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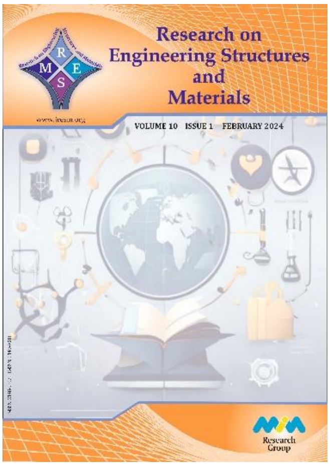

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Online Publication Date: 22 January 2024
URL: http://www.jresm.org/archive/resm2024.83ma1117rs.html
DOI: http://dx.doi.org/10.17515/resm2024.83ma1117rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Daniel O, Olumide O, Oluwasegun A, Yusuf B. RSM based modelling and optimization of Marshall properties of steel-slag and lime-modified asphalt mixtures. *Res. Eng. Struct. Mater.*, 2024; 10(3): 1065-1084.

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Research Article

RSM based modelling and optimization of Marshall properties of steel-slag and lime-modified asphalt mixtures

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Article Info

Article history:

Received 17 Nov 2023
Accepted 22 Jan 2024

Keywords:

Response surface methodology;
Box Behnken design;
Modified asphalt mixtures;
Steel slag;
Lime;
Marginal aggregates

Abstract

Statistical and optimization techniques are useful tools in understanding the interactions and relationships between the asphalt mix variables and the contribution of each variable to the resulting asphalt mixture properties. This study explores the response surface methodology to study the influence of steel slag and lime on the Marshall properties of asphalt mixtures using Box Behnken Design tool. The independent variables considered are steel slag (0-100%), lime (0-4%) and bitumen (4-8%). The stability, flow, Marshall quotients, bulk density, Vb and VMA obtained were 1.98-6.35kN, 3.27-4.53 mm, 0.53-1.60kN/mm, 2.08-2.29 kg/m^3, 7.67-14.7% and 14.02-24.63%, respectively; indicating that the steel-slag and lime-modified asphalt mixtures satisfy the specification limits recommended by the asphalt institute and Nigeria General Specification for Roads and Bridges. The models' analysis of variance revealed could well predict the Marshall properties of the mixtures, and the terms of steel-slag, lime and bitumen content are significant. Likewise, based on the optimization analysis, 24.93% of steel slag, 2.43% of lime and 5.51% of bitumen content were selected as the optimal values for the modified asphalt mixtures. Additionally, a mean error of less than 5% was attained for all the responses, demonstrating the effectiveness of RSM in designing asphalt mixtures.

1. Introduction

The exceptional performance of asphalt mixture has made it a widely used paving material worldwide [1]. In service life, asphalt pavements are exposed to mechanical load from vehicle axles and negative environmental conditions such as thermal load [2]. Permanent deformation is created in the asphalt by the repeated vehicular loads arising from the traffic density [3-4]. These loads result in pavement degradation, thereby reducing the intended service life. To minimize the impacts, there is a need to modify the asphalt mixtures to improve the properties of the asphalt. Incorporating various materials in the asphalt mix has been found suitable for transforming the mechanical and binding properties of asphalt. Modifying the asphalt mixes enhances the performance and increases the service life of asphalt pavement [5-6]. Steel slags are industrial waste from the production of steel. They are non-metallically inert, containing silicates, aluminosilicates, and calcium aluminosilicates [7].

It constitutes about 15 – 20 % of steel/iron production. It has been estimated that 14, 21, 30, and 100 million tons of steel slags are annually generated as waste in Europe, Japan, India, and China, respectively [8]. Currently, there is no reliable data regarding the annual

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DOI: http://dx.doi.org/10.17515/resm2024.83ma1117rs

generation of slag in Nigeria. However, it has been reported that one tone of rolled steel would produce half tone of slag [9-10]. Nigeria has over 30 steel manufacturers with annual steel production of 2.2 million tons [11], which suggested that roughly 1 million tons of slag are produced during the year. Most of the waste is in landfills and occupies huge land areas. Also, it threatened the natural water and soil due to the proclamation of alkaline leachates [12]. As a result, researchers have made efforts to use steel slag as construction materials. Steel slag is reported to improve the strength properties of concrete and geopolymer concrete [13]. Using steel slag in an asphalt mixture would promote sustainable construction and reduce its environmental effect [14].

