Nigerian Journal of Engineering, Vol. 30, No. 3, December 2023, ISSN (print): 0794 – 4756, ISSN(online):2705-3954.

Nigerian Journal of Engineering,
Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria
journal homepage: www.njeabu.com.ng

Enhancing Rutting Resistance in Bituminous Concrete: A Response Surface Methodology Approach for Optimizing Bitumen and Hydrochar-Based Geopolymer Content

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Research Article

Abstract

In recent times, there has been a wave of concern about enhancing the durability and performance of bituminous pavements, particularly rutting resistance considering the rising traffic volumes and environmental concerns. Thus, modifying bitumen with biowaste materials such as hydrochar-based geopolymer composites is one new technique for resolving these challenges. Thus, this study investigates how the bitumen and hydrochar-based geopolymer composites (HBGC) affect the rutting resistance (RR) of bituminous pavements, utilizing an optimization known as the Response Surface Methodology (RSM). Three main design factors were investigated: bitumen content, hydrochar content, and geopolymer content. The asphalt binder content varied from 4% to 6%, whereas the biochar and geopolymer content ranged from 0% to 4%. The RSM technique was used to analyze the interplay between various design elements and develop a prediction model for optimizing the RR. The ANOVA analysis demonstrated strong statistical performance, indicating a high correlation between actual and predicted outcomes. Notably, the synergistic effect of increasing bitumen content and the use of a hydrochar-based geopolymer composite modifier resulted in improved RR in bituminous concrete. Furthermore, the study indicated optimal input content of 5.75% for bitumen, 3.4% for hydrochar, and 3.24% for the geopolymer modifier to improve RR. Also, the model has a 5% percentage error, showing a significant correlation between predicted and actual data. This study demonstrates the effectiveness of using RSM to optimize and predict HBGC bituminous concrete RR, by providing durability and sustainability through HBGC utilization in bituminous concrete.

doi: 10.5455/nje.2023.30.03.02

Keywords

Optimization; Hydrochar; Geopolymer; Rutting resistance; Bituminous concrete

Article History

Received: – September, 2023
Reviewed: – October, 2023
Accepted: – November, 2023
Published: – December, 2023

1. Introduction

The resilience and lifespan of bituminous concrete pavements are crucial in the sphere of modern transportation infrastructure. These pavements, often known as asphalt concrete, are the backbone of our road networks, allowing millions of commuters to move efficiently and safely every day (Usman, et al., 2021). However, the ongoing challenge of permanent deformation, colloquially known as rutting, poses a significant threat to the performance and sustainability of these critical roadways (Du, et al., 2018). Rutting occurs because of the cumulative influence of strong traffic loads and environmental stressors on bituminous concrete surfaces. This phenomenon has the unintended effects of reduced road safety, pavement deterioration, and increased maintenance expenses (Bala & Dayyabu, 2021). Recognizing the importance of addressing these difficulties, researchers and engineers have set out on a quest to improve the rutting resistance (RR) of bituminous concrete(Usman et al., 2021).

Hydrochar-based geopolymer composites have received a lot of interest recently because of their potential to improve the performance of bituminous concrete (Yaro et al., 2023). Hydrochar is an environmentally friendly material that is produced through hydrothermal carbonization, a process that converts organic biomass such as agricultural by exposing them to regulated heating and pressurized water in an oxygen-limited environment (Jagaba et al., 2023; Zhao et al., 2014). This material has emerged as a promising component for geopolymer composites, offering the opportunity to create a sustainable and eco-conscious modifier aimed at increasing the RR of bituminous concrete. Given the critical relevance of improving RR in bituminous concrete design and maintenance, optimizing the materials used in the modification process and developing predictive models become critical. In this context, statistical modeling, and optimization techniques such as response surface methodology (RSM) stand out as powerful tools for comprehensively analyzing and optimizing the effects of hydrochar-based geopolymer composites on asphalt concrete RR.

