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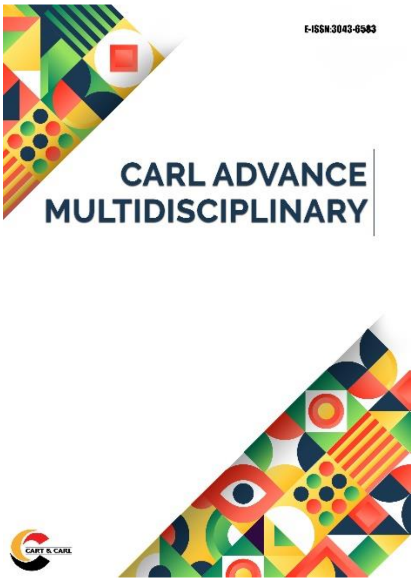

Box Behnken Design in Optimizing the Sustainability of Sasobit-Based Warm Mix Asphalt Concrete

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Abstract

This study evaluates the sustainability of Sasobit-based warm mix asphalt concrete (WMA) in comparison to traditional hot mix asphalt (HMA). A comprehensive sustainability assessment was conducted using life cycle assessment (LCA) and life cycle cost analysis (LCCA). The results show that Sasobit-based WMA reduces greenhouse gas emissions, energy consumption, and environmental impacts compared to HMA. Additionally, the LCCA reveals that Sasobit-based WMA has a lower life cycle cost than HMA. The findings of this study suggest that Sasobit-based WMA is a more sustainable option for pavement construction and rehabilitation. The results of this study can inform pavement design and construction practices, promoting the adoption of more sustainable asphalt technologies.

Keywords : Sustainability Evaluation, Sasobit, Greenhouse Gas Emissions, Box-Behnken Design, Warm Mix Asphalt Concrete

Introduction

The increasing global demand for infrastructure development, particularly in the transportation sector, has led to a significant rise in the production and use of asphalt concrete. However, the traditional hot mix asphalt (HMA) production process is energy-intensive and generates substantial greenhouse gas (GHG) emissions, contributing to climate change and environmental degradation. In recent years, warm mix asphalt (WMA) technology has emerged as a sustainable alternative to traditional HMA. WMA production involves reducing the mixing and compaction temperatures, resulting in lower energy consumption and GHG emissions. Warm Mix Asphalt Concrete (WMAC) is a notable advancement in green technology within highway engineering. It offers a sustainable alternative to conventional Hot Mix Asphalt (HMA) by significantly lowering production temperatures and energy usage. Produced at temperatures 20–40°C below those of HMAC, WMAC reduces greenhouse gas emissions and fuel consumption while maintaining comparable performance and durability (Rubio et al., 2013).

A key environmental advantage of WMAC is its ability to reduce emissions during asphalt mixing and paving. This benefit is particularly critical in urban areas, where air quality is a concern. Research indicates that WMAC can substantially decrease emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) compared to HMA (Airey et al., 2016). Additionally, the lower production temperature lead toto energy savings and resource conservation, which also translate into cost reductions.

WMAC also supports sustainable development by enhancing worker safety and health. The reduced temperatures during its production and application lower exposure to harmful fumes and extreme heat, creating a safer work environment for construction teams (Zaumanis et al., 2014). This makes WMAC both an environmentally friendly and socially responsible choice.

Technically, WMAC uses various innovations, such as chemical additives, organic waxes, and water-based foaming systems, to reduce the viscosity of asphalt binders. These methods ensure that the material retains adequate workability and compaction at lower temperatures without compromising pavement performance over time (Goh et al., 2011). Globally, WMAC has been embraced as part of the shift toward more sustainable construction methods. Countries like Germany, the United States, and Japan have incorporated WMAC into their road construction practices, demonstrating its capacity to address both environmental and infrastructure needs. However, challenges such as higher initial costs and limited technical expertise, particularly in developing countries, continue to hinder its wider adoption (Mogawer et al., 2012). Asphalt concrete pavement consists of coarse aggregates, fine aggregates, and asphalt cement, a petroleum-derived binder. Aggregates, which serve as the primary load-bearing elements, typically constitute 90-95% of the mixture's weight, with the remaining portion attributed to asphalt cement.

The classification of asphalt pavement as either hot mix asphalt concrete (HMAC) or warm mix asphalt concrete (WMAC) depends on the manufacturing process and the temperatures applied during production. (Asphalt Institute, 2019). Hot mix asphalt concrete (HMAC) refers to asphalt mixtures prepared at temperatures ranging from 150°C to 180°C (Behl et al., 2013). The HMAC industry continuously strives to innovate technologies aimed at improving pavement durability, optimizing construction processes, conserving resources, enhancing material properties, and addressing environmental concerns (Newcomb, 2017). However, HMAC production significantly impacts fuel consumption due to the heating requirements for aggregates and binders, while also contributing to the release of harmful air pollutants. Warm mix asphalt concrete (WMAC) encompasses a range of technologies and products designed to reduce the mixing and compaction temperatures of hot mix asphalt concrete (HMAC) during production, while ensuring or improving its workability. WMAC achieves this by lowering the binder's viscosity, reducing the surface tension at the asphalt-aggregate interface, or enhancing the mix's workability at lower temperatures. Temperature regulation of aggregates, binder, and the mix is a critical challenge in HMAC production.

To address this, asphalt industries have developed WMA technologies, whichnot only lower mixing and compaction temperatures but also reduce energy consumption and minimize environmental pollution. As noted by Abdullah et al. (2014), WMAC technologies are categorized into three primary types: foaming asphalt methods, the use of organic additives, and the application of chemical additives.