Lime is a natural, chemically active material with the ability to resist moisture, reduce the chemical ageing of bitumen, and improves the bonding strength between asphalt binder and aggregates [15-16]. It is commonly used as an anti-stripping agent and added to aggregates to improve the resistance of asphalt pavement to moisture damage. Moisture on asphalt pavement can damage the structure, such as rutting, raveling, cracking, bleeding, and localized failure [17]. There are three major forms of lime; dolomitic lime (CaO.MgO), hydrated lime (Ca (OH)2), and quick lime (CaO), but hydrated lime is usually used in asphalt mixtures [17].

Statistical and optimization techniques are useful tools for understanding the interactions and relationships between the asphalt mix variables and the contribution of each variable to the resulting properties of the asphalt [18-23]. One of the commonly adopted statistical tools in the design of experiments (DOE) is response surface methodology (RSM) [4]. The RSM approach considers the influence of several factors at different levels on the response simultaneously and gives a suitable predictive model to describe the relationship between the various factors [24-25]. This offers an opportunity to modify the mix proportions of the asphalt constituents to achieve desired properties, and it eliminates a situation whereby the target strength characteristic is not attained or the production of asphalt with excessive strength [2, 26]. Additionally, compared to traditional methods, utilizing RSM would significantly reduce the number of experiments needed to model the response functions [27]. Designing, conceiving, developing, and assessing new scientific studies and products depend on the RSM. It is also effective in enhancing current research and output. Hence, by incorporating RSM into pavement technologies, researchers can access more rapid, accurate, and reliable methods of analyzing changes in pavement performance and improved experimental matrices [28].

The mix proportioning of the constituent materials is crucial to achieve the desired targeted qualities. Hence, the design of the experiment (DOE) using software tools like RSM for mix proportioning is essential. The RSM was utilized in this study to investigates the influence of steel slag and lime on the Marshall properties of asphalt mixtures. The utilization of RSM in this study will identify the ideal substitution of steel-slag and lime in asphalt mixtures that are most effective to the performance of steel-slag and lime-modified asphalt mixtures.

2. Materials and Methods

2.1. Materials

- *Aggregate*: The granite used for the coarse aggregate was 12.5mm, and 10mm granite, was sourced from a local market in Omu-Aran, Kwara State. As the fine aggregate, quarry dust that passes through a 4.75 mm sieve was employed. The filler used in this study is stone dust that passes a 75-m sieve. Table 1 displays the aggregates' characteristics and Fig. 1 shows the grading curve used for asphalt mixture.

- *Steel slag*: The steel slags from Prism Steel Mills Limited in *Ikirun*, Nigeria, were used in this study (see Figure 2). Because it was produced during the refinement of scrap steel in an electric-arc furnace, this slag is also known as an electric-arc furnace (EAF) slag. The 12.5mm coarse aggregate was replaced with steel slag.
- *Bitumen*: Penetration grade 60/70 of bitumen was used in this study. Table 2 displays the properties of bitumen.

