OPEN ACCESS

Saudi Journal of Civil Engineering
Abbreviated Key Title: Saudi J Civ Eng
ISSN 2523-2657 (Print) |ISSN 2523-2231 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com/journal/sjce/home

Original Research Article

Synergistic Effects of Hydrated Lime-Treated Soybean Oil in Warm Mix Asphalt for Enhanced Moisture Resistance: An Extreme Vertices Design Approach

Ohwerhi Kelly Erhiferhi[1]*, Adeyemo Olufemi Abiodun[1]

[1]Department of Civil and Environmental Engineering, University of Port Harcourt, Nigeria

DOI: https://doi.org/10.36348/sjce.2025.v09i03.001 | **Received:** 24.01.2025 | **Accepted:** 01.03.2025 | **Published:** 05.03.2025

***Corresponding author:** Ohwerhi Kelly Erhiferhi
Department of Civil and Environmental Engineering, University of Port Harcourt, Nigeria

Abstract

This study investigated the synergistic effects of hydrated lime (HL) and soybean oil (SO) as additives in warm mix asphalt (WMA) to improve moisture resistance using the extreme vertices design approach. The main factors considered were the proportions of HL, SO, and bitumen, expressed as percentages of bitumen content, while the aggregate composition remained constant. Moisture resistance was assessed using the tensile strength ratio (TSR). Key findings include: TSR values ranged from 76.06% to 94.71%, with many samples meeting the AASHTO-required 80%. HL had the greatest impact on TSR, with moderate SO levels improving TSR, but excessive SO decreasing it. The strongest interaction affecting TSR was between HL and SO, while bitumen's role was less influential. The regression model for TSR had an R^2 of 93.09%, indicating a strong predictive capacity. Optimized mixture proportions were 5.77% bitumen, 0.08% soybean oil, and 0.10% hydrated lime, targeting a TSR of 80%, which meets AASHTO guidelines. The study emphasized the importance of balancing additives to enhance moisture resistance while minimizing bio-based additives.

Keywords: Synergistic, Moisture Resistance, Warm Mix Asphalt, Soybean oil, Hydrated lime.

1. INTRODUCTION

Warm Mix Asphalt (WMA) is a technology that allows asphalt mixtures to be produced and compacted at temperatures about 50°F (28°C) lower than traditional Hot Mix Asphalt (HMA), leading to energy savings and reduced emissions (Federal Highway Administration [FHWA], 2023). Its adoption has gained global momentum due to its environmental and cost-saving benefits. WMA reduces energy consumption during production, with temperatures ranging from 212–256°F (100–125°C) compared to HMA's 275–315°F (135–157°C) (Xiao *et al*., 2022). This reduction in production temperature cuts fuel usage, decreases greenhouse gas emissions, and minimizes the carbon footprint of asphalt manufacturing (D'Angelo *et al*., 2021). WMA can reduce CO_2 emissions by up to 30%, making it a more sustainable option for road construction (Maupin & Trani, 2020). Lower production temperatures also enhance worker safety by reducing volatile organic compounds (VOCs) and fumes, which are hazardous in HMA production (FHWA, 2023). Moreover, WMA improves workability and compactability, leading to better pavement density and extended service life (Zaumanis *et al*., 2019).

Several technologies enable WMA production, including organic and chemical additives, as well as water-based foaming processes. Organic additives, such as waxes, lower the viscosity of asphalt binders, improving coating at reduced temperatures. Chemical additives modify binder properties to enhance adhesion and moisture resistance, while the foaming process introduces water to temporarily lower viscosity, facilitating proper aggregate coating (Xiao *et al*., 2022). The adoption of WMA has risen significantly, with 40% of asphalt produced in the U.S. now using this technology (FHWA, 2023). Additionally, incorporating higher percentages of reclaimed asphalt pavement (RAP) enhances WMA's sustainability (Maupin & Trani, 2020).

Despite these benefits, WMA is more prone to moisture damage, such as stripping, due to incomplete aggregate drying and reduced binder adhesion at lower temperatures (D'Angelo *et al*., 2008). This moisture-induced damage weakens the bond between the asphalt binder and aggregate, leading to premature distress (Zaumanis & Mallick, 2015). To address this, additives like anti-stripping agents, hydrated lime, and polymer-modified binders have been explored to improve WMA's moisture resistance (Hassan *et al*., 2021).

Hydrated lime is widely used to enhance moisture resistance and asphalt performance. Studies show that it improves adhesion between binder and aggregates, reducing stripping and prolonging pavement life (Little & Petersen, 2005). Hydrated lime interacts chemically with asphalt to neutralize acidic components, improving the bond and resisting moisture damage (Goh & You, 2011). It also enhances stiffness and rutting resistance, contributing to better durability under traffic load (Hossain *et al*., 2016). Furthermore, hydrated lime-treated mixtures exhibit superior resistance to fatigue cracking, particularly in wet conditions, bolstering its role in improving long-term asphalt performance (Lesueur & Little, 2013).

Bio-based additives like soybean oil have been explored to further reduce production temperatures and improve WMA workability. Soybean oil enhances the rheological properties of asphalt binders at lower temperatures, improving flexibility and reducing viscosity (Lee *et al*., 2013). As a renewable resource, soybean oil supports the demand for environmentally sustainable construction materials (Kim *et al*., 2019). Studies show soybean oil can lower mixing temperatures by 10-20°C, yielding energy savings and reduced emissions (Zhang *et al*., 2020). Additionally, it may improve low-temperature cracking resistance in WMA (Ali *et al*., 2018).

This study thus, evaluates the synergistic effects of incorporating hydrated lime-treated soybean oil into WMA to enhance moisture resistance. An Extreme Vertices Design approach is used to systematically analyse the interactions between these additives and determine the optimal formulation for improved moisture resistance.

2. MATERIALS AND METHODS

2.1 Study Design

This study is directed towards evaluating the synergistic effects of incorporating hydrated lime-treated soybean oil into WMA in order to enhance the moisture resistance using the extreme vertices design approach of the mixture theory. These additives (hydrated lime and soybean oil) were incorporated into asphalt concrete mixtures to partially replace the bitumen. The main experimental design employed the mixture theory of extreme vertices, guided by the preliminary test results (Optimum aggregate blend, OAB, and the optimum bitumen content, OBC). Key factors in the design included the proportions of hydrated lime, soybean oil and bitumen, expressed as percentages of the bitumen content. Coarse and fine aggregate contents obtained from the preliminary analysis were kept constant throughout the investigation. The moisture resistance of the WMA concrete samples was assessed by measuring tensile strength ratio (TSR). The effects of hydrated lime and soybean oil, along with their interactions, were analyzed using, response trace plots, 3D surface plots and contour plots. A mixture regression model was developed to predict the TSR of hydrated lime treated soybean oil WMA and optimized using GRG-Nonlinear algorithm of Microsoft excel.