Foamed asphalt is one of the technologies used in the production of warm mix asphalt (WMA), utilizing water as a foaming agent. When water is exposed to high temperatures, it vaporizes, creating numerous tiny bubbles in the asphalt and causing it to foam. Another WMA approach involves organic additives, commonly referred to as waxes or "asphalt flow improvers," which lower the viscosity of asphalt at specific temperatures, enabling mixing and placement at reduced temperatures. Chemical additive technologies for WMAC combine emulsifiers, surfactants, polymers, and other additives to enhance coating, workability, and compaction of the mixture. Despite its advantages, including lower energy consumption, reduced pollution during production and paving, improved working conditions, and greater potential for using recycled materials, WMAC carries a higher risk of water damage. To mitigate this, anti-stripping agents are often introduced (Jamshidi et al., 2013). Sasobit, a synthetic wax, is a commonly used additive in WMA production. It helps to reduce the viscosity of the asphalt binder, allowing for lower mixing temperatures and improved workability. Despite its benefits, the sustainability of Sasobit-based WMA has not been comprehensively evaluated.

This study aims to evaluate the sustainability of Sasobit-based WMA in comparison to traditional HMA. A comprehensive sustainability assessment will be conducted using life cycle assessment (LCA) and life cycle cost analysis (LCCA). LCA will be used to evaluate the environmental impacts of Sasobit-based WMA, including GHG emissions, energy consumption, and resource depletion. LCCA will be used to evaluate the economic feasibility of Sasobit-based WMA, including its production costs, maintenance costs, and life cycle costs. The findings of this study will provide valuable insights into the sustainability of Sasobit-based WMA and inform pavement design and construction practices.

Material and Methods

This experimental research evaluates the production and sustainability of foamed, organic, and chemical-based warm mix asphalt concrete (WMAC) technologies compared to traditional hot mix asphalt concrete (HMAC). Sasobit were used as WMAC agents for foamed, organic, and chemical-based WMACs, respectively, while hydrated lime (HL) served as an anti-stripping agent. The study used granite (12.5 mm maximum size), fine sand, and asphalt cement, optimizing aggregate blends via linear programming and determining the optimum bitumen content (OBC) through the Marshall mix design for medium traffic. WMAC formulations partially substituted OBC with WMAC agents and HL, while experimental designs based on the Box-Behnken method varied factors like bitumen content, WMAC additives, HL, and production temperature, keeping the aggregate blend constant. Performance was assessed through moisture susceptibility, carbon monoxide emissions, and production costs. Optimization employed second-order response surface models calibrated using least squares, with analysis through mean effects plots, interaction plots and Pareto charts. Multi-objective optimization using response surface methodology with desirability functions (RSMdf) was also conducted, presenting a comprehensive framework to achieve sustainability and performance objectives.

Materials

All the materials utilized in this thesis were obtained from the surroundings of Port Harcourt City. Prior to their use in experimental investigations, these materials were processed following established standards.

Aggregates

a. Granite

The experimental setup involved using granite with a maximum size of 12.5mm as the coarse aggregate. This granite was obtained from a local building material shop in Ozuoba, Port Harcourt, with Akamkpa quarry site in Calabar, being the primary source, based on the information from the supplier. The granite was prepared according to the following procedures;

i. The acquired granite underwent a washing process to eliminate dirt and undesired particles.
ii. Subsequently, the washed granite was left to air dry in sunlight for a period of 48 hours.

b. Fine sand

For experimental purposes in this study, fine river sand was utilized as the fine aggregate. This sand was obtained from a local building material shop in Ozuoba, Port Harcourt, with Choba River being the primary source. The obtained fine river sand underwent the following preparation procedures.

i. The fine sand was left to air dry under sunlight for a duration of 48 hours to ensure complete removal of any moisture content.
ii. The fine river sand underwent filtration using a 4.75mm sieve to eliminate any dirt or organic materials present.
iii. Next, the sieved sand underwent sieve analysis following the ASTM (2006) standards and was classified accordingly.

c. Asphalt cement

Bitumen of penetration grade 60/70 was sourced from Mile 3 in Port Harcourt. Other properties of this bitumen are outlined in Table 1.

Table 1: Asphalt Cement (Bitumen) properties

Property	Value
Specific gravity	1.09
Softening point	53 °C
Penetration	68
Flash point	250 °C

Warm Mix Asphalt Concrete (WMAC) Agents

a. Sasobit

In this study, Sasobit, also known as Fisher-Tropsch processed paraffin wax, was obtained from a chemical laboratory in Mile 3 market, Port Harcourt. The acquired Sasobit was securely stored prior to the start of the experiment. Sasobit was used in the production of the organic substance-based WMAC.

b. Hydrated lime

Solid anti-strip in the form of hydrated lime, packaged in 25 kg bags, was utilized in this research. The hydrated lime was obtained from Davidson hydrated lime at Old Aba road, Port Harcourt. The oxide composition of lime, as outlined in Table 2, was sourced from literature. Nnochiri et al. (2018) detailed the chemical or oxide composition of hydrated lime in their study. According to Table 2, the hydrated lime met the minimum requirement for a cementitious material in terms of loss on ignition, as per ASTMC618 (2008), which specifies a maximum value of 10%. The lime possessed a high calcium oxide content, thereby fulfilling the requirement for a cementitious material.

Table 2: Oxide composition of Hydrated Lime

S/No.	Property (Oxide)	**Hydrated lime**
1	Calcium Oxide (CaO)	68.12
2	Aluminum Oxide (Al_2O_3)	0.72
3	Iron Oxide (Fe_2O_3)	0.05
4	Silicon Oxide (SiO_2)	1.71
5	Loss on Ignition (LOI)	3.21
	(Al_2O_3+ SiO_2+ Fe_2O_3)	78.67

Nnochiri et al. (2018)

Experimental Equipment/Apparatus

The major apparatus or equipment used in thesis for experimental applications are hereby outlined;

i. Mould assembly comprises a 4.5 kg rammer dropping from a height of 450 mm, an asphalt mould measuring 63.5mm by 100mm, a mould collar, and a compaction table.
ii. Precision weighing scales with capacities of 40 kg and 5 kg are used for accurate mass measurements.

