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Original Article

Enhancing Asphalt Performance and Sustainability: A Comprehensive Study on Warm Mix Technologies, Additives, and Environmental Benefits

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Abstract *- The purpose of this paper is to examine the many facets of Warm Mix Asphalt (WMA) production by looking at its raw materials, production processes, techniques for low-temperature production, energy consumption patterns, financial benefits, and the role of various additives in lowering gas emissions. The goals of this research are to learn about the ingredients and production methods used to make WMA, examine novel approaches to making WMA at lower temperatures, analyse the effects of additional additives, analyse the energy consumption patterns and associated economic benefits of making WMA, and learn about the extent to which various additives contribute to the reduction of gas emissions specifically in the production of Warm Mix Asphalt.*

Keywords *- Additives, Energy consumption, Hot mix asphalt, Sustainable construction, Warm mix asphalt.*

1. Introduction

Choosing asphalt mixes for road building is crucial and requires carefully weighing performance, sustainability, and cost-effectiveness. Over the years, there has been a tremendous change in the asphalt industry towards ecologically friendly and creative solutions to the issues faced by conventional Hot Mix Asphalt (HMA). Warm Mix Asphalt (WMA) is one option for improving pavement performance while reducing negative environmental effects.

In order to lessen the negative effects of paving projects on the environment due to factors like energy usage, greenhouse gas emissions, and worker safety, the asphalt industry has been looking at new ways of manufacturing and laying asphalt. The use of WMA, which allows asphalt to be mixed and compacted at lower temperatures than traditional HMA, is an encouraging development in this area. This cooler environment benefits construction workers in many ways: less energy and less pollutants are produced, and the workers' environment is enhanced.

Despite the many empirical works demonstrating WMA's usefulness, a thorough theoretical examination is required to fully appreciate the many ways in which it excels above HMA. This work aims to bridge this gap in our understanding by taking a theoretical approach to examining WMA and HMA. We want to clarify WMA's performance, environmental, and economic advantages over HMA by synthesising the literature, mathematical modelling, and comparative analysis.

Following this brief introduction, this article will proceed to a detailed examination of WMA and HMA, including an examination of their theoretical foundations and a comprehensive assessment of their relative benefits. This work adds to the continuing dialogue about sustainable and high-performance asphalt pavement alternatives by illuminating the theoretical elements of WMA's advantage over HMA.

2. Scope

In order to determine whether or not Warm Mix Asphalt (WMA) is preferable to Hot Mix Asphalt (HMA) when it comes to constructing roads, this study conducts an in-depth analysis to weigh the two materials against one another. All of the benefits WMA offers are considered, from its performance to its environmental effect to its economic viability.

3. Objectives

The paper's primary goals are outlined below:

3.1. Constituent and Manufacturing Process of Warm Mix Asphalt

The main goal is to learn everything possible about the raw ingredients and production procedures for making Warm Mix Asphalt. The purpose of this subsection is to provide light on the specific ingredients and processes that give WMA its distinctive qualities.

3.2. Techniques for Producing Warm Mix Asphalt Blends at Lower Temperatures and Additional Additives

In order to accomplish this objective, we will investigate new processes that make it possible to produce Warm Mix Asphalt at lower temperatures. The research will examine how different additives might improve WMA's performance while decreasing petrol emissions and increasing sustainability.

3.3. Energy Usage and Financial Gains in Warm Mix Asphalt Production

The objective is to analyze the energy consumption patterns in Warm Mix Asphalt production and to evaluate the corresponding financial advantages. This section highlights the economic benefits associated with energy-efficient practices in WMA production.

3.4. Decrease in Gas Emissions through the Application of Various Additives

This core objective aims to delve specifically into the role of diverse additives in reducing gas emissions during Warm Mix Asphalt production. By examining the impact of additives, the study aims to provide insights into their effectiveness in achieving environmental sustainability within the context of WMA.