The RSM represents an effective and advantageous approach to evaluating the influence of bitumen and hydrochar-based geopolymer composites on the RR of bituminous concrete. These approaches provide a diverse set of benefits that considerably add to our understanding of asphalt concrete engineering and advancement in the field. One of the most significant benefits of these strategies is their ability to enable a full study of various factors (Jagaba et al., 2023). Bituminous concrete is a complex material that is influenced by a variety of parameters such as the kind and quantity of bitumen used, the incorporation of geopolymer composites, and environmental conditions. Statistical modeling enables researchers to methodically investigate the interactions of various variables and their effects on RR, providing a comprehensive picture of the material's behavior (Usman et al., 2021). Another critical aspect is efficiency in experimental design as it enables researchers to successfully organize trials while minimizing resource-intensive trial and error procedures (Jagaba et al., 2023). This efficiency translates into significant time and cost savings, which is an important aspect of any research endeavor.Furthermore, the development of mathematical models using these methodologies provides useful insights. These models act as prediction tools, guiding the optimization process. Researchers can establish mathematical correlations between factors and outcomes by extrapolating data from carefully prepared experiments (Birniwa et al., 2022). These correlations can then be used to discover optimal settings for achieving improved RR. Thus, the application of statistical modeling and optimization in asphalt concrete research helps to create more durable and sustainable pavement (Bala & Dayyabu, 2021).

The purpose of this study is to evaluate the influence of bitumen and hydrochar-based geopolymer composite content affect the bituminous concrete's rutting resistance. We use the optimization tool to study how different input factors, notably bitumen content, hydrochar content, and geopolymer content, interact and influence the performance of bituminous concrete to its rutting resistance. This study will help to improve the bituminous concrete design life relating to rutting while learning more about the potential of using hydrochar-based geopolymer composites as an environmentally friendly bituminous concrete modifier.

2. Materials and Methods

2.1 Bitumen, aggregate and filler

The study used penetration grade 60/70 as the control binder and in the synthesis of the modified asphalt binder. The aggregates were chosen with an emphasis on producing optimal aggregate interlocking using the dense gradation method. Crushed granite stones were used for both coarse and fine aggregate, which was blended to achieve a well-proportioned bituminous concrete. Figure 1 shows the study aggregate gradation for bituminous wearing courses based on the Malaysian Public Works Department (PWD). In addition, ordinary Portland cement passed through sieve No. 200 was used as the mineral filler in the investigation. Table 1 shows the physical properties of the bitumen and aggregate utilized in the study following the PWD stipulated standards (Raya, 2008).

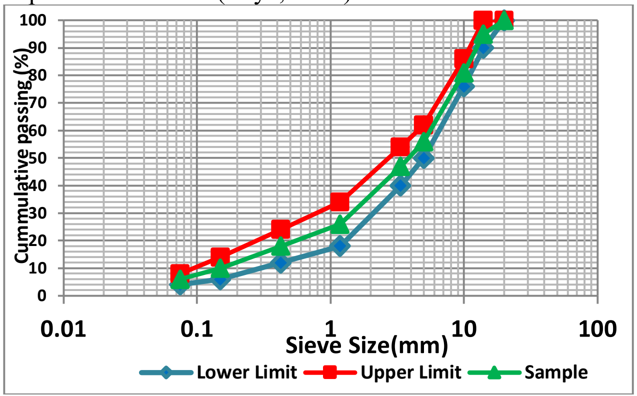


Figure 1: Study aggregate gradation for bituminous wearing course based on PWD standards

Table1: Study materials conventional tests

Properties	Specification	Units	Results	Limits
Bitumen				
Softening point	ASTMD36-12	°C	49.5	45–52
Ductility at 25 °C	ASTM D113-07	cm	121	>100
Penetration	ASTMD5-13	mm	91	80–100
Mass loss	ASTM D2872	%	0.03	-
Specific gravity	ASTMD70-18	-	1.022	1.0–1.05
Fine aggregate				
Flat and elongated tests	ASTM D 4791	%	17.9	
Bulk specific gravity	ASTM C 128	g/cm^3	2.49	
Absorption	ASTM C 127	%	1.22	< 2