iii Sets of sieves organized in accordance with IS: 383-(1970) standards were employed in this study for aggregate gradation purposes.
iv. Muffle furnace (Heating capacity of 1375°C); for preheating of moulds, aggregates, bitumen and other apparatus.
v. Universal Strength Testing Machine; for Marshall stability and flow testing, and indirect tensile strength testing.
vi. GHGs' measuring device

Methods:

1. BBD Design of Experiment for SOWMAC

In developing the design of experiment for the SOWMAC, the OAAC (5.95 %) as obtained from the preliminary investigation was varied to accommodate the sasobit and the anti-stripping agent, hydrated lime (HL). The aggregates (sand and granite) contents were kept constant throughout the duration of the experiment at percentages of 51.26 % for granite and 42.79 % for sand respectively. The sasobit content was limited to 0-4 % by weight of the asphalt cement content, and hydrated lime was kept within the range of 0-10 % by weight of the asphalt cement content, thereby, limiting the actual asphalt cement content to the range of 5.35 – 5.95 %. This proportioning translates sasobit content to be in the range of 0 – 0.238 % by weight of the WMAC mix and the HL to the range of 0 – 0.6 % by weight of the WMAC mix. Production temperature of WMAC as deduced in the literatures lies within 120°C to 140°C. From the conditions or constraints specified in selection of factors, the lower and upper bound of the different factors are thereby laid out in Table 3. The Minitab software generated 27 different combinations of asphalt cement, sasobit, hydrated lime and production temperature. This is as shown in Table 4.

Table 3. Boundary conditions for BBD design development (SOWMAC)

Constraints	**Factors**			
	AC (%)	**S_a (%)**	**HL (%)**	**P_T (°C)**
Lower bound	5.350	0	0	120
Upper bound	5.950	0.238	0.60	140

AC= Asphalt Cement, S_a = Sasobit, HL= Hydrated Lime, P_T = Production Temp

Performance Measurement

Carbon monoxide (CO) measurement

During production of optimized HMAC and WMACs in an enclosed muffle furnace, CO emitted were measured using a highly sensitive equipment when WMACs. The CO observed from the measuring device was collected after twenty (20) minutes of mixing or until the reading was constant.

Table 4:BBD mixture design for SOWMAC Production

Run Order	**AC (%)**	**Sa (%)**	**HL (%)**	**P_T (°C)**
1	5.95	0.119	0.3	140
2	5.65	0.119	0.3	130
3	5.65	0.238	0.6	130
4	5.65	0	0	130
5	5.65	0.238	0	130
6	5.65	0.119	0	140
7	5.35	0.119	0	130
8	5.95	0	0.3	130
9	5.95	0.119	0.6	130
10	5.95	0.119	0	130
11	5.35	0.119	0.6	130
12	5.95	0.119	0.3	120
13	5.65	0.119	0.3	130
14	5.65	0.119	0.6	140
15	5.65	0.238	0.3	140
16	5.35	0	0.3	130
17	5.35	0.119	0.3	140
18	5.35	0.119	0.3	120
19	5.65	0.238	0.3	120
20	5.65	0.119	0.6	120
21	5.65	0	0.3	120
22	5.65	0	0.6	130
23	5.65	0.119	0.3	130
24	5.95	0.238	0.3	130
25	5.35	0.238	0.3	130
26	5.65	0.119	0	120
27	5.65	0	0.3	140

Tensile strength ratio (TSR) of WMAC samples

The moisture susceptibility of prepared samples was determined through measurement of tensile strength ratio (TSR). Tensile strength ratio is evaluated by comparing the tensile strength of conditioned samples to unconditioned samples (Equation 1).

$$TSR = \frac{\sigma_{Tw}}{\sigma_{Td}} X\ 100$$

Where; TSR = Tensile strength ratio, σ_{Tw} = Tensile strength of conditioned specimen, σ_{Td}= Tensile strength of unconditioned specimen
The tensile strength of WMACs was measured using the splitting cylinder technique according to ASTM D6931. The indirect tensile strength was evaluated mathematically using Equation 2.

$$\sigma = 2P/\pi Dt$$

Where; P is equivalent to the failure load, D is the diameter or width of the asphalt concrete specimen and t represent the thickness of the asphalt concrete specimen.

Cost Analysis of WMACs'

Table 4 presents the current prices of WMAC constituents used in this study. These prices were used to estimate the cost of actualizing the different WMAC technologies in naira per cubic metre, also involving the cost implication of energy usage.

For the energy consumption cost analysis which related production temperature to energy consumption was very handy. According to ELGAS (2019), a kilogram of LPG would produce energy content at the rate of N0.00684 per kcal. Therefore, a tonne of LPG would produce energy content at the rate of N6.84 per kcal. This information in combination with the amount of fuel or energy consumption encountered in the production of the asphalt concretes (optimized HMAC and the WMACs). Total production cost was then obtained as the addition of cost of constituents' materials and amount of energy consumed in the production of asphalt concretes.

Table 4: Prices of WMAC components

S/N	Item	Market procurement pattern	Unit cost (₦ per kg)
1	River sand	₦ 2,000 for 50 kg	40.00
2	Granite	₦ 3,000 for 50 kg	60.00
3	Asphalt cement	₦ 55,000 for 25 kg	2200.00
4	Hydrated lime	₦ 50,000 for 25 kg	2000.00
5	Sasobit	₦ 20,000 for 10 kg	2000.00

Optimization Models Development

The BBD processes the experiment results and yields a response model in the form of Equation 3.

$$Y = \beta_0 + \sum_{i=1}^{n}(\beta_i z_i) + \sum_{i=1}^{n}(\beta_{ii} z_i^2) + \sum_{i=1}^{n}\sum_{j=1}^{n}(\beta_{ij} z_i z_j) + e$$

Where,

β_0 is a constant, β_i is a linear coefficient, β_{ii} is the quadratic coefficient and β_{ij} is the interaction coefficient and e is the error term. From the obtained mathematical form, we can scope variables (i.e, combinations of factors) where optimal performance is obtained.

