2 eq	911,349	819,865	1,731,214	12,740,287	2,232,380	14,972,668
Potential - Calcination	kg CO2 eq	0.00	0.00	0.00	2,987,047	0.00	2,987,047
Acidification Potential	kg SO2 eq	8,746	7,890	16,636	32,680	21,518	54,199
HH Particulate	kg PM2.5 eq	484	436	921	10,705	1,189	11,894
Eutrophication Potential	kg N eq	543	490	1,034	6,645	1,338	7,983
Ozone Depletion	kg CFC-11 eq	0.00	0.00	0.00	0.34	0.00	0.34
Smog Potential	kg O3 eq	276,056.37	249,109	525,165	770,317	679,522	1,449,839
Total Primary Energy	MJ	13,289,397	11,954,940	25,244,338	583,126,016	32,549,895	615,675,911
Non-Renewable Energy	MJ	13,283,9119	11,950,004		577,626,426	32,536,454	610,162,881
Fossil Fuel Consumption	MJ	13,263,727	11,931,842	25,195,570	554,370,186	32,486,979	586,857,166

Figure 5 shows some parameters of the Life cycle stages of HMA, which we obtained from Athena pavement LCA, and Figure 6 presents a comparative analysis of environmental impacts and energy usage across different life cycle stages of WMA pavement. Using a logarithmic scale, the graph evaluates major effects, such as Global Warming Potential, Acidification Potential, Eutrophication Potential, Ozone Depletion Potential, Smog Potential, and various energy consumption parameters (Total Primary Energy, Non-Renewable Energy, and Fossil Fuel Consumption).

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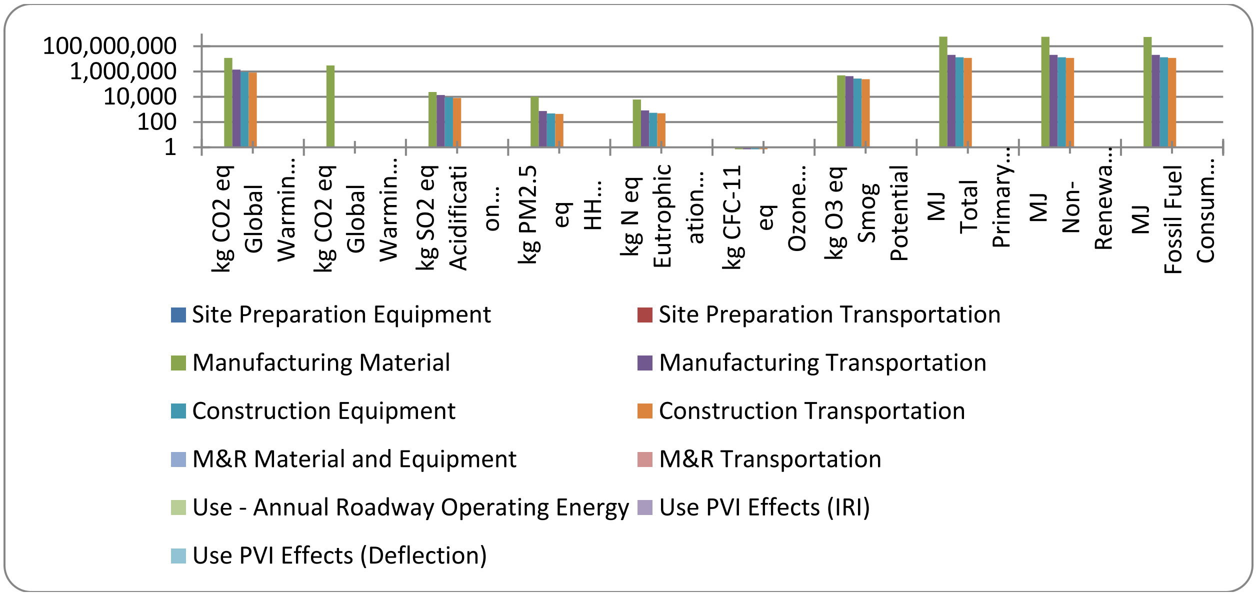

Figure 5. Life cycle stages output of HMA

Table 7 outlines the environmental impacts of WMA associated with material manufacturing, with a total global warming potential of 12.37 million kg CO_2 eq, with 2.84 million kg CO_2 eq from calcination, and a total primary energy use of 506.90 million MJ, mostly from non-renewable energy sources. Compared to HMA manufacturing (GWP of 13.24 million kg CO_2 eq and energy use of 590.43 million MJ), it reflects a reduction in overall emissions and energy consumption. These differences imply that the WMA manufacturing process is more efficient than HMA.