Coarse aggregate				
Elongation	BS 812 Part 105.2	%	11.24	<20
Flakiness	BS 812 Part 105.1	%	9.1	<20
Abrasion loss	ASTM C131	%	20.92	
Absorption	ASTM C 127	%	0.62	<2
Bulk specific gravity	ASTM C 127	g/cm^3	2.79	
Aggregate crushing value	BS 812- 110	%	21.11	<30
Hydrochar-based geopolymer composites				
Specific gravity	ASTM C188-17	g/cm^3	2.59	-
Moisture content	ASTM D2216-71	%	0.87	-
Loss of ignition (LOI)	ASTM C311-17	%	9.92	-
Specific surface area	ASTM C1274 - 12	m^2/g	1.103	-
Color	Dusky grey			

2.2 Hydrochar-based geopolymer.

The waste coconut shells (WCS) were purchased from a local company that specializes in coconut oil processing. These WCS samples were properly cleaned and processed, including soaking in distilled water, dehydration, acetone rinsing, and drying. The WCS was hydrothermal carbonization, which involved subjecting them to regulated heating and pressured water in an oxygen-limited atmosphere. The hydrochar and geopolymer composite material was created by combining scrap coconut shells with a mixture of fly ash and metakaolin geopolymer. The method involved blending 15 g of waste coconut shell with 20 g of fly ash and metakaolin geopolymer, followed by 12g of NaOH as an alkali-activator. To ensure homogeneity, the WCS, fly ash, and metakaolin geopolymer combination was finely ground using a porcelain ball grinder. The resulting blend was then passed through screen No.200, and the filtrate was used in the study as a sustainable bitumen modifier.

2.3 Bitumen modification process

In this study, the composite modified bitumen blend was produced by mixing hydrochar and geopolymer with a 60/70 PEN grade bitumen. To guarantee a well-mixed and uniform blend, we added varying volumes of biochar to the base asphalt binder for roughly 1 hour at a high mixing speed of 3800 rpm. Following that, we gradually added varied percentages of geopolymer and mixed them for another 45 minutes at the same pace. This precise mixing procedure was created to enhance the viscoelastic properties of the bitumen for proper use in the bituminous concrete.

2.4 Rutting resistance test

This study performed the rutting resistance test using the wheel tracking test following the BS 598-110 criteria. Compact bituminous concrete samples with varied amounts of bitumen were created and carefully tested. The test, which was done at a set temperature of 60°C following a 6-hour preconditioning period, used a standard axle with defined dimensions and weight. The Wessex wheel tracker evaluated the mean rut depth (MRD) in bituminous concrete samples at 42 passes per minute for 45 minutes and the rut depth was recorded.

2.5 Optimization tool for experimental design and statistical analysis

The optimization tool employed the RSM-based Box Behnken design (BBD) to evaluate the synergetic influence of the three study input factors which are bitumen, hydrochar, and geopolymer content on the MRD of bituminous concrete samples. Statistical analysis and experimental design were conducted employing the Design Expert software package version 13.0.0. The BBD approach allowed for a thorough investigation of the links between input factors and responses. Bitumen content ranged from 4% to 6%, whereas hydrochar and geopolymer content ranged from 0% to 6%. The optimization tool generates 17 randomly ordered trials, with five replications at the center point to account for errors in experimentation as shown in Table 2. The values and ranges of the input variables were detailed in a table, and the response variables were calculated using a second-order polynomial equation (Equation 1).

$$Y = \boldsymbol{\beta_0} + \sum_{x=1}^{n} \boldsymbol{\beta_n X_n} + \sum_{x=1}^{n} \sum_{y \geq x}^{n} \boldsymbol{\beta_{xy} X_x X_y} + \boldsymbol{\varepsilon} \quad \textbf{(1)}$$

Where Y depicts the relationship between the predicted data, (β_0) is the fixed response value, (β_x), the linear impact, (β_{xy}) the synergetic impact, (X_x and X_y) coded elements, and (ε) is the stochastic error within the model.