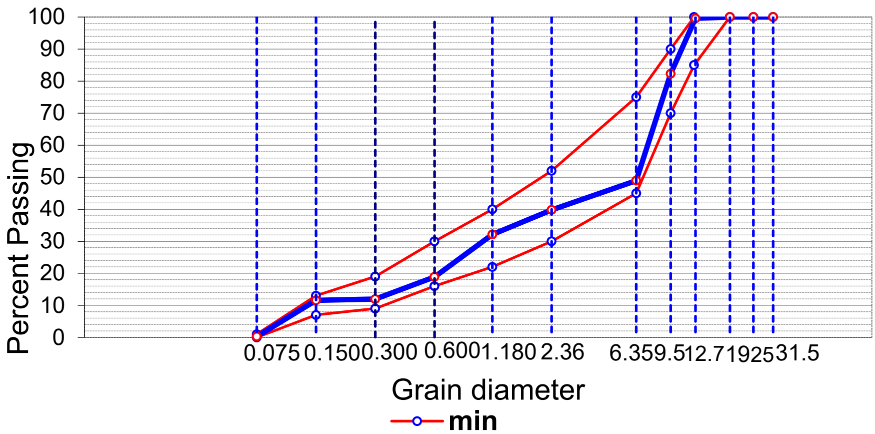


Fig. 1. Asphalt mixture grading curve

Fig. 2. Samples of steel-slag

Table 1. Aggregate properties

Parameters	Steel-slag	Granite	Specification	Standard
Aggregate Impact Value (%)	9.5	19.44	30% max	[29]
Aggregate crushing value (%)	13.6	17.2	30% max	
Specific gravity	2.44	2.71	2.5-3.0	
Flakiness index (%)	19.1	23.6	30% max	
Elongation (%)	18.7	13.3	30% max	
Aggregate abrasion value (%)	30.2	26.7	40% max	
Water absorption (%)	1.69	0.17	4% max	

Table 2. Bitumen Properties

Parameters	Specification	Value	Standard
Penetration @ 25°C	60-70	66	
Ductility @ 25°C	100 MIN	121	
Solubility	99.5 MIN	107.00	
Viscosity (secs)	2400 MIN	2753	
Flash Point (C)	≥ 250	287	
Softening Point	55-65	56	[29]
Specific gravity @ 25°C	1.01-1.06	1.02	
Minimum Loss on Heat for 5 hours at 163ºC	Max. 0.2	0.08	
Drop in Penetration after heating	Max. 20	13.5	

2.2. Mix Design

The Design Expert software version 13 was used to create the experimental runs utilising the Box Behnken Design (BBD) approach. Table 3 displays the three factors (independent variables) that were taken into consideration: steel slag (A), lime (B) and bitumen (C). The generated experimental run used for steel-slag and lime-modified asphalt mixtures is shown in Table 4.

Table 3. Independent parameters, including coded levels

Parameters	Code	Unit	Coded parameter levels		
			-1	0	+1
Steel Slag	A	%	0	50	100
Lime content	B	%	0	2	4
Bitumen content	C	%	4	6	8

Table 4. Experimental design for steel-slag and lime modified asphalt mixtures

S/N	Steel Slag; A (%)	Lime Content; B (%)	Bitumen Content; C (%)
1	0	2	4
2	0	4	6
3	100	2	4
4	100	2	8
5	0	0	6
6	50	0	4
7	50	2	6
8	50	0	8
9	100	4	6
10	50	2	6
11	50	2	6
12	50	2	6
13	50	2	6
14	0	2	8
15	100	0	6
16	50	4	4
17	50	4	8

2.3. Mixture Preparation and Testing

Two design techniques that are commonly used in asphalt mixtures are the Marshall and Superpave techniques, in which the volumetric features are seen as responses to the creation of more dependable asphalt mixtures.