For a four-factor design, Equation 4 according to the RSM, becomes;

$$Y = \beta_0 + \beta_1 z_1 + \beta_2 z_2 + \beta_3 z_3 + \beta_4 z_4 + \beta_{11} z_1^2 + \beta_{22} z_2^2 + \beta_{33} z_3^2 + \beta_{44} z_4^2 + \beta_{12} z_1 z_2 + \beta_{13} z_1 z_3 + \beta_{14} z_1 z_4 + \beta_{23} z_2 z_3 + \beta_{24} z_2 z_4 + \beta_{34} z_3 z_4$$

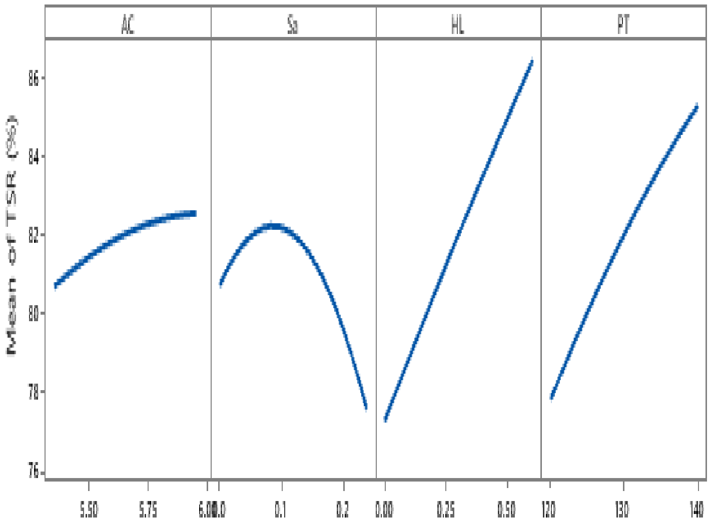
Results and Discussion

Parametric and Sensitivity Analysis of Factors on Tensile Strength Ratio (TSR) of SOWMAC

The response surface effects plots of factors on the tensile strength ratio (TSR) of SOWMAC (Figure 1). It can be observed from that increase in the asphalt cement content results to increase in TSR of SOWMAC. Specifically, TSR increased from 80.7% at an asphalt cement content of 5.35% to a TSR of 83% at an asphalt cement content of 5.95%. Increase in sasobit content from 0-0.119%, results to an increase in TSR from 80.7% to 83%. Beyond 0.119% sasobit content, TSR decreases with further addition. Specifically, TSR reduced significantly to 78% as the sasobit content is increased to 0.238%.

Hydrated lime has the most significant impact on the TSR of SOWMAC. TSR increased almost linearly with increase in hydrated lime. Specifically, TSR increased from 78% at 0% hydrated lime content to about 87% at hydrated lime content of 0.60%. It can also be observed that the TSR of SOWMAC has a positive correlation with production temperature. TSR increased as the production temperature increases but not as sharp as that due to the hydrated lime increment. TSR increased from 78% at production temperature of 120°C to a significant value of 86% at a production temperature of 140°C.

From the response surface interaction plots, it can be observed that the interaction between asphalt cement and sasobit have the greatest impact on the TSR. This is so because the curves were the least parallel compared to the curves of other interactions. The production temperature interaction with asphalt cement proved to have the second most impact on the TSR as the curves are second least parallel. Interactions such as, hydrated lime-production temperature, asphalt cement-hydrated lime, sasobit-production temperature and sasobit-hydrated lime ranked 3rd, 4th, 5th and 6th in that order. In a quest to rank the effect of all model parameters on the TSR of SOWMAC, Pareto chat as presented in Figure 2 was adopted. From the Pareto chart, it can be observed clearly that hydrated lime with a standardize effect (bar value) of 4.285 is ranked 1st as having the most significant impact on the TSR of SOWMAC. Production temperature with a bar value of 3.490 is ranked 2nd. The square interaction of sasobit is ranked 3rd with a bar value of 1.790 with the linear sasobit effect ranking 4th with a bar value of 1.465. Two-way interactions, asphalt cement- sasobit, asphalt cement-production temperature and hydrated lime-production temperature with bar values of 1.122, 1.049 and 0.994 ranked 5th, 6th and 7th respectively. The linear effect of asphalt cement ranked last of all the linear effects with a bar value of 0.873 and consequently ranked 8th of all the model parameters. For the two-way interaction effects, asphalt