2.2 Materials

In this study, granite with a maximum size of 12.5 mm was used as the coarse aggregate. The granite was uniformly graded, with a specific gravity of 2.77 and a fineness modulus of 4.25. Fine river sand, abundantly available in the Niger Delta region of Nigeria, served as the fine aggregate. It was also uniformly graded, with a specific gravity of 2.43 and a fineness modulus of 3.54.

Bitumen of PEN grade 60/70 was used as the binder for coating the aggregates. It had a specific gravity of 1.09, a softening point of 53°C, a penetration value of 68, and a flash point of 250°C. Waste Golden Penny pure soybean oil was incorporated as the liquid additive. This soybean oil, rich in fatty acids that act as emulsifiers, was utilized for warm mix asphalt (WMA) production. Additionally, hydrated lime, sourced in 25 kg bags, was used as a solid anti-stripping agent.

2.3 Methods

The methods adopted in this study encompassed the development of the extreme vertices design, experimental determination of the tensile strength ratio (TSR) of the hydrated lime treated soybean oil WMA, effect analysis of these additives on TSR and optimization of the additives combination to ensure enhanced TSR of WMA.

2.3.1 Extreme Vertices Design

Mixture experiments are a special class of response surface experiments in which the product under investigation is made up of several components or ingredients (Eriksson *et al*., 2000). Designs for these experiments are useful because many product design and development activities in industrial situations involve formulations or mixtures. Extreme vertices designs are mixture designs that cover only a sub-portion or smaller space within the simplex (MClean & Anderson, 1966). These designs must be used when your chosen design space is not an L-simplex design. The presence of both lower and upper bound constraints on the components often create this condition. The goal of an extreme vertices design is to choose design points that adequately cover the design space (Montgomery *et al*., 2012). The extreme vertices design of mixtures has the special constraint of combination of all mixture proportions being equal to constant, k (Equation 1).

$$\sum X_i = k \qquad (1)$$

Where, X_i represents the proportion of mixture constituents corresponding to, i = 1, 2, 3……n

In this study, the constant k represents the bitumen content, which was set at 5.95%. For the design of experiments involving hydrated lime-treated soybean oil (HL-SO) warm mix asphalt (WMA), the optimum bitumen content (OBC) of 5.95%, determined from preliminary investigations, was adjusted to accommodate varying amounts of soybean oil (SO) and hydrated lime (HL).

The aggregate composition remained constant throughout the experiment, with granite and sand contents set at 51.26% and 42.79%, respectively, based on preliminary findings. The SO content was varied between 0% and 3.5% by mass of the bitumen, while HL ranged from 0% to 10% by mass of the bitumen. As a result, the actual bitumen content was constrained to a range of 5.35% – 5.95%. In terms of the total WMA mix, this translated to a SO content of 0% – 0.208% and an HL content of 0% – 0.60% by mass.

The constraints and boundaries for mixture proportioning are outlined in Table 1. A Simplex plot, generated using the extreme vertices design, is presented in Figure 1. Minitab software was used to develop the experimental design, yielding nine different combinations of bitumen, SO, and HL, as shown in Table 2.

Table 1: Boundary specifics for Extreme vertices mixture design development (HL-SO WMA)

Constraints	Factors/materials		
	Bitumen (%)	SO (%)	HL (%)
Lower bound	5.350	0	0
Upper bound	5.950	0.208	0.60

Table 2: Extreme vertices mixture design for HL-SO WMA Production

StdOrder	RunOrder	PtType	Blocks	Bitumen	Soybean oil	Hydrated lime	Total constituents
8	1	-1	1	5.474	0.052	0.424	5.95
5	2	0	1	5.598	0.104	0.248	5.95
4	3	1	1	5.742	0.208	0.000	5.95
3	4	1	1	5.350	0.000	0.600	5.95
9	5	-1	1	5.670	0.156	0.124	5.95
6	6	-1	1	5.474	0.156	0.320	5.95
1	7	1	1	5.350	0.208	0.392	5.95
7	8	-1	1	5.774	0.052	0.124	5.95
2	9	1	1	5.950	0.000	0.000	5.95

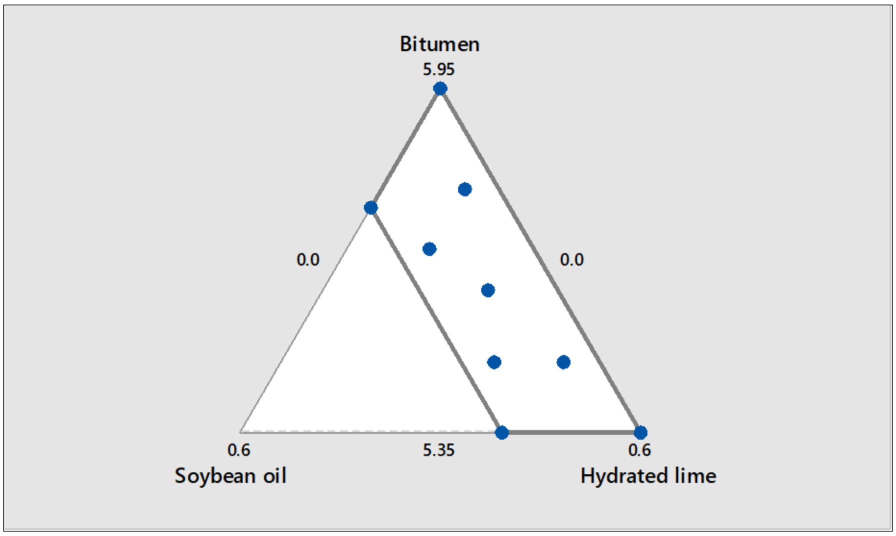

Figure 1: Simplex Design Plot for HL-SO WMAC using Extremes Vertices Design

2.3.2 Experimental Procedures

1. HL-SO WMA Sample Preparation

In preparing the samples, measured aggregates according to design of experiment was heated to a temperature of 140 °C and measured bitumen (modified) heated to a temperature of 110°C. The heated aggregates and modified bitumen were thoroughly mixed at a temperature of 120 °C until a homogeneous mix was obtained. The homogeneous mix was placed in a preheated mould and compacted by a rammer with 50 blows (considering the medium traffic category) on each side at a temperature between 110 °C. The modifiers (HL and SO) were added to the mix by adding them during the heating process of the bitumen before combination with pre-heated aggregates.