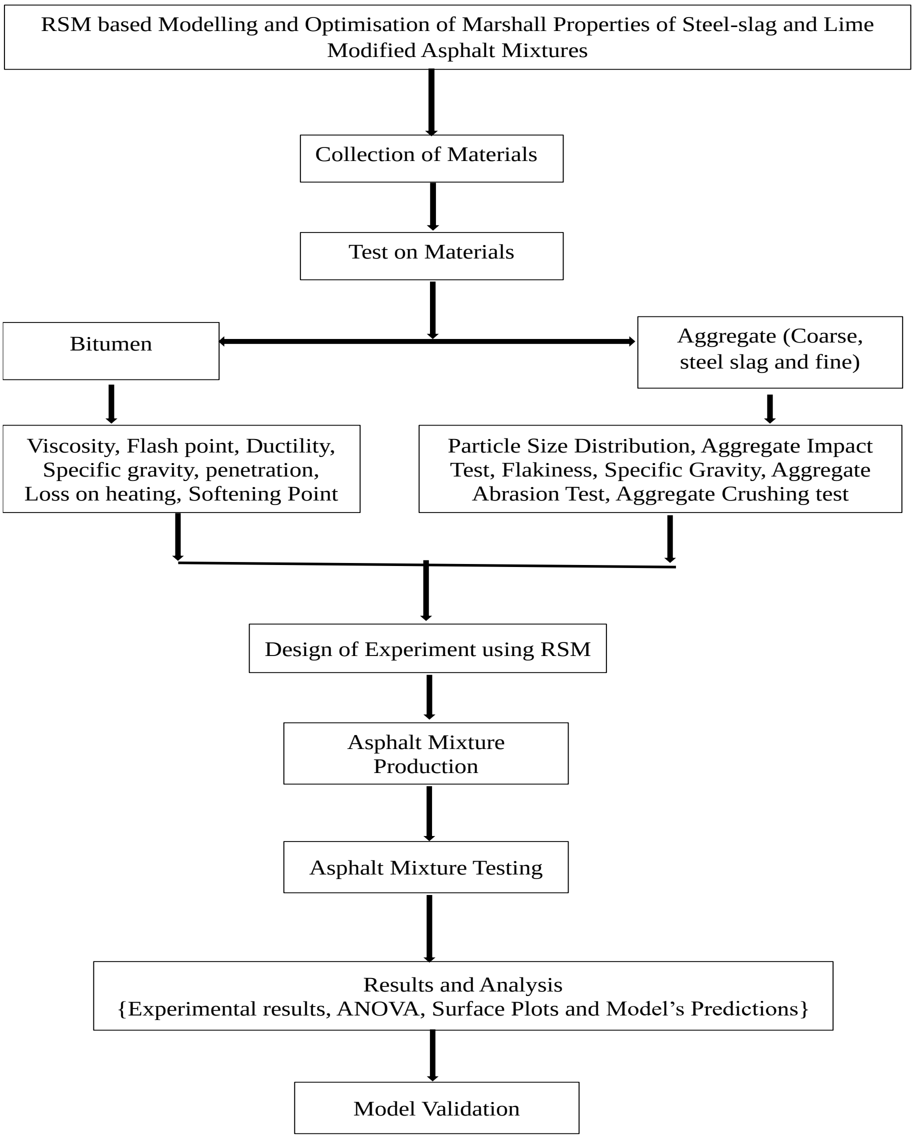


Fig. 3. Flow chart for the study

Nonetheless, the Marshall approach's relative simplicity, affordable equipment, and straightforward process make it a highly well-liked asphalt mixture design method [1, 30-31]. In this study, the asphalt mixtures were made using the Marshall method in compliance with ASTM D 1559-89 [32] standards using Table 4. The constituent materials were heated, mixed, then compacted using 75 blows (top and bottom) to create the mixes.

Following compaction, the mixtures, measuring roughly 101 mm in diameter and 63.5 mm in thickness, were suitably placed on a level, smooth surface and let to rest overnight at room temperature before being tested. Figure 3 displayed the flowchart of the research methodology used to achieve the study.