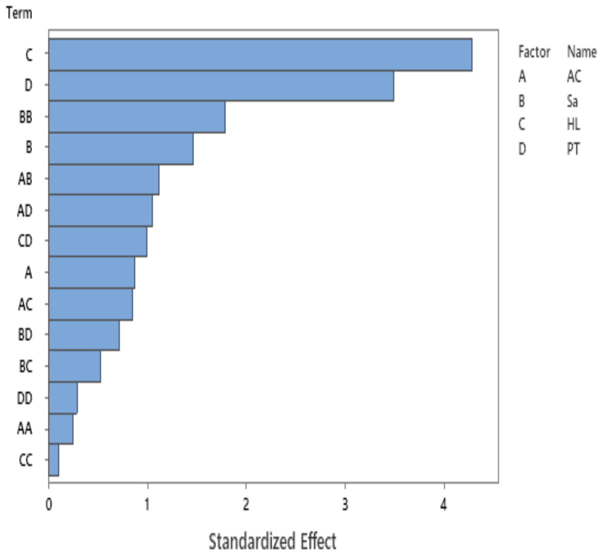


Figure 1: Response Surface Effects Plots of Factors on TSR of SOWMAC

Figure 2: Pareto Effect Charts of Factors on TSR of SOWMAC

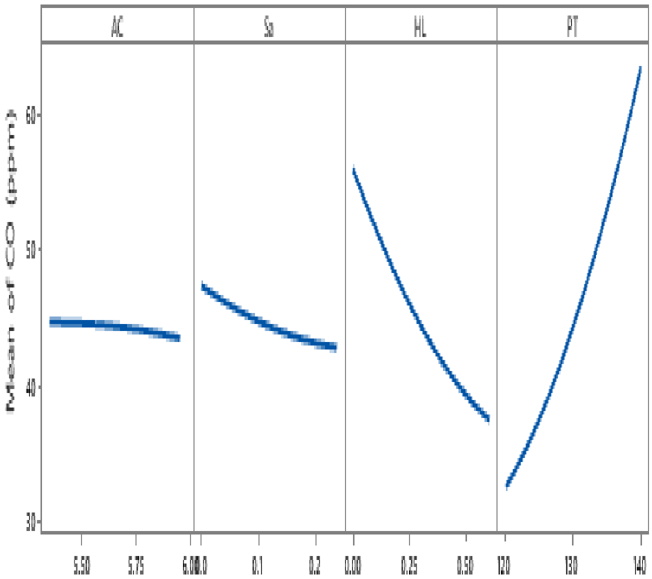
AC = Asphalt cement; Sa= Sasobit; HL = Hydrated lime; PT= Production temperature

Parametric and Sensitivity Analysis of Factors on CO Emissions from SOWMAC

The response surface effects plots of factors on the CO emissions from SOWMAC (Figure 3). It can be observed from that increase in the asphalt cement content results in little or no change in CO emitted from SOWMAC. Specifically, emitted CO insignificantly reduced from 45 ppm at an asphalt cement content of 5.35% to 44.5 ppm at an asphalt cement content of 5.95%. Increase in sasobit content slightly reduces the amount of CO emitted from SOWMAC. Emitted CO in ppm reduces from 49 ppm at sasobit content of 0% to 44 ppm at a sasobit content of 0.238%. This accounts for a reduction of emitted CO of about 10.20%.

Hydrated lime has negative impact on the emitted CO from SOWMAC. That is, increase in hydrated lime content subsequently leads to significant reduction on the CO emitted from SOWMAC. Specifically, emitted CO reduced drastically from 58 ppm at 0% hydrated lime content to about 40 ppm at hydrated lime content of 0.60%. This accounts for a reduction in emitted CO of about 31.03%. It can also be observed that the amount of CO emitted from SOWMAC has a strong correlation with production temperature. Emitted CO significantly increased as the production temperature increases. Emitted CO increased from 32ppm at production temperature of 120°C to a significant value of 63ppm at a production temperature of 140°C. This accounts for an increment in emitted CO of about 96.88%. From the response surface interaction plots, it can be observed that the interaction between hydrated lime and production temperature have the greatest impact on the amount of CO emitted from SOWMAC. Asphalt cement-sasobit and sasobit-hydrated lime interactions have similar effects on the emitted CO, as their curves have relatively same parallelism behavior. The production temperature interaction with sasobit proved to have the 4th most significant impact on the emitted CO. Interactions such as, asphalt cement-hydrated lime and asphalt cement-production temperature ranked 5th and 6th respectively.

In a quest to rank the effect of all model parameters on the emitted CO of SOWMAC, Pareto chart as presented in Figure 4 was adopted. From the Pareto chart, it can be observed clearly that production temperature has an overwhelming effect on the emitted CO with a standardize effect (bar value) of 12.069 and subsequently ranking 1st. Hydrated lime with a bar value of 7.215 is ranked 2nd. The square interaction of production temperature is ranked 3rd with a bar value of 1.880 with the linear sasobit effect ranking 4th with a bar value of 1.771. The two-way interaction effect of hydrated lime and production temperature with a bar value of 1.250 is ranked first of the two-way interactions but 5th overall. Next, is the square interaction of hydrated lime with a bar value of 1.224. In this analysis, the linear effect of asphalt cement also ranked last of all the linear effects with a bar value of 0.459 and consequently ranked 9th of all the model parameters. For the two-way interaction effects, asphalt cement-sasobit and sasobit-hydrated lime interactions with bar values of 0.795 ranked 2nd with an overall ranking of 7th. Sasobit-production temperature interaction with a bar value of 0.341 is ranked 4th in terms of the two-way interactions and 11th overall. Two-way interactions of asphalt cement-production temperature and asphalt cement -hydrated



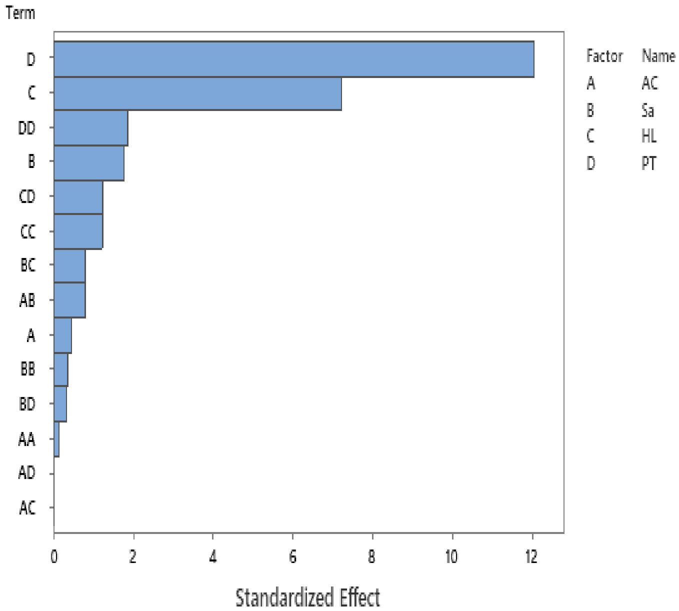


Figure 3: Response Surface Effects Plots of Factors on CO Emissions from SOWMAC

Figure 4: Pareto Effects of Factors on CO Emissions from SOWMA

AC = Asphalt cement; Sa= Sasobit; HL = Hydrated lime; PT= Production temperature

lime also recorded the least impact on the amount of CO emitted during production of SOWMAC.