4. Literature Review

WMA technology is employed to lower the production and placement temperatures of asphalt mixtures [1]. This technology involves incorporating substances like zeolites, waxes, asphalt emulsions, or even water into the asphalt binder before mixing. The typical production temperature for WMA ranges from 100 to 140 ºC [2]. In addition to promoting sustainable development, WMA offers advantages in terms of enhancing field compaction, supporting longer haul distances, enabling pavement in cool weather, and fostering a more environmentally friendly setting by reducing fuel consumption and emissions. Furthermore, WMA demonstrates its effectiveness by minimizing issues like thermal cracking, block cracking, and oxidative hardening [3]. The enhanced viscosity of the asphalt binder due to WMA leads to improved aggregate coating [4]. Cecabase emerges as a common additive for WMA applications. This liquid chemical additive holds significance with a recommended dosage of 0.2-0.5% for all binder types. Introducing a cecabase does not alter the bitumen grade and requires no curing time. It can be introduced to the binder either at the mixing plant or the asphalt terminal, and it remains stable when stored for at least one week at 160 ºC. This additive contributes to better workability of bituminous mixtures, enabling their production and paving at lower temperatures compared to standard HMA. Importantly, these benefits are attainable without necessitating any process modifications or compromising mechanical properties [5,6].

5. Constituent and Manufacturing Process of Asphalt Blend

WMA and HMA share identical components. WMA boasts a user-friendly application and can be produced using existing HMA plants without significant adjustments. However, HMA production accounts for a larger share of CO2 emissions throughout both the building phase [7] and the rebuilding phase [8]. The sole distinction between WMA and HMA lies in production temperature [9]. HMA necessitates a high temperature spanning 150 to 180^{O}C, whereas WMA is processed within a lower temperature range of 110 to 140^{O} C [10]. Table 1 outlines the merits and demerits of HMA and WMA [10, 11].

6. Techniques for Producing Asphalt Blends at Lower Temperatures and Additional Additives

It has been shown in the literature [12] that the blending and compaction temperatures of WMA might be diminished by the utilization of natural increments, synthetic added substances, and water-frothing techniques.

Table 1. Illustrates the strengths and weaknesses of asphalt blends

S.No.	Blend Category	Manufacturing Temperature	Pros	Cons
1	Warm Mix Asphalt	110º-140º C	• Reduced manufacturing temperature • Minimal Emissions • Enhanced Energy Efficiency • Improved Working Environment • Extended Transportation Range • Negligible Plant Wear and Tear • Reduced Binder Aging	• Limited Blend Effectiveness • Increased Initial Expenses Due to Additive Utilization • Inadequate Aggregate Coverage and Adhesion
2	Hot Mix Asphalt	150º -180º C	• Enhanced Blend Performance • Reduced Initial Expenses	• Elevated Manufacturing Temperature • Substantial Emissions • More Energy Usage

Table 2. Outlines Warm Mix Technologies and Supplementary Additives.

S.No.	Additives	By-Product	WMA Operation	Firm	Amount	Temperature Reduction
1	Organics	Sasobit	FT Wax	Sasol	1% -2.5% by asphalt binder Weight	20º-30º C
2	Chemical	Evotherm	Emulsion	Meadwestvaco	0.5% - 0.7% by asphalt binder Weight	20º-45º C
3	Foaming Technique	Advera	Water Containing	PQ Coperation	0.25% by mixture weight	10º-30º C

Deficient total drying, inadequate bitumen covering, and expanded aversion to dampness owing to water present are only some of the performance difficulties that may arise if lower temperatures are used for mix manufacture and paving. However, experts have undertaken substantial studies into these difficulties and proposed remedies. [13].