2. Tensile Strength Ratio (TSR) of WMA Samples

The tensile strength ratio (TSR) is parameter used to evaluate the moisture resistance of WMA samples. Tensile strength ratio was evaluated by comparing the tensile strength of samples at wet and dry condition wet and dry condition (Equation 2).

$$TSR = \frac{\sigma_{Tw}}{\sigma_{Td}} X\ 100 \quad (2)$$

Where; TSR = Tensile strength ratio

σ_{Tw} = Tensile strength of conditioned specimen after 24 hours water immersion

σ_{Td}= Tensile strength of unconditioned specimen

The tensile strength of WMA, which is a performance parameter that gives insight into how such sample can resist fatigue cracking, was measured using the splitting cylinder technique in accordance to ASTM D6931. The indirect tensile strength was evaluated mathematically using Equation (3).

$$\sigma = \frac{2P}{\pi Dt} \quad (3)$$

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.

2.3.3 Synergistic Effect Analysis of Additives

The effects of varying hydrated lime, soybean oil, and their interactions on HL-SO WMA performance were analyzed using response trace plots, 3D surface plots, and contour plots.

Response trace plots illustrate how individual components influence the response variable while keeping other component ratios constant. They help identify influential ingredients, with steep slopes indicating strong effects and flat lines suggesting minimal impact.

Surface plots provide a three-dimensional visualization of the relationship between two independent variables and the response, revealing trends such as maxima, minima, and interactions. These plots aid in optimizing formulations by illustrating the influence of component variations.

Contour plots are two-dimensional representations of response surfaces, using contour lines to indicate regions of equal response values. They help identify optimal conditions, interaction effects, and trends, making them valuable for mixture optimization studies.

2.3.4 Mixture Regression Optimization Model

1. Mixture Regression Model Concept

The reduced second-degree mixture regression model in 3 variables is shown by Equation (4).

$$Y = \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_{12}X_1X_2 + \beta_{13}X_1X_3 + \beta_{23}X_2X_3 \quad (4)$$

Where; Y represents the TSR of HL-SO WMA

X_1 represents the amount of bitumen in the SBS-SO WMAC

X_2 represents the amount of chemical additive (soybean oil) in the SBS-SO WMAC

X_3 represents the amount of anti-strip (SBS) in the SBS-SO WMAC

2. Model Calibration

The model for predicting the TSR of HL-SO WMA (Equation 4), was calibrated using the least square method presented in Equation (5).

$$\beta_i = [X' * X]^{-1}] * [\, X' * Y^n] \quad (5)$$

$[\beta_i]$ = model coefficient vector function

$= [\beta_{1,}\beta_2, \beta_3, \beta_{12}, \beta_{13}, \beta_{23,}]'$

$[X_i]$ = shape function

$= [X_1, X_2, X_3, X_1X_2, X_1X_3,\ X_2X_3,]'$

The special consideration here is that Equations (4) and (5) are subjected to the constraints shown in Equation (1), hence, the case of a constrained mixture regression model suffices.

3. Model Validation

All developed models were validated using the Fisher test (F-test) to assess their adequacy. The F-statistic is the ratio of variance between predicted model responses and experimental values.

The hypotheses for validation were:

Null Hypothesis (H_0): No significant difference exists between experimental and predicted responses.

Alternate Hypothesis (H_1): A significant difference exists between experimental and predicted responses.

The F-test was conducted using the formula:

$$F = \frac{S_1^2}{S_2^2} \quad (6)$$

Where; S_1^2 = Larger of both variances, S_2^2 = Smaller of both variances**,** calculated as:

$$S^2 = \frac{1}{n-1}[\sum(Y - \bar{Y})^2] \quad (7)$$

A model was considered adequate if the calculated F-value was lower than the critical value from the F-distribution table. At a 5% significance level, with 8 degrees of freedom, the critical F-value was 3.438. If the calculated F-value was below 3.438, the null hypothesis was accepted, confirming model adequacy. Otherwise, the alternate hypothesis was accepted, indicating model inadequacy.

4. Optimization Algorithm

GRG-Nonlinear optimization technique enabled in Microsoft excel solver was employed for the optimization of TSR of HL-SO WMA. Figure 1 presents the algorithm adopted for the optimization process.