3. Results and Discussion

3.1 Marshall Properties of the Steel-slag and Lime-Modified Asphalt Mixtures

Figure 4 displays the Marshall properties of the steel-slag and lime-modified asphalt mixtures. While the Marshall stability values vary, mixture (Mix-9) with 100% steel slag and 4% lime has the highest Marshall Stability at 6.35kN and mixture (Mix-12) with 50% steel-slag and 2% lime has the lowest Marshall Stability at 1.98kN. In addition, whereas the mixture (Mix-15) with 100% steel slag and 0% lime produced the highest flow, the mixture (Mix-5) with 0% steel slag and 0% lime produced the lowest flow. This mixture's high flow value also implies strong flexibility, which improves the HMA pavement's capacity to deform without cracking. It can infer that the mixture's Marshall stability is increased by adding steel slag and lime, whilst the flow is the opposite. As a result, when modifying asphalt mixtures for strength (stability), steel slag and lime are preferred. However, the Marshall test necessitates both higher stability and lower flow [33]; while the Marshall flow of asphalt concrete refers to its resistance to slow settlements and movements in the sub-grade without cracking, the Marshall stability of asphalt concrete refers to its resistance to pushing and rutting under traffic [16]. In addition, except mixes 14, 15, and 17, all of the modified asphalt mixtures' obtained flows fall within the advised range of 2-4 mm for wearing course application. Additionally, only mixes 12, 5, and 2 falls below the suggested minimum of 3.5kN for the stability value.

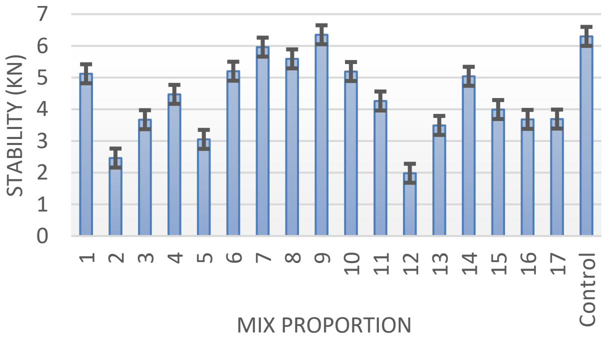
The material's resistance to shear loads and permanent deformation is measured by the Marshall quotient (MQ). The ratio of the asphalt mixture's stability to flow is sometimes called the rigidity of the asphalt mix [34]. Mix-7 with 50% steel slag and 2% lime and Mix-9 with 100% steel slag and 4% lime had the highest MQ of 1.60 kN/mm, as shown in Figure 4c. The stability that is reached when the flow is still low is what is causing this increase in MQ; as the flow increases, the strength drops [35]. In addition, it has been found that the combinations with the highest MQ values contain both lime and steel slag. Consequently, lime and steel slag can be used to enhance asphalt mixtures.

Additionally, Figure 4d demonstrates that mixes 15 (100% steel slag and 0% lime), 11 (50% steel slag and 2% lime), and 6 (50% steel slag and 0% lime) all achieved the highest bulk density value of 2.29 kg/m^3. The inclusion of micro-fine lime particles in the HMA, which raise the mix's density [36], causes the increase in bulk density.

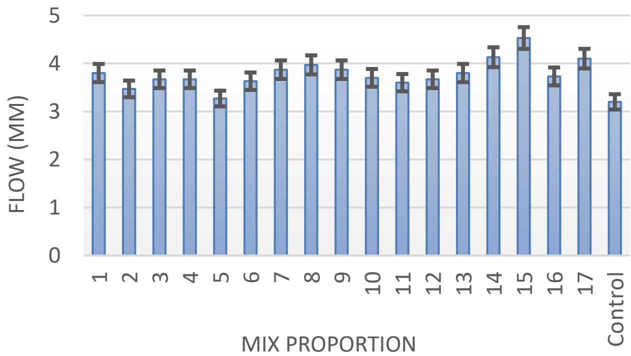
The term "void in mineral aggregate" (VMA) refers to the empty space between the aggregate particles in a compacted mix. It indicates the available space for bitumen to coat each aggregate particle adequately. It can be seen from Figure 4f that the VMA values of the steel slag and lime-modified asphalt mixtures range from 14.82% to 24.63% for mixture 3 (100% steel slag and 2% lime) and mixture 8 (50% steel slag and 0% lime), respectively. This trend of VMA values is due to the difference in the aggregate gradings of the two materials (steel slag and granite)

Overall, the results shown in Figure 4 might not truly reflect the effect of steel slag and lime on Marshall's properties because of the variations in values obtained. However, in general, it can be seen that it is possible to produce steel-slag and lime-modified asphalt mixes that satisfy the specification limits recommended by the Asphalt institute [37] and Nigeria General Specification for Roads and Bridges [29].