When the temperature of the asphalt binder rises over the melting points of the organic additives used in it, such as waxes or fatty amides, the binder becomes less viscous. Ideally, the melting point of these additives would be greater than the asphalt mixture's maximum service temperature, but that is not a requirement. This characteristic enhances the asphalt's resistance to rutting at elevated temperatures and diminishes its susceptibility to becoming brittle in colder conditions [1]. Chemical additives, on the other hand, are fluid surfactants that work at a tiny connection point, leaving the thickness of the black-top cover unaltered. As surface modifiers, they further develop wetting characteristics by decreasing strain between black-top covers and particles, reducing internal friction [14, 15]. Adding modest quantities of water to hot asphalt binders is how foaming methods operate to reduce the binder's viscosity. Improved aggregate coverage is achieved when the water evaporates, causing the binder to expand and lower viscosity. Binder temperature and water content are two of several variables that affect how much space is created [16].

7. Energy Usage and Financial Gains

There is an immediate need to decrease energy consumption to mitigate climate change's impacts. Equally important is reducing raw material usage to minimize waste generation [17]. The black-top asphalt industry antagonistically affects the climate due to its high energy consumption. Asphalt pavement construction uses many materials, equipment, and technology that may harm the environment due to their waste creation, wastewater discharge, and emission levels. Gillespie [18] used a relapse examination to decide the estimated measure of energy expected to produce black-top blends. Based on the data, we know that this procedure uses around 9 litres of fuel and 8 kilowatt-hours of power per tonne, releasing 28.8 kilogrammes of CO2 into the atmosphere.

The reduced energy consumption during Warm Mix Asphalt (WMA) production holds significant economic advantages within pavement construction. Kristjánsdóttir et al. [19] state that places where petrol is expensive may profit greatly from WMA. The decrease in production temperature directly correlates with the decrease in energy consumption [20]. By comparing WMA and Hot Mix Asphalt (HMA) with varying temperature reduction ranges, it was found that warm technology could lead to energy savings of 20% to 75% [1, 21-22]. This variation in energy savings is attributable to studies' varied use of WMA technology; some combined WMA with other approaches, including Recycled Asphalt Pavement (RAP) technology. The decrease in energy usage is influenced by the kind of fuel and energy source [12]. Energy requirements for asphalt manufacturing vary from one place to another [18]. The decreased energy requirements for WMA production compared to HMA production result in a savings of 12-14% in fuel and a savings of $1.61 per tonne of mixture on average in the state of Louisiana, USA [22].

Using RAP has several benefits, including lowering the price of repairs and rehabilitation and lowering negative environmental effects [23]. It also becomes possible to drastically reduce the quantity of asphalt binder needed while constructing roads. When used in hot-mix asphalt (HMA), RAP may reduce construction costs by as much as 79.7 percent when compared to combinations without RAP [24]. All endpoint influences in WMA, including environmental change, petroleum product exhaustion, and all-out total energy utilization, are decreased by 13-14% when 15% RAP is implemented [25]. An additional benefit is a decrease in expenditures of 25% compared to HMA [26], thanks to the use of 30% RAP and 0.3% natural zeolite. Energy requirements for manufacturing HMA and WMA might vary by 8.6-18.4%, as shown out by Almeida-Costa and Benta [27]. Oner and Sengoz [28] conducted a cost-benefit investigation of hot-blend black-top (HMA) and warm-blend black-top (WMA) with 10%, 20%, and 30% RAP by weight of the complete blend and various warm additives. Results showed that regardless of distance from the plant to the building site, employing 30% RAP with organic additions was the most cost-effective alternative.

Table 3. Decrease in gas emissions through the application of various additives

S.No.	Additives	Percentage Reduction in	Reference
1	Evotherm	CO_2=60%, SO_2=75.2% and NO_X=72.6	[38]
2	Evotherm	CO_2=17.35%, SO_2=17.24%, NO_X=20 and CO=19.51%	[39]
3	Evotherm	CO_2=46%, SO_2=41%, NO_X=58 and CO=63%	[40]
4	Sasobit	SO_2=83.3%, NO_X=21.2%, CO=63.2% and VOC=51.3%	[41]
5	Aspha-min	SO_2=83.3%, NO_X=30.8%, CO=62% and VOC=62.8%	[41]
6	Rediset	CO_2=31.7%	[42]
7	Foaming	CO_2=58.5%, SO_2=99.9%, NO_X=66.7% and CO=91.9%	[43]