Table 7. LCA output of WMA (Manufacturing)

Name	Unit	Manufacturing		
		Material	Transport	Total
Global Warming Potential	kg CO2 eq	11,015,805.79	1,357,239.07	12,373,044.86
Global Warming Potential - Calcination	kg CO2 eq	2,835,249.35	0.00	2,987,047.36
Acidification Potential	kg SO2 eq	22,029.83	13,096.63	35,126.46
HH Particulate	kg PM2.5 eq	10,078.43	722.86	10,801.30
Eutrophication Potential	kg N eq	5,880.28	814.32	6,694.60
Ozone Depletion Potential	kg CFC-11 eq	0.33	0.00	0.33
Smog Potential	kg O3 eq	451,259.03	413,617.68	864,876.71
Total Primary Energy	MJ	487,115,152.60	19,788,943.78	506,904,096.38
Non-Renewable Energy	MJ	481,946,900.39	19,780,772.46	501,727,672.85
Fossil Fuel Consumption	MJ	459,188,240.99	19,750,682.99	478,938,923.98

Table 8 emphasizes the importance of reducing materials-related emissions and energy consumption for sustainable construction.

Table 8. LCA output of WMA (Construction and Embodied Effects)

Name	Unit	Construction			Embodied Effects		
		Equipment	Transport	Total	Materials and Equipment	Transport	Total
Global Warming Potential	kg CO2 eq	893,864.56	787,888.50	1,681,753.06	11,909,670.35	2,145,127.57	14,054,797.92
Calcination	kg CO2 eq	0.00	0.00	0.00	2,987,047.36	0.00	2,987,047.36
Acidification Potential	kg SO2 eq	8,580.66	7,582.29	16,162.95	30,610.49	20,678.92	51,289.42
HH Particulate	kg PM2.5 eq	475.14	419.86	894.99	10,553.57	1,142.72	11,696.29
Eutrophication Potential	kg N eq	533.51	471.47	1,004.98	6,413.79	1,285.79	7,699.58
Ozone Depletion	kg CFC-11 eq	0.00	0.00	0.00	0.33	0.00	0.33
Smog Potential	kg O3 eq	270,836.54	239,393.33	510,229.87	722,095.57	653,011.01	1,375,106.58
Total Primary Energy	MJ	13,034,386.92	11,488,666.94	24,523,053.86	500,149,539.52	31,277,610.72	531,427,150.24
Non-Renewable Energy	MJ	13,029,006.02	11,483,923.18	24,512,929.20	494,975,906.40	31,264,695.64	526,240,602.05
Fossil Fuel Consumption	MJ	13,009,209.11	11,466,470.22	24,475,679.33	472,197,450.10	31,217,153.21	503,414,603.31

Compared to Hot Mix Asphalt (HMA), WMA shows generally lower impact values, particularly in the manufacturing-related emissions and energy categories, highlighting its environmental advantage, as shown in Figure 6.