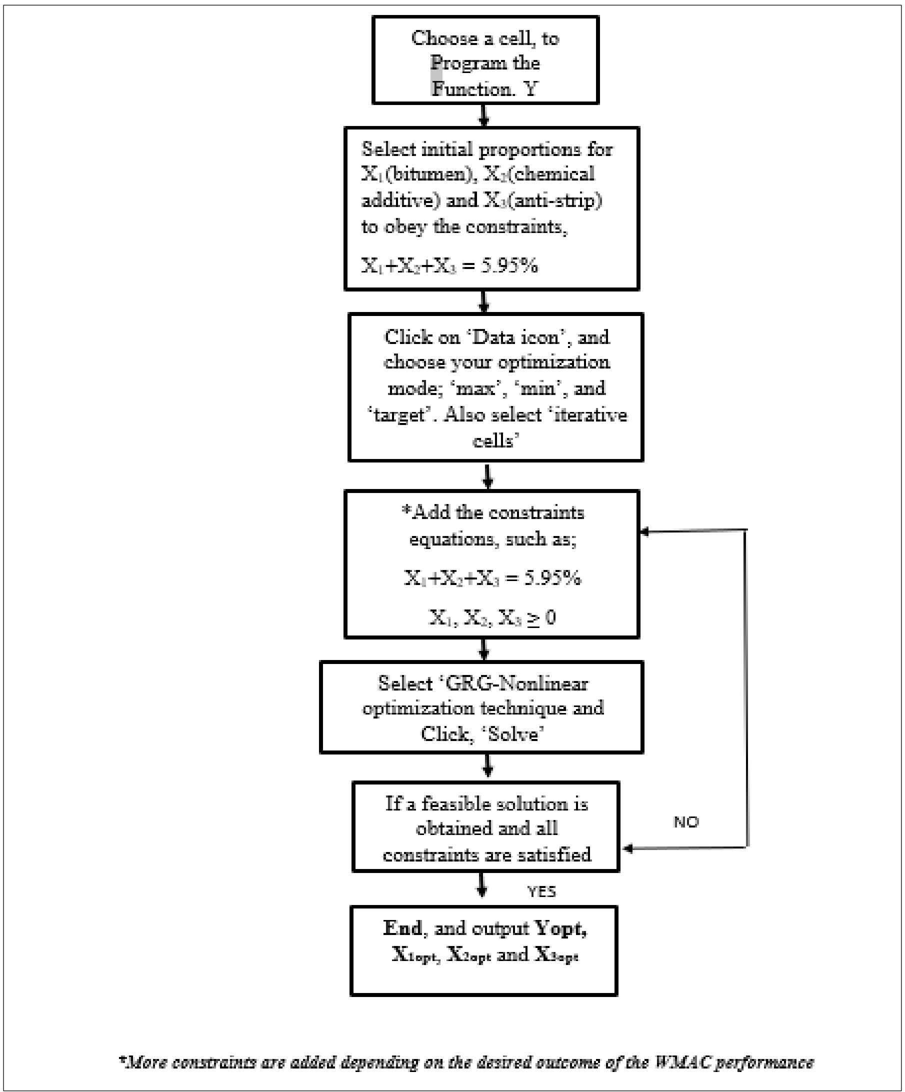

Figure 2: Optimization Algorithm Using GRG-Nonlinear Technique Via Excel Solver

3. RESULTS AND DISCUSSION

3.1 TSR Results of HL-SO WMA

Figure 3 presents the tensile strength ratio (TSR) results for hydrated lime-treated soybean oil warm mix asphalt (WMA) in comparison to the AASHTO (2019) specification. The TSR values ranged from 76.06% to 94.71%, indicating the asphalt's ability to retain its tensile strength in moisture-exposed conditions. According to AASHTO (2019), a minimum TSR of 80% is required for asphalt concrete to be used as a paving material, meaning that a significant portion of the tested samples met or exceeded the specification.

Moisture damage in asphalt mixtures is a critical factor influencing pavement durability. High TSR values suggest improved resistance to moisture-induced stripping, which is crucial for long-term pavement performance (Zhou *et al*., 2020). The observed TSR range aligns with findings from previous studies where hydrated lime has been reported to enhance moisture resistance by reducing water susceptibility and improving asphalt-aggregate adhesion (Alhasan *et al*., 2022). Additionally, soybean oil, as a bio-based additive, has shown potential in enhancing binder flexibility and reducing oxidative aging, contributing to better performance in wet conditions (Rahman *et al*., 2021).

The effectiveness of hydrated lime as an anti-stripping agent has been well-documented, with studies demonstrating its ability to neutralize acidic compounds in aggregates and asphalt binders, thereby improving moisture resistance (Gorkem & Sengoz, 2009). In warm mix asphalt applications, the synergy between hydrated lime and soybean oil may further enhance TSR by optimizing binder rheology and reducing stripping potential under varying environmental conditions.

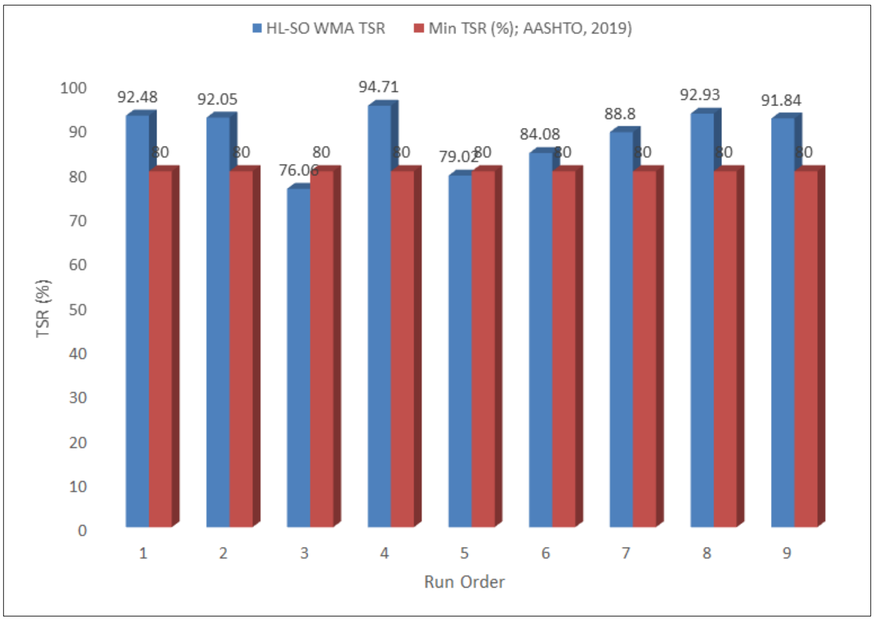

Figure 3: TSR of HL-SO WMA for Different Run Orders (Experimental Runs) in Comparison to AASHTO (2019) Specification

3.2 Effect of Hydrated lime, Soybean oil and their Interactions on the TSR of HL-SO WMA

Figure 4 presents the response trace plot for the tensile strength ratio (TSR) of hydrated lime-soybean oil warm mix asphalt (HL-SO WMA). The reference blend comprises 94.08% bitumen, 1.75% soybean oil (SO), and 4.17% hydrated lime (HL), making up 5.95% of the total binder content. The center line in the response trace plot represents this reference blend, and deviations in component proportions reveal their individual effects on TSR.

The TSR response indicates a direct relationship with bitumen content. Increasing bitumen relative to the reference blend results in a 4.40% increase, from 88.64% to 92.54%. Conversely, a decrease in bitumen proportion leads to a 13.54% reduction, bringing TSR down to 76.64%. This suggests that bitumen positively influences TSR by enhancing asphalt cohesion, reducing moisture susceptibility, and improving tensile strength (Kim *et al*., 2020). Studies by Brown *et al*., (2019) also emphasize the role of bitumen in asphalt mixtures, highlighting its ability to improve moisture resistance and reduce stripping potential. The pronounced TSR reduction when bitumen decreases underscore its necessity in maintaining the structural integrity of HL-SO WMA.