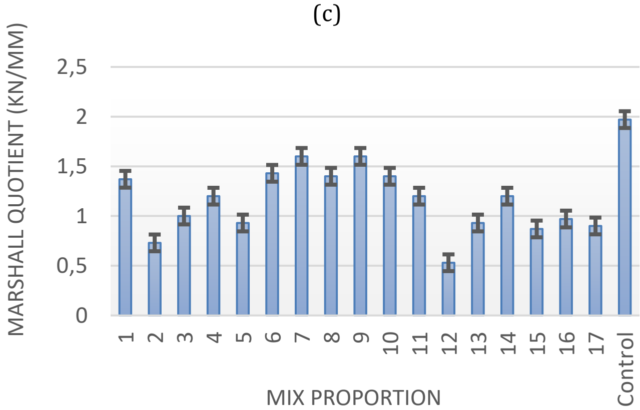
(a)


STABILITY (KN)
0
1
2
3
4
5
6
7
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 Control
MIX PROPORTION

(b)


FLOW (MM)
0
1
2
3
4
5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 Control
MIX PROPORTION

(c)


MARSHALL QUOTIENT (KN/MM)
0
0,5
1
1,5
2
2,5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 Control
MIX PROPORTION

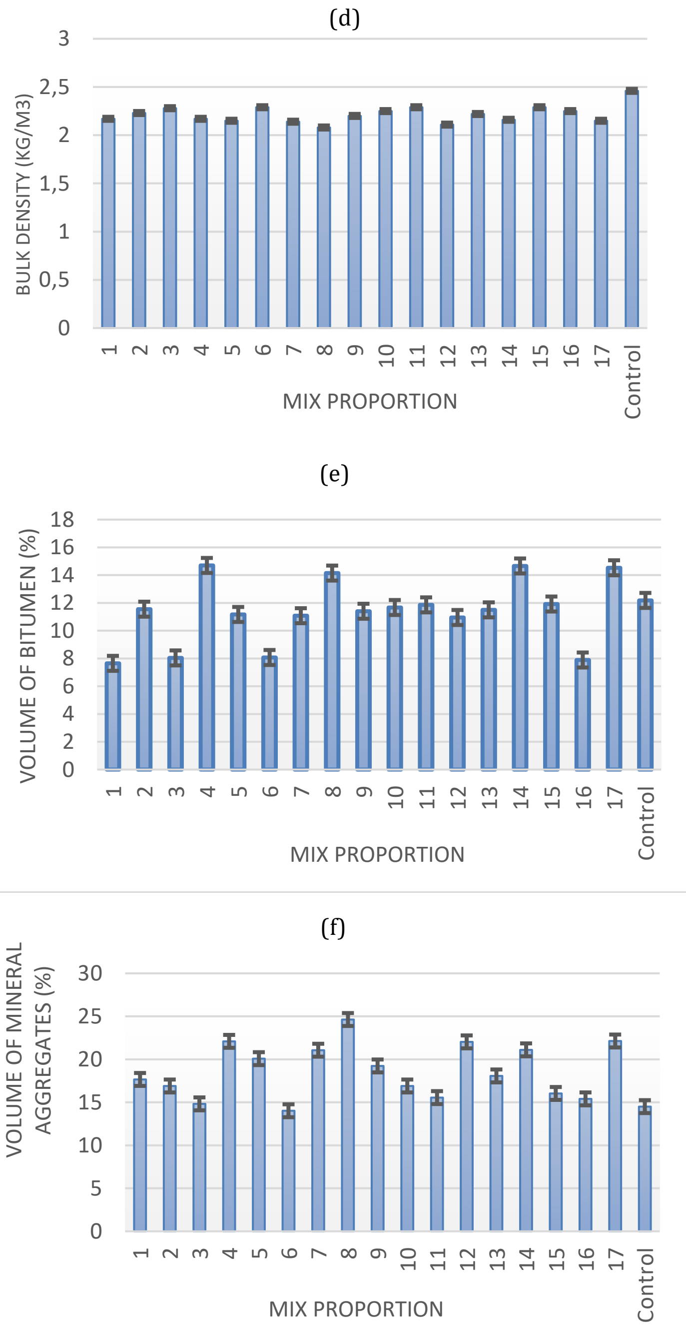


Fig. 4. Marshall Properties of Steel-slag and lime-modified asphalt mixtures (a) Stability (b) Flow (c) MQ (d) Bulk density (e) Vb and (f) VMA

3.2 Response Surface Analysis

3.2.1 The Analysis of Variance (ANOVA) and Regression Models for the Modified Asphalt Mixtures

Table 5 shows the results of the ANOVA for the Marshall characteristics of steel slag and lime-modified asphalt. After demonstrating the highest F-values for flow, stability, Marshall quotient, bulk density, volume of bitumen, volume of mineral aggregates, and volume filled with bitumen, respectively, along with the necessary Prob>F0.05 in all of the models investigated for the volumetric properties, bitumen content was found to be the most influencing and significant factor among the independent variables. These values were 10.87, 33.92, 41.74, 13.44, 853.26 and 22.8. The model's F-values of 4.84, 14.59, 12.64, 4.50, 284.85, and 7.76 for all the responses, along with Prob>F values of 0.0001 for all responses, demonstrate the model's relevance. A P>F value of 0.05 typically denotes that the model's terms are significant (Bala et al., 2018). In all the models, the difference between the adjusted and predicted R^2 is less than 0.2, justifying that the models