The parametric analysis revealed that at first, increasing the asphalt cement content improves TSR of SOWMAC, as it helps create a better bond between the asphalt and the aggregate, making the mix more resistant to water and stronger overall (Wu et al., 2020; Jiang et al., 2021). However, adding too much asphalt cement can have the opposite effect. When the binder content exceeds the optimal level, it forms a slippery layer that reduces the friction between aggregates, weakening the structure of the mix (Moghadas Nejad et al., 2019). Additionally, the extra binder can make the asphalt more prone to stripping, where the bond between asphalt and aggregate breaks down in the presence of moisture, reducing the pavement's durability (Liu et al., 2017).

The impact of sasobit content on the tensile strength ratio (TSR) of SOWMAC shows how crucial it is to strike the right balance for optimal performance. At first, as sasobit content increased, TSR improved slightly. This is because sasobit helps the asphalt binder foam more effectively, which improves the coating on the aggregates and strengthens the bond between the binder and the aggregate particles (Jiang et al., 2021). Sasobit also reduces the binder's viscosity, making it easier to spread evenly over the aggregates. This improved distribution boosts moisture resistance and enhances TSR (Wu et al., 2020a). However, when sasobit content exceeded the optimal level, TSR dropped significantly. Too much sasobit can cause excessive foaming, leading to uneven aggregate coating or the formation of voids in the asphalt mix. These voids allow moisture to penetrate, weakening the bond between the binder and aggregates and making the mix more prone to moisture damage (Kim et al., 2022a). Furthermore, excess sasobit can disrupt the binder's cohesive properties, undermining the overall strength and stability of the mixture (Liu et al., 2017). This pattern highlights the need to carefully optimize sasobit content to achieve the best possible TSR without compromising the durability or mechanical integrity of SOWMAC.

Hydrated lime has shown to positively influence the TSR of SOWMAC. The study revealed that TSR increased almost linearly as more hydrated lime was added. This improvement happens because hydrated lime works as an anti-stripping agent, strengthening the bond between the asphalt binder and aggregates. It also chemically alters the binder to make it more resistant to moisture damage, which enhances the mixture's durability (Hasan et al., 2020; Kim et al., 2022b). Additionally, hydrated lime helps by filling small voids in the mix, making it more compact and limiting the pathways through which moisture can seep in. These combined chemical and mechanical benefits result in a stronger, more moisture-resistant asphalt mixture, which explains the steady rise in TSR with increasing hydrated lime content (Wu et al., 2020b).

TSR of SOWMAC showed a clear positive relationship with production temperature. As the temperature rose, TSR improved gradually, although the increase is less dramatic compared to the effect of adding hydrated lime. This improvement is mainly due to the way higher temperatures reduce the viscosity of the asphalt binder, allowing it to coat the aggregates more effectively and enabling better compaction. These changes enhance the mix's resistance to moisture damage (Jiang et al., 2021b; Kim et al., 2022c). Higher production temperatures also help evaporate residual water from the foaming process, minimizing moisture entrapment in the asphalt matrix. This further strengthens the bond between the binder and aggregates, boosting TSR values (Wu et al., 2020c).

The interaction of various factors affecting TSR of SOWMAC provides key insights for optimizing its mix design. Among these, the combination of asphalt cement and sasobit had the most significant impact on TSR, as sasobit enhances binder workability by reducing viscosity, improving binder distribution, and asphalt cement ensures strong bonding, enhancing moisture resistance (Jiang et al., 2021; Kim et al., 2022d). The second most influential interaction is between production temperature and sasobit. Higher temperatures improve sasobit's foaming ability, which strengthens binder-aggregate adhesion and promotes better compaction, though excessive heating can degrade the binder properties (Wu et al., 2020; Hasan et al., 2020). Other interactions, though less impactful, also contribute. The interaction between hydrated lime and production temperature (ranked third) emphasizes how heat activates the benefits of lime as an anti-stripping agent. The interaction between asphalt cement and production temperature (fourth) and between asphalt cement and hydrated lime (fifth) highlights the importance of binder-chemical compatibility for moisture resistance. Lastly, the sasobit-hydrated lime interaction (sixth) shows how these two components work together to improve workability and moisture resistance, though their combined impact on TSR is less pronounced compared to the top interactions (Moghadas Nejad et al., 2019; Liu et al., 2017).

To rank the effects of various model parameters on TSR of SOWMAC, the analysis showed that hydrated lime had the greatest impact, followed by production temperature. Hydrated lime is ranked first due to its anti-stripping properties, which improve binder-aggregate adhesion and reduce moisture damage, thereby enhancing TSR (Hasan et al., 2020). Production temperature, ranked second, affects the viscosity and foaming properties of the asphalt binder, promoting better compaction and reducing moisture sensitivity (Wu et al., 2020; Jiang et al., 2021). The square interaction of sasobit is ranked third, as sasobit reduces binder viscosity and enhances binder-aggregate adhesion, improving TSR performance (Kim et al., 2022e). The linear effect of sasobit is ranked fourth, as sasobit boosts binder workability but shows diminishing returns beyond an optimal level (Wu et al., 2020). Square interactions between asphalt cement and production temperature are ranked fifth and sixth, respectively, emphasizing the importance of binder compatibility and temperature effects on TSR performance (Liu et al., 2017; Moghadas Nejad et al., 2019). For two-way interactions, the asphalt cement-sasobit interaction ranks first, highlighting the combined effects of binder workability and moisture resistance (Jiang et al., 2021). The sasobit-production temperature interaction ranks second, further demonstrating the influence of temperature and sasobit foaming on TSR (Wu et al., 2020; Hasan et al., 2020). The two-way interactions of asphalt cement-hydrated lime and sasobit-production temperature showed the least impact on TSR variation, indicating limited synergistic effects on TSR performance (Liu et al., 2017; Moghadas Nejad et al., 2019)

From the parametric analysis of factors affecting CO emissions from SOWMAC within the considered design space, it was observed that increasing asphalt cement content had little to no significant impact on CO emissions. Specifically, CO emissions decreased marginally as the asphalt cement content increased, though the reduction was minimal and not statistically significant (Wu et al., 2020; Kim et al., 2022c). This behavior can be attributed to the role of asphalt cement, which primarily affects the asphalt binder properties rather than directly influencing combustion or emissions. The small reduction in CO emissions might be linked to improved binder-aggregate adhesion and compaction, which could slightly reduce the release of volatile organic compounds during production (Hasan et al., 2020).