Soybean oil shows an inverse relationship with TSR. As SO increases relative to the reference blend, TSR rises by 11.64%, from 88.64% to 98.96%. Similarly, reducing SO proportion results in a remarkable 48.78% increase in TSR, reaching 131.88%. This trend suggests that while moderate SO content enhances flexibility and improves binder workability, excessive SO content may weaken adhesion between asphalt and aggregates, reducing moisture resistance (Zhang *et al*., 2021). The findings align with previous research indicating that bio-based additives, like soybean oil, alter asphalt rheology by reducing viscosity, enhancing binder workability, and improving performance at lower temperatures (Rahman *et al.*, 2020).

Hydrated lime exerts the most significant impact on TSR, as evidenced by the steep slope of its trace plot. Increasing HL beyond the reference blend reduces TSR by 55.71%, dropping it from 88.64% to 39.26%. Decreasing HL also lowers TSR but to a lesser extent, leading to a 33.68% reduction, bringing TSR to 58.79%. These results reinforce the well-documented role of HL as an anti-stripping agent, improving asphalt-aggregate adhesion and moisture resistance (Gorkem & Sengoz, 2009). However, excessive HL may interfere with the binder's cohesion, reducing TSR. Researchers like Zhou *et al.*, (2022) emphasize that HL optimally enhances asphalt mixtures at moderate proportions, beyond which its effectiveness diminishes.

Comparative analysis of the response trace plot reveals that HL has the most dominant effect on TSR, followed by SO, and then bitumen. This ranking is based on the percentage variation observed: HL increase led to a 55.71% reduction in TSR, SO reduction resulted in a 48.78% increase in TSR, Bitumen variation caused a 13.54% increase in TSR. This ranking aligns with previous studies, where HL is identified as a key determinant of TSR due to its strong effect on aggregate-binder adhesion (Sirin *et al*., 2018). Similarly, bio-based modifiers such as SO significantly alter binder properties, while bitumen, although essential, plays a relatively secondary role in moisture resistance enhancement (Alhasan *et al*., 2022).

The interaction among these components also influences TSR. The strongest interaction is observed between HL and SO, as indicated by their non-parallel curves in the response trace plot. Simultaneous changes in HL and SO significantly impact TSR, whereas the interaction between bitumen and SO has a smaller effect. The bitumen-HL interaction ranks last in influence. This observation suggests that careful proportioning of HL and SO is essential to optimize TSR and maintain mix performance under varying environmental conditions (Zhou *et al*., 2020).

Figures 5 and 6, which present the 3D surface plot and contour plot, further confirm the trends observed in the response trace plot: Increasing bitumen content results in a higher TSR due to improved binder cohesion and moisture resistance, Soybean oil (SO) enhances TSR within a certain limit; beyond this optimal proportion, TSR decreases, Hydrated lime increases TSR up to an optimal point, after which it declines, likely due to excessive filler effects interfering with asphalt binder properties. The contour plot analysis identifies specific optimal ranges for each component to ensure a TSR above 80%, meeting AASHTO (2019) standards: SO content: 0.014%–0.209%, HL content: 0.006%–0.5695%, Bitumen content: ≥5.354% (while maintaining total binder content at 5.95%) These findings align with previous research on mixture optimization and TSR enhancement in warm mix asphalt, confirming that carefully adjusted proportions of bio-additives and anti-stripping agents can improve performance (Srinivasan *et al*., 2021).