are significant and selected to fit the experimental data more. The range of expected values at design points against the average prediction error yields what is known as "adequate precision" (AP). According to the fundamental criteria, an AP ratio greater than 4 is acceptable [24]. For all responses, this study found AP ratios of 7.1081, 12.1590, 10.8185, 5.6483, 44.2315 and 7.8572. The selected models may satisfactorily travel the design space using BBD to supply the parameters for the ideal mix design, as indicated by these values, which also suggest an adequate signal. The coefficients of the polynomial model were calculated to fit the experimental data. The final regression model equations regarding significant factors are expressed in Equations [1]-[6]. Similar regression equations were reported by Lapian et al. [3] and Wang et al. [1].

Table 5. ANOVA results for properties of steel-slag and lime modified asphalt mixtures

Response	SoD	SoS	DoF	MS	F-value	P-value	Comment
Flow							
	Model	0.7717	3	0.2572	4.84	0.0178	SD=0.2306
	A	0.1326	1	0.1326	2.49	0.1383	Mean=3.12
	B	0.0612	1	0.0612	1.15	0.3026	R^2=0.6185
	C	0.5778	1	0.5778	10.87	0.0058	Adj. R^2=0.4581
	Residual	0.6911	13	0.0532			AP=7.1081
	Lack of Fit	0.4193	9	0.0466	0.6854	0.7078	
	Pure Error	0.2719	4	0.0680			
Stability							
	Model	45.91	9	5.10	14.59	0.0009	SD=0.5913
	A	3.77	1	3.77	10.78	0.0134	Mean=5.82
	B	1.44	1	1.44	4.11	0.0823	R^2=0.9494
	C	11.86	1	11.86	33.92	0.0006	Adj. R^2=0.8843
	AB	3.50	1	3.50	10.00	0.0159	AP=12.1590
	AC	2.71	1	2.71	7.74	0.0272	
	BC	0.0506	1	0.0506	0.1448	0.7148	
	A^2	1.15	1	1.15	3.29	0.1124	
	B^2	18.80	1	18.80	53.78	0.0002	
	C^2	3.04	1	3.04	8.69	0.0215	