Table 2: Study design of experiment and response

Run no.	Input factor			Response
	Hydrochar (%)	Geopolymer (%)	Bitumen (%)	Mean rut depth (mm)
1	0	0	5	5.11
2	6	0	5	3.64
3	0	6	5	4.03
4	6	6	5	3.22
5	0	3	4	6.18
6	6	3	4	4.72
7	0	3	6	3.99
8	6	3	6	3.28
9	3	0	4	5.57
10	3	6	4	5.08
11	3	0	6	4.01
12	3	6	6	3.05
13	3	3	5	3.29
14	3	3	5	3.29
15	3	3	5	3.31
16	3	3	5	3.29
17	3	3	5	3.31

3. Results and Discussion

3.1 AVOVA and Fit Statistical Analysis

To acquire a better knowledge of the model's performance in terms of rutting deformation, a thorough statistical study was carried out. We developed a quadratic model for predicting rutting depth using effective regression analysis. The addition of higher-order polynomials indicated statistical significance and remained resistant to any software restrictions, which led to the selection of this quadratic model (Jagaba et al., 2022). Equation 2 summarises the model designed to estimate MRD. A closer look at the equations reveals that there are both positive and negative signs preceding the terms. These symbols indicate whether individual factors interact with the response variable in a synergistic or antagonistic direction. When we see positive signs, it means that the factors have positive impacts on the response. The existence of negative indicators, on the other hand, indicates an antagonistic effect, implying a negative impact on the response variable. In summary, these indicators shed light on the complex interactions that exist between the factors and MRD.

$$\boldsymbol{MRD} = 3.298 - 0.55625A - 0.36875B - 0.9025C + 0.165AB + 0.1875AC - 0.1175BC + 0.4085A^2 + 0.2935B^2 + 0.836C^2 \quad (2)$$

Where A denotes hydrochar, B denotes geopolymer, and C denotes bitumen content.

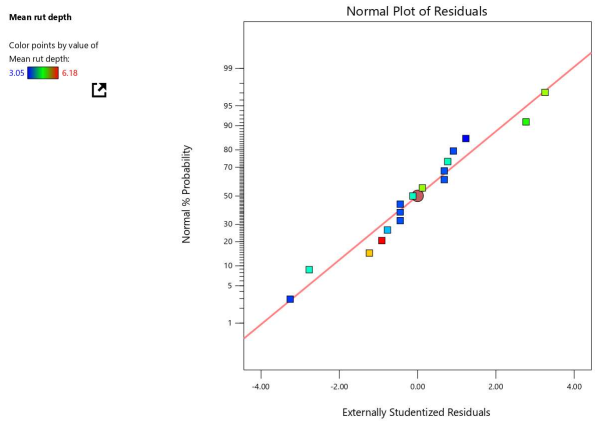
Table 3 presents a full ANOVA summary of our ARD model, which is an important tool for evaluating the model's performance. The coefficient of determination (R^2), which stands at 0.9998, is used to assess the model's interaction. This R^2 result is within 0.2 of the predicted R^2 value. This harmony suggests that the model is well-balanced, with neither overfitting nor underfitting concerns. We used a 95% confidence interval ($P < 0.05$) to verify the significance of the response model and its constituent terms in the context of our MRD investigation. A low P-value indicates that both the quadratic model and its component terms are statistically significant. In this case, a 95% confidence interval corresponds to the likelihood of a P-value less than 0.05 (Bala et al., 2020). Our findings show that the reported F-value of 4579.15 in the rutting resistance model is most likely due to random noise, with a 0.01% chance. This strongly supports the conclusion that the model and its terms have significance in understanding the rutting resistance of bituminous concrete.

Table 3: ANOVA, fit analysis, and model validation

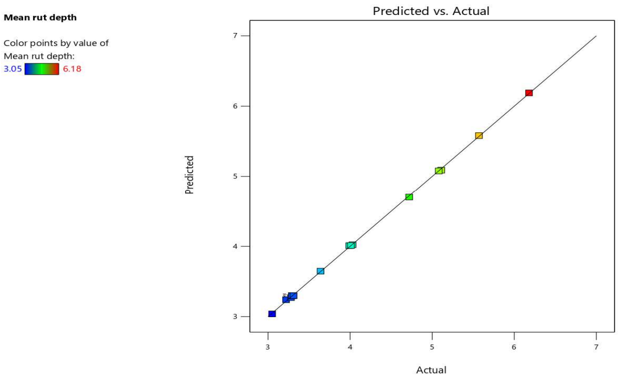
Variable	Mean rut depth (mm)
	Observation
Model	
Remark	Significant
Type	Quadratic
F-value	4579.15
P-value	< 0.0001
Sum of square	14.75
Degree of freedom	9
Mean square	1.64
Lack of fit	
Remark	Insignificant
F-value	5.62
P-value	0.0643
Sum of square	0.0020
Degree of freedom	3
Mean square	0.0007
Fit statistics	
Standard deviation	0.0189
Mean	4.02
Adequate precision	217.1102
R^2	0.9998
Adjusted R^2	0.9996
Predicted R^2	0.9978