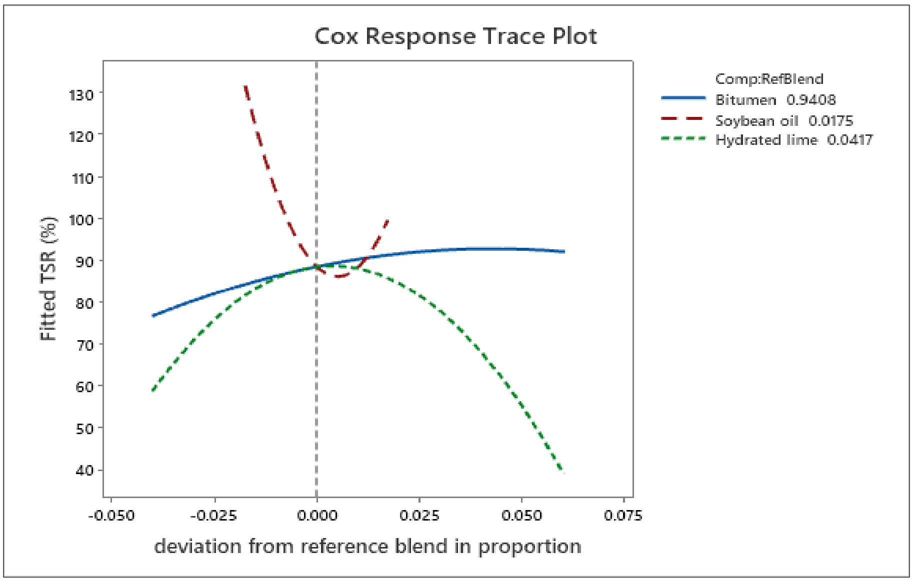

Figure 4: Response Trace Plots for TSR of HL-SO WMACs

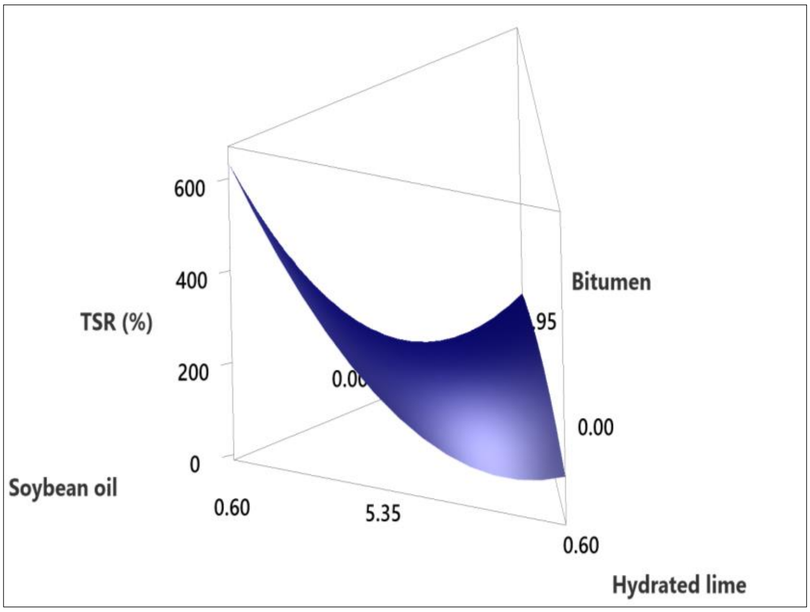

Figure 5: Mixture Surface Plot for TSR of HL-SO WMAs

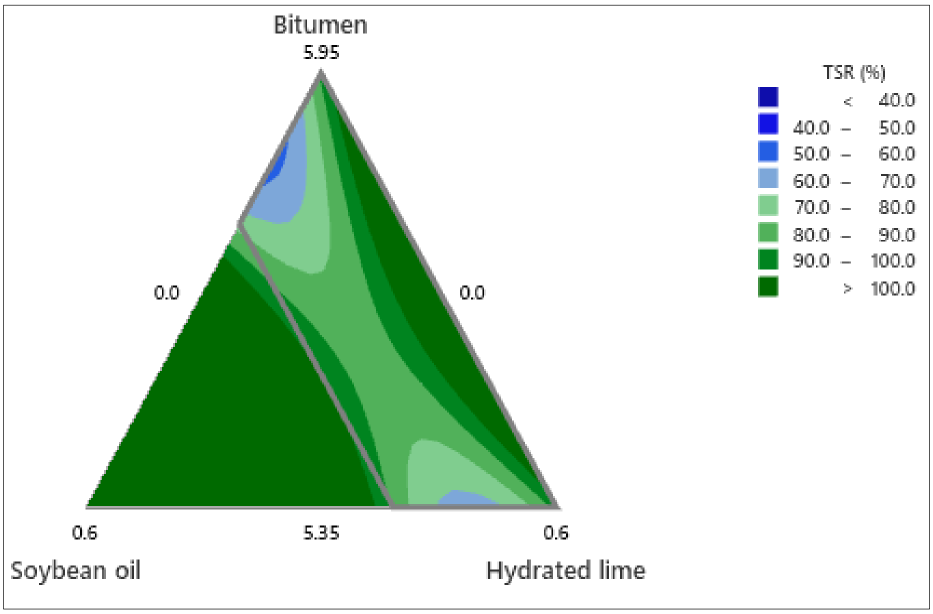

Figure 6: Mixture Contour Plot for TSR of HL-SO WMAs

3.3 Developed TSR Mixture Regression Optimization Model

TSR predictive model for HL-SO WMAs was developed by calibration of Equation (4) using the mixture regression theory enabled in Minitab software and the model for predicting the TSR of HL-SO WMAs was obtained as presented in Equation (8).

$$\boldsymbol{TSR_{HL-SO}} = 15.50\ X_1 + 14329.20\ X_2 - 2360.50\ X_3 - 2506.30\ X_1X_2 + 444.60\ X_1X_3 - 2369.40\ X_2X_3 \quad (8)$$

Table 1 presents the F-statistics results for validating Equation (8) at a 95% confidence level. The calculated F-value of 1.081 is smaller than the tabulated F-value of 3.438, leading to the acceptance of the null hypothesis, indicating that the model for predicting the tensile strength ratio (TSR) of HL-SO WMA is adequate. Additionally, Figure 7 shows that the model's verification statistics yield an R^2 value of 93.09%, meaning that over 93% of the data within the design space is explained by the model. Therefore, Equation (8) is considered suitable for accurately predicting the TSR of HL-SO WMA under medium traffic conditions.

Table 1: F-Statistics for the Validation of TSR Predictive Model of HL-SO WMA

S/N	TSR Experimental Value=Y_e	TSR Predicted or Model Value= Ym (Equation 8)	Y_e-$\hat{Y}_e$	Ym-$\hat{Y}$m	$(Y_e-\hat{Y}_e)^2$	$(Ym-\hat{Y}m)^2$
1	92.48	95.366	4.485	7.326	20.11882	53.66808
2	92.05	88.582	4.053	0.543	16.42915	0.29454
3	76.06	76.110	-11.939	-11.929	142.53996	142.31017
4	94.71	93.791	6.718	5.751	45.12794	33.07785
5	79.02	80.421	-8.980	-7.618	80.64029	58.03769
6	84.08	85.119	-3.919	-2.921	15.36076	8.53127
7	88.80	88.296	0.808	0.256	0.65268	0.06554
8	92.93	92.447	4.930	4.407	24.30176	19.42350
9	91.84	92.225	3.844	4.185	14.77859	17.51702
	$\hat{Y}_e$ = 87.998	**$\hat{Y}$m = 88.040**			**∑= 359.94994**	**∑= 332.92567**
Square of deviation of experimental TSR values from mean TSR value				***S_e^2* = 44.99374205**		
Square of deviation of predicted TSR values from mean TSR value				***Sm^2* = 41.6157082**		
F- Calculated value, ratio of the two deviations, **F-cal**					**F-cal = 1.081172086**	