An increase in sasobit content was observed to reduce the amount of CO emissions from SOWMAC. Specifically, CO emissions in parts per million (ppm) decreased as sasobit content rose (Wu et al., 2020; Kim et al., 2022c). Sasobit acts as a foaming agent, lowering the viscosity of the asphalt binder and improving the binder's ability to coat aggregates, thereby enhancing the overall performance of the mixture (Jiang et al., 2021). This reduction in CO emissions is likely due to sasobit's role in reducing binder volatility and promoting more efficient combustion of the asphalt, leading to lower emissions (Hasan et al., 2020). Moreover, sasobit increases the workability of the asphalt, which improves compaction and reduces the release of volatile organic compounds (VOCs) like CO during production (Wu et al., 2020).

Hydrated lime has a negative impact on CO emissions from SOWMAC, as an increase in hydrated lime content results in a significant reduction in CO emissions (Hasan et al., 2020; Kim et al., 2022b). Hydrated lime acts as an anti-stripping agent, enhancing the adhesion between the asphalt binder and aggregate, which improves the mix's resistance to moisture damage (Liu et al., 2017). This improved bonding reduces the release of volatile organic compounds, including CO, during the production and application of the asphalt mixture (Wu et al., 2020). Furthermore, hydrated lime contributes to reducing the porosity of the mix, minimizing the pathways through which CO can escape, leading to lower emissions (Moghadas Nejad et al., 2019).

The amount of CO emitted from SOWMAC has a strong positive correlation with production temperature. As production temperature rose, CO emissions increased significantly (Wu et al., 2020; Jiang et al., 2021). Higher production temperatures reduce the viscosity of the asphalt binder, promoting better foaming and evaporation of volatile compounds, including CO (Hasan et al., 2020). The elevated temperature also accelerates the volatilization of asphalt components, leading to higher emissions of CO during production (Kim et al., 2022b). However, if production temperature exceeds a certain threshold, it can also lead to binder oxidation and softening, potentially exacerbating CO emissions (Moghadas Nejad et al., 2019).

The interaction effects of various factors on CO emissions from SOWMAC reveal a complex relationship between materials and production conditions. The combination of hydrated lime and production temperature has the most significant impact on CO emissions, driven by hydrated lime's anti-stripping properties, which reduce binder volatility and improve binder-aggregate adhesion (Hasan et al., 2020; Moghadas Nejad et al., 2019). This interaction helps minimize CO emissions by reducing porosity and improving the overall performance of the binder. The asphalt cement-sasobit and sasobit-hydrated lime interactions exhibit similar behavior, with their CO emission curves showing parallelism. These interactions highlight the complementary effects of sasobit's foaming properties and hydrated lime's anti-stripping benefits, leading to reduced CO emissions through enhanced binder performance (Wu et al., 2020; Kim et al., 2022b). The production temperature interaction with sasobit ranks fourth, as higher temperatures boost sasobit's foaming capability, improving binder-aggregate adhesion, but also increase CO emissions due to the volatilization of asphalt components (Wu et al., 2020; Jiang et al., 2021). Finally, interactions involving asphalt cement-hydrated lime (ranked fifth) and asphalt cement-production temperature (ranked sixth) underscore the role of binder properties and temperature effects on CO emissions from SOWMAC (Liu et al., 2017; Moghadas Nejad et al., 2019).

In the effort to rank the impact of various model parameters on CO emissions from SOWMAC, the analysis indicates that production temperature has the most substantial effect, ranking first. Higher production temperatures increase binder volatility and promote the complete evaporation of asphalt components, leading to increased CO emissions (Wu et al., 2020; Jiang et al., 2021). Hydrated lime ranks second due to its role in reducing porosity and enhancing binder-aggregate adhesion, which helps mitigate moisture damage and reduce CO emissions (Hasan et al., 2020; Kim et al., 2022b). The square interaction of production temperature ranks third, capturing the combined effect of temperature and binder properties (Moghadas Nejad et al., 2019). The linear effect of sasobit ranks fourth, as it reduces binder viscosity and improves binder-aggregate adhesion, contributing to CO emission reductions but with limited effectiveness beyond a certain point (Wu et al., 2020; Kim et al., 2022d). For two-way interactions, the hydrated lime-production temperature interaction ranks first among two-way effects and fifth overall, highlighting hydrated lime's key role in reducing CO emissions at elevated temperatures (Hasan et al., 2020; Moghadas Nejad et al., 2019). The square interaction of hydrated lime ranks sixth, reinforcing its role as an anti-stripping agent. The asphalt cement-sasobit and sasobit-hydrated lime two-way interactions rank seventh, reflecting their combined effect on reducing CO emissions (Wu et al., 2020; Kim et al., 2022b). However, the sasobit-production temperature interaction ranks fourth among two-way interactions but 12th overall, indicating a limited influence compared to other interactions (Jiang et al., 2021). Lastly, interactions between asphalt cement-hydrated lime and sasobit-production temperature show minimal impact on CO emissions, suggesting limited synergistic effects (Liu et al., 2017; Moghadas Nejad et al., 2019).

The parametric analysis of factors affecting the total production cost of SOWMAC indicates that increasing asphalt cement content leads to a significant rise in production costs. This trend is primarily due to the higher quantity of asphalt cement required to produce the mixture. Asphalt cement, which acts as the binder in the asphalt mixture, contributes to a large portion of the total cost due to its high cost and increased consumption associated with higher content levels (Jiang et al., 2021). The increased demand for asphalt cement raises both material costs and the energy required during the production process, including heating and blending, thus contributing to higher overall production costs (Wu et al., 2020). Additionally, asphalt cement is a significant contributor to the mix's overall viscosity and binding strength, which enhances performance but also leads to increased input costs (Liu et al., 2017).