3.2 Model diagnostic plots and RSM 2D and 3D surface plots

Figure 2 is a visual depiction used to evaluate the accuracy of the rutting resistance model developed. The figure shows the predicted values (those predicted by the model) to actual observed values. The graphic representation shows a cluster of data points, each representing a response, placed around the line of equality. This clustering and close alignment with the line of equality show a strong level of agreement relating to the model's predicted outcomes and laboratory data (Bala & Dayyabu, 2021). It essentially represents the model's capacity to give accurate forecasts because the points "match up" with the predicted outcomes(Yaro et al., 2021). The proximity of these data points to the line of equality emphasizes the precision and correctness of our model's fit, showing that it accurately describes the actual data. This graphic representation demonstrates the model's dependability and ability to make correct predictions of the rutting depth (Bala et al., 2018).



(a)



(b)

Figure 2: Model diagnostic plots for the developed model

Figure 3 shows the 2D surface plots as well as 3D response surface plots that show the rutting depth model at various bitumen content. These plots, offer a graphical picture of the model's behavior. The appearance of 3D contour lines with elliptical shapes is notable in these displays. These circular contour lines indicate a substantial interaction between the input variables (Usman et al, 2021). These variables under consideration have a significant impact on the model's response. As mentioned by Saeed et al. (2021) this finding accentuates the significance of these factors in deciding the model's outcome. In essence, these visual representations provide crucial insights into the intricate interactions and interactions between the input factors, allowing us to better understand how changes in the study input factors' content (bitumen, hydrochar, and geopolymer) affect the rutting depth model's predictions.

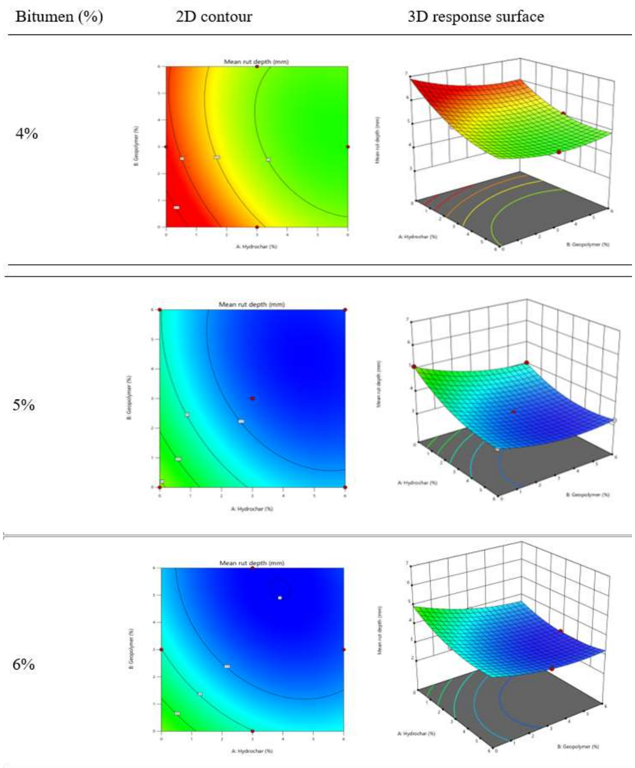


Figure 3: 2D and 3D surface plots show the combined impact of hydrochar and geopolymer on bituminous concrete MRD at varying bitumen contents

3.3 Model variable optimization

We used a numerical optimization method in this study to optimize our design variables and thoroughly validate the precision of the model we produced. Our specific goals were to reduce material utilization while maintaining set ranges for biochar, geopolymer content (ranging from 0% to 6%), and bitumen content (varying from 4% to 6%). We observed the optimum combination of solutions using Expert software, focusing on those with the highest desired score, which equated to an ideal 1.0 Figure 4 depicts the numerous input factors and response trends found during the optimization process. Using RSM software, we arrived at the optimal mix design solution with the maximum desirability value of 1. The results of the optimization indicate certain values that are considered best for optimizing and predicting the rutting resistance performance of the modified bituminous concrete, precisely aligning with the stipulated standards. According to these findings, the input variables for obtaining the desired performance were hydrochar of 3.40%, geopolymer of 3.24%, and bitumen content of 5.75%.