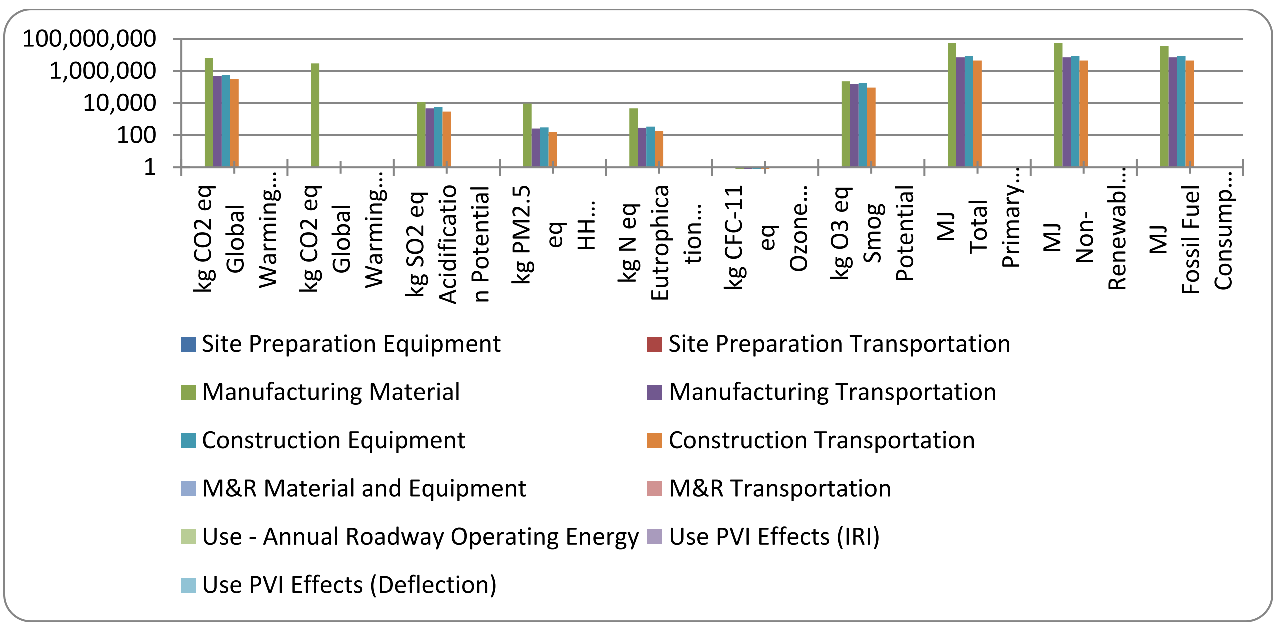

Figure 6. Life cycle stages output of WMA

Research demonstrates that WMA technology decreases total environmental effects by 15% through its distinct reductions of airborne pollutants by 25%, lower fuel depletion by 17%, reduced smog accumulation by 9%, and reduced global warming by 4%. Figure 7 shows the percent reduction of various LCA categories for using WMA over HMA.

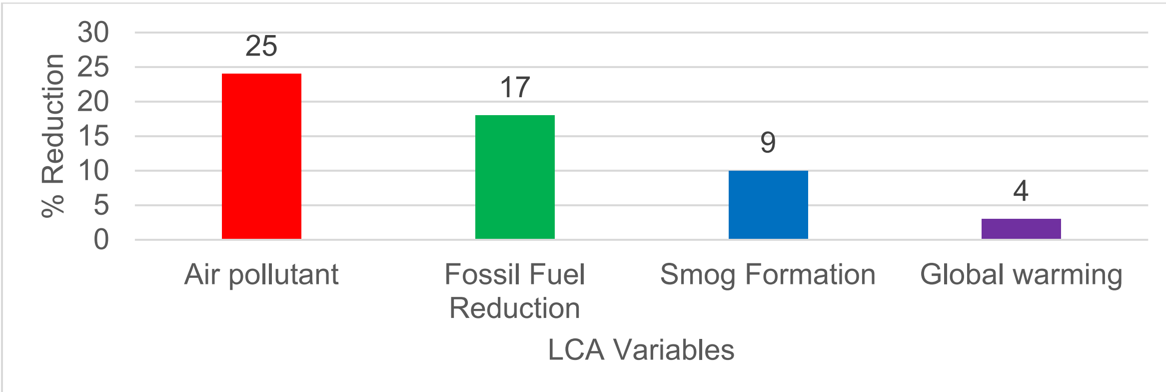

Figure 7. Percent reduction of LCA variables of WMA over HMA

Figure 8 illustrates CO_2 emissions (in kilograms) associated with different phases of asphalt pavement construction, highlighting the relative environmental impacts of each phase. Among the five phases, the mixture mixing phase and the materials production phase contribute overwhelmingly to total CO_2 emissions, with the mixture mixing phase generating the highest emissions, approaching 5,000,000 kg.