Increasing sasobit content contributes to higher production costs for SOWMAC, but the effect is typically less significant compared to the impact of asphalt cement. Sasobit acts as a key foaming agent that reduces the viscosity of the asphalt binder, enhancing binder-aggregate adhesion and improving mix workability (Jiang et al., 2021; Wu et al., 2020). However, the addition of sasobit increases material costs and energy consumption during the foaming process, particularly due to additional materials and fuel usage for heating and mixing (Kim et al., 2022b). While sasobit contributes to higher costs, its impact is generally smaller compared to asphalt cement due to its lower cost per unit (Liu et al., 2017). Furthermore, although sasobit consumption may contribute to equipment wear, this effect is typically less significant than the impact of asphalt cement consumption (Hasan et al., 2020). Sasobit also offers offsetting benefits such as improved mix performance and reduced emissions (Wu et al., 2020). Thus, while increasing sasobit content raises production costs, the effect is generally less pronounced than the cost increase associated with higher asphalt cement content.

Hydrated lime also plays a role in increasing the total production cost of SOWMAC. The addition of hydrated lime raises production costs due to the extra materials required and the increased energy consumption needed for its incorporation into the mix. Hydrated lime acts as an anti-stripping agent, enhancing binder-aggregate adhesion and reducing moisture-related damage, which improves the performance of the mixture (Hasan et al., 2020; Kim et al., 2022b). However, these benefits come with added costs, as hydrated lime contributes to higher material expenses and increased energy consumption during mixing and dispersion, especially at elevated production temperatures (Moghadas Nejad et al., 2019). The need for additional equipment or process adjustments to accommodate hydrated lime use further exacerbates the rise in production costs (Liu et al., 2017). Despite these higher costs, the improved moisture resistance and enhanced durability provided by hydrated lime often justify the additional expenditure, particularly in regions facing significant moisture-related performance challenges (Wu et al., 2020).

The total production cost of SOWMAC shows minimal sensitivity to production temperature changes within the range of 120°C to 140°C. The production cost trend remains nearly linear and horizontal, suggesting that variations in production temperature have a negligible effect on overall production costs (Wu et al., 2020; Kim et al., 2022b). Energy consumption for mixing and equipment wear stays relatively stable, indicating that these factors do not significantly contribute to cost variations within this temperature range (Jiang et al., 2021; Liu et al., 2017). Although higher production temperatures may reduce binder viscosity and improve binder-aggregate adhesion, these benefits are often offset by minimal changes in energy consumption and equipment wear. Therefore, material costs appear to have a more significant influence on the overall production cost of SOWMAC than production temperature.

The interaction effects of the factors on total production cost of SOWMAC revealed that the interaction between asphalt cement and sasobit has the strongest impact on the total production cost of SOWMAC. Hydrated lime-production temperature has the second most significant impact as they have the second least parallel set of curves. Interactions such as; asphalt cement-hydrated lime and sasobit-hydrated lime are also significant in relation to impacting the total production cost. The production temperature interaction with sasobit and that of asphalt cement and production temperature interactions are not as significant as the others because their curves appear almost parallel.

In the effort to rank the influence of model parameters on the total production cost of SOWMAC, it is clear that hydrated lime and asphalt cement have the most significant effects, earning the 1st and 2nd rankings, respectively. The addition of hydrated lime increases material and energy costs due to its role in enhancing binder performance, while asphalt cement plays a crucial role in binder formulation and overall mix stability (Hasan et al., 2020; Liu et al., 2017). Sasobit is ranked 3rd due to its contribution to reducing binder viscosity and the additional costs associated with the foaming process, including material and energy consumption (Jiang et al., 2021; Wu et al., 2020). Among two-way interactions, the interaction between asphalt cement and sasobit ranks first, highlighting their combined impact on binder properties and production costs (Kim et al., 2022b). Following this, the interaction between hydrated lime and production temperature ranks 5th, emphasizing the effect of hydrated lime's anti-stripping properties and production temperature on energy consumption and mix performance (Moghadas Nejad et al., 2019). In contrast, the linear effect of production temperature ranks last among linear factors, indicating minimal influence on production costs within the narrow temperature range considered (Wu et al., 2020). The interaction between asphalt cement and production temperature ranks 11th, showing limited synergy between these factors in influencing production costs. For square interactions, the hydrated lime square interaction ranks 13th overall, demonstrating its relatively minor impact compared to other parameters (Liu et al., 2017). These rankings emphasize that hydrated lime, asphalt cement, and sasobit have the dominant roles in determining the total production cost of SOWMAC, while production temperature and some interaction effects contribute less significantly.

Conclusion

This study comprehensively evaluated the sustainability of Sasobit-based warm mix asphalt concrete (WMA) in comparison to traditional hot mix asphalt (HMA). The life cycle assessment (LCA) and life cycle cost analysis (LCCA) revealed that Sasobit-based WMA reduces greenhouse gas emissions, energy consumption, and environmental impacts compared to HMA. Additionally, the LCCA showed that Sasobit-based WMA has a lower life cycle cost than HMA. The findings of this study suggest that Sasobit-based WMA is a more sustainable option for pavement construction and rehabilitation. The results of this study can inform pavement design and construction practices, promoting the adoption of more sustainable asphalt technologies. The study recommends that:

i. Adoption of Sasobit-based WMA: Transportation agencies and contractors should consider adopting Sasobit-based WMA as a sustainable alternative to traditional HMA.
ii. Further research: Further research is recommended to investigate the long-term performance of Sasobit-based WMA and its potential applications in different climatic conditions.
iii. Development of sustainable asphalt technologies: The development of sustainable asphalt technologies should be prioritized to reduce the environmental impacts of infrastructure development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit Authorship Contribution Statement

All authors contributed equally.

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