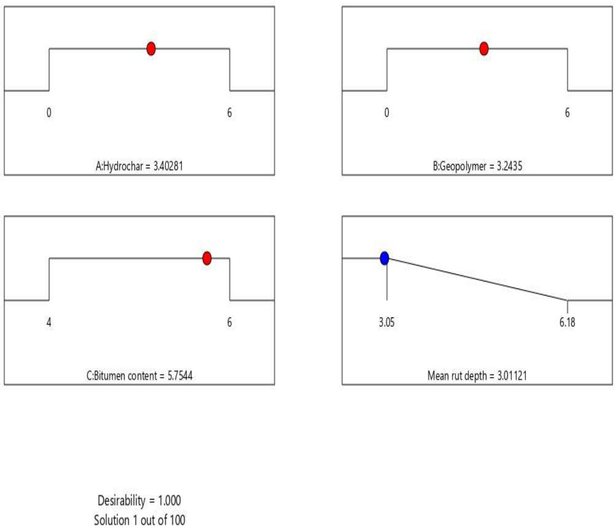


Figure 4: Numerical multi-objective optimization ramps for BGC-MAB asphalt concrete

We further ran supplemental experiments based on the optimized model to properly validate its performance. We used Equation 3 to calculate the percentage error (%) between the experimental findings and the predictions provided by our model during this phase. This thorough methodology allowed us to assess the model's correctness as well as its effectiveness in optimizing material utilization.

$$\boldsymbol{Average}\ (\%)\boldsymbol{Error} = \left|\frac{\boldsymbol{Model\ value - Laboratory\ value}}{\boldsymbol{Model\ Value}}\right| \times \mathbf{100} \quad \textbf{(3)}$$

Table 4 summarises the optimized solutions and the percentage error differences associated with them. Notably, all the percentage error values are less than 5%, demonstrating a remarkable level of agreement between the developed model and the actual laboratory values (Bala & Dayyabu, 2021; Yaro et al., 2022). This strong alignment emphasizes our prediction model's accuracy and dependability, demonstrating its efficiency in optimizing the properties of the modified bituminous concrete in terms of rutting resistance according to standard design parameters.

Table 4: Optimized model Verification

Parameter	Hydrochar (%)	Geopolymer (%)	Bitumen (%)
Model generated values	3.4	3.24	5.75
Model MRD		3.01	
Laboratory MRD		3.14	
Average percentage error (%)		4.32	

Conclusions

This study investigates the optimization of bituminous concrete mixtures using response surface methodology, with a particular focus on enhancing rutting resistance using a hydro char-based geopolymer composite modifier from the study the following conclusions were drawn:

- The use of a hydrochar-based geopolymer composite as a modifier had a substantial influence on the bituminous concrete rutting resistance.
- The RSM models used in the present study demonstrated an impressive level of correlation, predictability, and alignment between projected and actual experimental results. The strong R-squared (R^2) values and accuracy level above 4.0 attest to this great performance.
- The model statistical findings unambiguously indicate the models' dependability and efficacy in traversing the model space and producing precise predictions.
- The RSM 2D and 3D graphs in the study show that the combined impact of the input variables greatly influences the rutting resistance of bituminous concrete. Notably, hydrochar and bitumen appear as the key influences in this interaction.
- The study optimum content was established via RSM multi-objective optimization to be 3.40% hydrochar, 3.24% geopolymer, and 5.75% bitumen content. The average percentage error between the study model-predicted values and laboratory data was observed to be less than 5%, proving the model's accuracy in optimizing and predicting bituminous concrete's rutting resistance.
- This study has provided useful insights into the optimization of bituminous concrete mixtures using response surface methods, with an emphasis on enhancing rutting resistance. Its contributions to theory and practice highlight the possibility of increased pavement performance, cost savings, and sustainability in the field of road construction.

Acknowledgement

The author wishes to express profound gratitude to Universiti Teknologi PETRONAS and Ahmadu Bello University for their outstanding assistance in carrying out this research.