At a production temperature of 120°C, incorporating Ca(OH)2-infused zeolite led to energy savings of 24,831 gigajoules annually for 140,000 tons on account of Warm Blend Black-top (WMA) [29]. The warming and drying processes during the assembling of Hot Blend Black-top (HMA) and WMA were concentrated inside and out by Romier et al. [30]. The intensity balance for HMA is 175 MJ, while it is 83 MJ for WMA, addressing a half decline in warming energy per ton of WMA. Fuel use for making WMA and HMA blends was examined by Oliveira, Silva, Fonseca, Kim, Hwang, Pyun, and Lee [31]to determine how efficient the plants were. Fuel usage drops from 9.3 litres per tonne for HMA manufacturing to 6.3 litres for WMA production—a difference of 32%.

Fuel usage for HMA production is between 6.2 and 7.2 kg per tonne, whereas fuel consumption for WMA production is between 5 and 6 kg per tonne, as reported by Jain and Singh [11]. Hettiarachchi et al. [32] showed that by lowering the manufacturing temperature of the black-top combination by 20 °C, energy utilization might be cut by 25%. Similarly, Prowell, Hurley, and Forthcoming [33] proposed that fuel utilization in WMA creation could be brought down by 30-35%, assessing that a 6°C temperature reduction could result in a 3% fuel usage reduction. Moreover, theoretical calculations indicate that a 28°C temperature drop could yield an 11% reduction in petroleum fuel consumption [34]. Hassan [35] claims that, contrasted with HMA, WMA utilizes 18% less petroleum products. Be that as it may, the assembling cost of WMA is inflated by the price of warm mix additives. WMA might add $2.50 to $4.00 per tonne to the price of asphalt mixes, as suggested by [36].

Initial cost comparisons between HMA and WMA were made, considering the material, mixing, and shipping costs associated with organic, chemical, and foamy WMA additives. The findings indicated that the use of organic and foamy additions might result in marginal cost savings compared to HMA, whereas the use of chemical additives could result in marginal cost increases. Furthermore, the study indicated that incorporating Recycled Asphalt Pavement (RAP) could significantly lower WMA production costs than HMA [32]. Also, the monetary benefits coming from energy investment funds could offset the expenses of WMA-added substances and hardware establishment [13]. Bueche and Dumont's analysis of seven plants [37] revealed an average energy consumption of 356 MJ per ton for HMA creation and 226 MJ per ton for WMA. The diminished temperature in WMA creation could likewise achieve extra expense reserve funds, given the decreased mileage on the black-top plant [28].

8. Conclusion

The amount of energy used and the emissions generated during the manufacturing of asphalt mixes depend on a number of factors. These include the aggregate type, aggregate heat capacity, aggregate moisture content, fuel type, fuel consumption, and production temperature. Depending on the asphalt mixture, the Warm Mix Asphalt (WMA) manufacturing temperature is generally lower by 10 to 40 degrees Celsius than that of standard Hot Mix Asphalt (HMA). This reduction in temperature yields positive impacts on multiple fronts, including decreased fuel consumption and lowered CO2 emissions. Furthermore, adopting WMA contributes to environmental advantages by diminishing gas and fume emissions, consequently mitigating the effects of global warming.

When assessing the Life Cycle Assessment (LCA) of WMA in comparison to HMA in terms of environmental aspects, WMA demonstrates a tendency to be more environmentally favorable.

Since WMA requires 20-70% less energy usage, the economic benefit of warm technology comes in the decreased cost load. The decreased production temperature might lead to greater cost savings due to the decreased strain on the factory. An additional benefit of low viscosity is that it makes it possible to employ higher percentages of recycled asphalt pavement (RAP), reducing the required operating temperature of the paving process and saving money while protecting the environment.

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