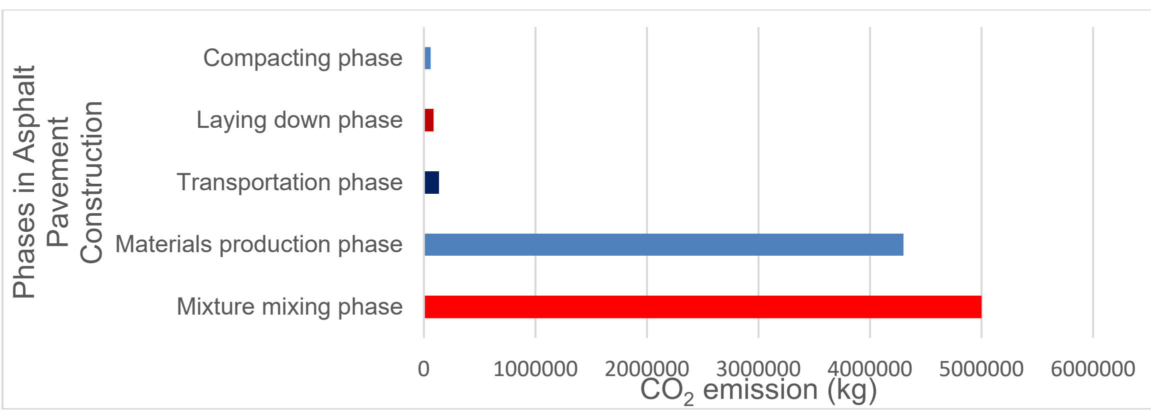

Figure 8. CO_2 emission in various phases of Asphalt Pavement Construction

WMA reduces energy consumption to half its original amount when compared to HMA, resulting in 83 MJ/t of energy usage for WMA versus 175 MJ/t of energy usage for HMA. Plants that implement WMA technology benefit from decreased equipment deterioration because of substandard operational temperatures that extend the usable time for maintenance and equipment components. The temporary temperature reduction leads to massively reduced harmful emissions when producing and placing asphalt, which creates safer working conditions for operational staff. Lower levels of volatile organic compounds (VOCs), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) in the workplace constitute a major advantage because these substances are dangerous for human health when breathed through inhalation or touched with skin over time.

5.1 Proposed Improvement

Future research on WMA needs to combine modern methodologies, like optimization approaches, modeling, and machine learning, to assess the environmental and energy efficiency of WMA, both in isolated and in other combined

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technologies. Investigating the utilization of waste-derived compounds in WMA applications is crucial, especially for evaluating their environmental and economic benefits with conventional additives. Moreover, the ecological impacts of various WMA additives need to be explored. To increase the credibility of laboratory results, it is essential to conduct field validation across many geographical and environmental circumstances to verify the real-world advantages of WMA technologies.

6. Conclusion

Environmental impacts and CO_2 emissions across various stages of asphalt pavement construction reveal that the materials production phase and mixing phase are the main contributors to greenhouse gas emissions. Minor contributions from transportation, laying down, and compacting phases indicate that improvements in these areas would have a relatively low effect compared to targeting the production and mixing stages. This emphasizes the urgent need to implement technologies that minimize energy consumption and emissions during material production and asphalt mixing, as these stages combined account for over 90% of total emissions. WMA technologies significantly lower production temperatures, resulting in reduced fuel consumption, fewer pollutant emissions, and overall environmental benefits when compared to traditional HMA.

Moreover, the research findings suggest that WMA offers considerable advantages not only in environmental performance but also in economic efficiency. The ability of WMA to incorporate higher percentages of reclaimed materials, such as RAP, further enhances its sustainability profile. Research has also shown that WMA can reduce CO_2 emissions by up to 60%, depending on the additive or process used.

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Dr. Zahid Hossain, P.E., F. ASCE, M.ACI, is a Professor of Civil Engineering at Arkansas State University, where he also serves as the Director of Graduate Programs in Engineering, encompassing Civil, Electrical, and Mechanical disciplines. He is the Director of the Asphalt Materials Testing and Processing Laboratories at A-State and the Associate Director of the Transportation Consortium of the South Central States (Tran-SET). Dr. Hossain holds a Doctor of Philosophy in Civil Engineering, as well as dual Master of Science degrees in Civil Engineering and Computer Science, all from the University of Oklahoma, Norman, Oklahoma, USA.

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