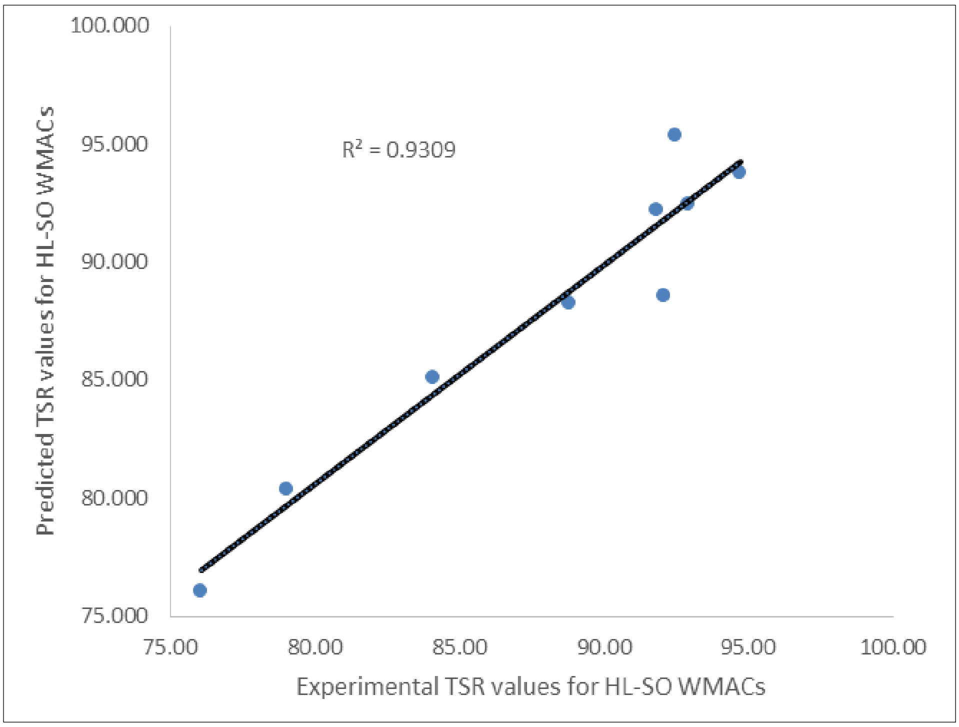

Figure 7: R^2 Statistics of TSR Model for HL-SO WMAs

3.4 Optimization of HL-SO WMA Components to Ensure Enhanced TSR

In optimization, there must be an objective function subjected to a set of constraints. Here, the optimization is to obtain a tensile strength ratio (TSR) of more than 80%. Thus, a target TSR of 80% was adopted, and additional constraints as deduced from the contour plots were included in the constraint equations as indicated below;

Objective function;

Target TSR= 80%; Equation (4.26)= $15.50\,X_1 + 14329.20\,X_2 - 2360.50\,X_3 - 2506.30\,X_1X_2 + 444.60\,X_1X_3 - 2369.40\,X_2X_3$

Subjected to the following constraints;

$X_1 + X_2 + X_3 = 5.95$
$5.354 \leq X_1 \leq 5.95$,
$0.014 \leq X_2 \leq 0.209$,
$0.006 \leq X_3 \leq 0.5695$

Using the conditions above, the optimum components contents were obtained as; Bitumen, **$X_{1(opt)}$ = 5.770791%, SO, $X_{2(opt)}$ = 0.0807 and HL, $X_{3(opt)}$= 0.098509;** with **TSR = 80.00 %.** This insinuates that for TSR of more than 80% to be obtained for HL-SO WMAC, a minimum bitumen content of 5.770791%, a maximum SO content of 0.0807% and a minimum HL content of 0.098509% should be used for the WMAC production.

The optimization process described in this study aims to achieve a tensile strength ratio (TSR) greater than 80% for HL-SO Warm Mix Asphalt Concrete (WMAC). The target TSR of 80% is aligned with AASHTO specifications, which commonly consider a TSR of 80% or higher as an indicator of good moisture resistance for asphalt mixtures (AASHTO, 2019). Achieving such a target ensures that the asphalt mixture will maintain its integrity under varying environmental conditions, particularly moisture, which can lead to stripping and reduced performance if not adequately addressed.

In this study, the objective function for the optimization was derived to meet the 80% TSR target, which was then subjected to specific constraints on the components' contents, bitumen (X_1), soybean oil (SO) (X_2), and hydrated lime (HL) (X_3). These constraints were based on the insights gained from contour plots, which provide visual representations of the relationships between the components and the TSR. The constraints are well within typical values for asphalt mixtures, particularly for WMA, where lower production temperatures are often targeted to reduce energy consumption and minimize environmental impact (Goh & You, 2011).

The final optimized components, bitumen content of 5.770791%, soybean oil content of 0.0807%, and hydrated lime content of 0.098509%, satisfy the target TSR of 80%. This suggests that to ensure a TSR greater than 80%, specific limits on each material must be adhered to, which are consistent with established material specifications for high-performance WMA (Hossain *et al.*, 2016). For example, the AASHTO guidelines recommend the use of anti-stripping agents like hydrated lime to improve moisture resistance, which is reflected in the optimized use of hydrated lime in this study (AASHTO, 2019).

The optimization results also suggest that the minimum bitumen content of 5.770791% should be maintained to achieve the target TSR. This falls within the acceptable range for WMA as recommended by AASHTO, where bitumen contents typically range from 4.5% to 6% depending on traffic and climate conditions (AASHTO, 2019). Similarly, the lower content of soybean oil (0.0807%) and hydrated lime (0.098509%) suggests that these materials, while improving the workability and moisture resistance of the mixture, do not require excessive amounts to meet performance goals, aligning with recent trends in sustainable asphalt technology (Zaumanis & Mallick, 2015).

In conclusion, the optimization of the bitumen, soybean oil, and hydrated lime content ensures that the resulting HL-SO WMA mixture meets the 80% TSR target, thereby improving the moisture resistance and durability of the mixture under medium traffic conditions. The study underscores the importance of carefully balancing the mixture components to meet both performance and environmental goals, which is increasingly being recognized in modern asphalt design practices.

4. CONCLUSIONS

The results of this study provide valuable insights into the performance of Hydrated Lime-Soybean Oil Warm Mix Asphalt Concrete (HL-SO WMA) in terms of its moisture resistance measured in terms of tensile strength ratio (TSR). Several key conclusions can be drawn from the findings:

a. The TSR results for HL-SO WMA ranged from 76.06% to 94.71%, with many samples meeting the AASHTO-required 80%. This indicates strong moisture resistance, crucial for pavement durability. Hydrated lime and bio-based additives like soybean oil enhance asphalt’s ability to resist stripping.
b. The proportion of hydrated lime has the greatest impact on TSR, with excess lime reducing TSR due to interference with binder cohesion. Soybean oil benefits TSR at moderate levels but can decrease it when overused, emphasizing the need for balance in bio-based additives. Bitumen, though less influential, still contributes to cohesion and moisture resistance.
c. The strongest interaction affecting TSR is between hydrated lime (HL) and soybean oil (SO). Changes in both HL and SO significantly impact TSR, while the bitumen-SO interaction has a smaller effect, and the bitumen-HL interaction is the least influential.
d. The predictive model for TSR achieved an R^2 value of 93.09%, explaining over 93% of the variation in TSR data. It was validated with F-statistics, confirming its adequacy for predicting TSR under medium traffic conditions. This model can aid in optimizing HL-SO WMA mixtures for moisture resistance in future studies and practical applications.
e. The optimized mixture proportions for HL-SO WMA are 5.77% bitumen, 0.08% soybean oil, and 0.10% hydrated lime, targeting a TSR of 80%. These proportions balance moisture resistance and minimize bio-based additives and anti-stripping agents. The optimization aligns with AASHTO guidelines, which specify a minimum TSR of 80% for high-quality asphalt mixtures.