References

Bala, N., & Dayyabu, A. (2021). *Rutting Resistance Evaluation of Composite Modified Asphalt Mixtures: A Response Surface Methodology Approach.* Paper presented at the 2021 1st International Conference on Multidisciplinary Engineering and Applied Science (ICMEAS).

Bala, N., Kamaruddin, I., Napiah, M., & Danlami, N. (2018). Polyethylene polymer modified bitumen: Process optimization and modeling of linear viscoelastic rheological properties using response surface methodology. *Journal of Engineering and Applied Sciences, 13*(9), 2818-2827.

Bala, N., Napiah, M., & Kamaruddin, I. (2020). Nanosilica composite asphalt mixtures performance-based design and optimisation using response surface methodology. *International Journal of Pavement Engineering, 21*(1), 29-40.

Birniwa, A. H., Kehili, S., Ali, M., Musa, H., Ali, U., Kutty, S. R. M., . . . Mahmud, H. N. M. E. (2022). Polymer-based nano-adsorbent for the removal of lead ions: kinetics studies and optimization by response surface methodology. *Separations, 9*(11), 356.

Du, Y., Chen, J., Han, Z., & Liu, W. (2018). A review on solutions for improving rutting resistance of asphalt pavement and test methods. *Construction and Building Materials, 168*, 893-905.

Jagaba, A. H., Bashir, F. M., Lawal, I. M., Usman, A. K., Yaro, N. S. A., Birniwa, A. H., . . . Shannan, N. M. (2023). Agricultural wastewater treatment using oil palm waste activated hydrochar for reuse in plant irrigation: synthesis, characterization, and process optimization. *Agriculture, 13*(8), 1531.

Jagaba, A. H., Kutty, S. R. M., Naushad, M., Lawal, I. M., Noor, A., Affam, A. C., . . . Abioye, K. J. (2022). Removal of nutrients from pulp and paper biorefinery effluent: Operation, kinetic modelling and optimization by response surface methodology. *Environmental research, 214*, 114091.

Raya, J. K. (2008). Standard specification for road works. *JKR/SPJ/rev2005*.

Saeed, S. M., Sutanto, M. H., Napiah, M., Usman, A., Batari, A., Aman, M. Y., & Yaro, N. S. A. (2021). Optimization of rubber seed oil content as bio-oil rejuvenator and total water content for cold recycled asphalt mixtures using response surface methodology. *Case studies in construction materials, 15*, e00561.

Usman, A., Sutanto, M. H., Napiah, M., Zoorob, S. E., Yaro, N. S. A., & Khan, M. I. (2021). Comparison of performance properties and prediction of regular and gamma-irradiated granular waste polyethylene terephthalate modified asphalt mixtures. *Polymers, 13*(16), 2610.

Usman, A., Sutanto, M. H., Napiah, M. B., & Yaro, N. S. A. (2021). Response surface methodology optimization in asphalt mixtures: A review. *Response Surface Methodology in Engineering Science*.

Yaro, N. S. A., Napiah, M. B., Sutanto, M. H., Usman, A., & Saeed, S. M. (2021). Modeling and optimization of mixing parameters using response surface methodology and characterization of palm oil clinker fine modified bitumen. *Construction and Building Materials, 298*, 123849.

Yaro, N. S. A., Sutanto, M. H., Habib, N. Z., Napiah, M., Usman, A., Al-Sabaeei, A. M., & Rafiq, W. (2022). Mixture design-based performance optimization via response surface methodology and moisture durability study for palm oil clinker fine modified bitumen asphalt mixtures. *International Journal of Pavement Research and Technology*, 1-28.

Yaro, N. S. A., Sutanto, M. H., Habib, N. Z., Usman, A., Kaura, J. M., Murana, A. A., . . . Jagaba, A. H. (2023). A Comprehensive Review of Biochar Utilization for Low-Carbon Flexible Asphalt Pavements. *Sustainability, 15*(8), 6729.

Zhao, S., Huang, B., Ye, X. P., Shu, X., & Jia, X. (2014). Utilizing bio-char as a bio-modifier for asphalt cement: A sustainable application of bio-fuel by-product. *Fuel, 133*, 52-62.