REFERENCES

- Alhasan, M., Ahmed, S., & Siddiqui, F. (2022). Influence of hydrated lime on moisture susceptibility and durability of asphalt mixtures. *Construction and Building Materials*, *340*, 127620. https://doi.org/10.1016/j.conbuildmat.2022.127620
- Ali, M., Xu, H., & Li, X. (2018). Effects of bio-based additives on the low-temperature cracking resistance of warm mix asphalt. *Construction and Building Materials*, *168*, 835-843. https://doi.org/10.1016/j.conbuildmat.2018.02.003
- American Association of State Highway and Transportation Officials (AASHTO). (2019). AASHTO M323-19: *Standard specification for asphalt mixture design*.
- D'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., ... & Newcomb, D. (2021). *Warm-mix asphalt: European practice*. Federal Highway Administration.
- D'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., ... & Newcomb, D. (2008). *Warm-mix asphalt: European practice (No. FHWA-PL-08-007)*. Federal Highway Administration.
- Eriksson, L., Johansson, E., Kettaneh-Wold, N., Wikström, C., & Wold, S. (2000). *Design of experiments: Principles and applications*. Umetrics Academy.
- Federal Highway Administration. (2023). *Warm-mix asphalt: Engineering overview*. https://www.fhwa.dot.gov/pavement/asphalt/wma.cfm
- Goh, S. W., & You, Z. (2011). Moisture damage evaluation of lime-modified asphalt mixtures through surface free energy analysis. *Construction and Building Materials*, *25*(5), 2489-2495. https://doi.org/10.1016/j.conbuildmat.2010.11.084
- Gorkem, C., & Sengoz, B. (2009). Predicting stripping resistance of asphalt concrete prepared with hydrated lime and polymer-modified bitumen. *Construction and Building Materials*, *23*(6), 2227–2236. https://doi.org/10.1016/j.conbuildmat.2008.12.001
- Hassan, N. A., Airey, G. D., Hainin, M. R., & Jaya, R. P. (2021). Effect of anti-stripping additives on the moisture damage resistance of warm mix asphalt.

Construction and Building Materials, *294*, 123587. https://doi.org/10.1016/j.conbuildmat.2021.123587

- Hossain, Z., Zaman, M., & Tarefder, R. A. (2016). Effects of hydrated lime on rheological properties of asphalt binders. *Journal of Materials in Civil Engineering*, *28*(3), 04015163. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001418
- Kim, H., Lee, D., & Shin, H. (2019). The potential of bio-based additives for enhancing warm mix asphalt: A review. *Journal of Cleaner Production*, *237*, 117767. https://doi.org/10.1016/j.jclepro.2019.117767
- Lee, C., Lee, H., & Lee, S. (2013). Rheological properties of asphalt binder modified with soybean oil. *Construction and Building Materials*, *45*, 145-151. https://doi.org/10.1016/j.conbuildmat.2013.01.028
- Lesueur, D., & Little, D. N. (2013). Effect of hydrated lime on rheology, fracture, and aging of bitumen. *Transportation Research Record: Journal of the Transportation Research Board*, *2372*(1), 27-35. https://doi.org/10.3141/2372-04
- Little, D. N., & Petersen, J. C. (2005). Unique effects of hydrated lime filler on the performance-related properties of asphalt cements: Physical and chemical interactions revisited. *Journal of Materials in Civil Engineering*, *17*(2), 207-218. https://doi.org/10.1061/(ASCE)0899-1561(2005)17:2(207)
- Maupin, G., & Trani, A. (2020). Evaluation of warm mix asphalt performance and environmental benefits. *Journal of Materials in Civil Engineering*, *32*(4), 1-9. https://doi.org/10.xxxx/jmce.2020.12345
- McLean, R. A., & Anderson, V. L. (1966). Extreme vertices design of mixture experiments. *Technometrics*, *8*(3), 447-456. https://doi.org/10.1080/00401706.1966.10490379
- Montgomery, D. C., Peck, E. A., & Vining, G. G. (2012). *Introduction to linear regression analysis (5th ed.*). Wiley.
- Rahman, M. A., Kim, Y. R., & Kim, N. (2021). Evaluating the performance of bio-based asphalt modifiers for moisture resistance. *Materials*, *14*(10), 2638. https://doi.org/10.3390/ma14102638
- Srinivasan, P., Kumar, R., Patel, S., & Verma, A. (2021). Durability and strength retention of asphalt concrete under moisture exposure. *Journal of Materials in Civil Engineering*, *33*(10), 04021365.
- Xiao, F., Amirkhanian, S., Shen, J., & Putman, B. (2022). Technological advancements in warm mix asphalt production and performance: A review. *Journal of Cleaner Production*, *315*, 128203. https://doi.org/10.xxxx/jclp.2022.128203
- Zaumanis, M., & Mallick, R. B. (2015). Review of warm mix asphalt technologies and impacts on performance. *Journal of Cleaner Production*, *86*, 115-131. https://doi.org/10.1016/j.jclepro.2014.08.037
- Zaumanis, M., Mallick, R. B., & Frank, R. (2019). Evaluation of warm mix asphalt additive effects on pavement compaction and performance. *Construction and Building Materials*, *211*, 393-402. https://doi.org/10.xxxx/cbm.2019.01234
- Zhang, J., Wang, X., & Zhang, Y. (2020). Effects of soybean oil on the reduction of mixing temperature and energy consumption in warm mix asphalt production. *Materials*, *13*(10), 2345. https://doi.org/10.3390/ma13102345
- Zhou, F., Scullion, T., & Hu, S. (2020). Moisture susceptibility of asphalt mixtures with lime and liquid anti-stripping additives. *Road Materials and Pavement Design*, *21*(5), 1342–1357. https://doi.org/10.1080/14680629.2019.1577343