	Residual	2.45	7	0.3496			
	Lack of Fit	0.8291	3	0.2764	0.6833	0.6072	
	Pure Error	1.62	4	0.4045			
Marshall Quotient (MQ)							
	Model	6.46	9	0.7175	12.64	0.0015	SD =0.2382
	A	0.6294	1	0.6294	11.09	0.0126	Mean=1.90
	B	0.2567	1	0.2567	4.52	0.0710	R^2=0.98
	C	2.37	1	2.37	41.74	0.0003	
	AB	0.2587	1	0.2587	4.56	0.0702	Adj. R^2=0.8675
	AC	0.1339	1	0.1339	2.36	0.1685	AP=10.8185
	BC	0.0048	1	0.0048	0.0841	0.7803	
	A^2	0.2209	1	0.2209	3.89	0.0891	
	B^2	2.37	1	2.37	41.80	0.0003	
	C^2	0.2203	1	0.2203	3.88	0.0895	
	Residual	0.3973	7	0.0568			
	Lack of Fit	0.0775	3	0.0258	0.3229	0.8100	
	Pure Error	0.3198	4	0.0800			
Bulk Density							
	Model	0.0486	3	0.0162	4.50	0.0225	SD=0.06
	A	0.0002	1	0.0002	0.0433	0.8384	Mean=2.21
	B	0.0000	1	0.0000	0.0035	0.9539	R^2=0.8509
	C	0.0485	1	0.0485	13.44	0.0028	Adj. R^2=0.70396
	Residual	0.0469	13	0.0036			AP= 5.6483
	Lack of Fit	0.0247	9	0.0027	0.4965	0.8240	
	Pure Error	0.0221	4	0.0055			
Volume of bitumen (Vb)							
	Model	87.20	3	29.07	284.85	< 0.0001	SD=0.3194
	A	0.1307	1	0.1307	1.28	0.2781	Mean=11.34
	B	0.0006	1	0.0006	0.0054	0.9426	R^2=0.9850
	C	87.07	1	87.07	853.26	< 0.0001	Adj. R^2=0.8616
	Residual	1.33	13	0.1020			AP= 44.2315
	Lack of Fit	0.7304	9	0.0812	0.5446	0.7939	
	Pure Error	0.5961	4	0.1490			
Voids in the Mineral Aggregates (VMA)							
	Model	99.99	3	33.33	7.76	0.0032	SD=2.07

A	1.59	1	1.59	0.3696	0.5537	Mean=18.69
B	0.1478	1	0.1478	0.0344	0.8557	R^2=0.6416
C	98.25	1	98.25	22.87	0.0004	Adj. R^2=0.5589
Residual	55.85	13	4.30			AP= 7.8572
Lack of Fit	25.60	9	2.84	0.3760	0.8973	
Pure Error	30.25	4	7.56			

$$Stability\ (kN) = 6.656 - 0.68625A + 0.42375B - 1.2175C - 0.935AB - 0.8225AC + 0.1125BC - 0.523A^2 - 2.113B^2 + 0.8495C^2 \quad (1)$$

$$Flow\ (mm) = 3.12412 + 0.12875A - 0.0875B + 0.26875C \quad (2)$$

$$MQ\ \left(\frac{kN}{mm}\right) = 2.25419 - 0.280495A + 0.179147B - 0.544157C - 0.254307AB - 0.182947AC - 0.0345347BC - 0.229049A^2 - 0.750617B^2 + 0.228752C^2 \quad (3)$$

$$Bulk\ Density = 2.21339 + 0.00441667A + 0.00125B - 0.0778333C \quad (4)$$

$$V_b = 11.3401 + 0.127833A + 0.00829167B + 3.29896C \quad (5)$$

$$VMA = 18.6876 - 0.445542A - 0.135917B + 3.50445C \quad (6)$$

3.2.2 Normality Plot for the Marshall Properties of Steel-slag and Lime-Modified Asphalt Mixtures

To ensure that the actual vs anticipated plots and residuals for every property under investigation were normal, data were evaluated. The normal probability plots of the residuals and the actual vs anticipated data for the asphalt mixtures treated with lime and steel slag are shown in Figure 5(a–f).

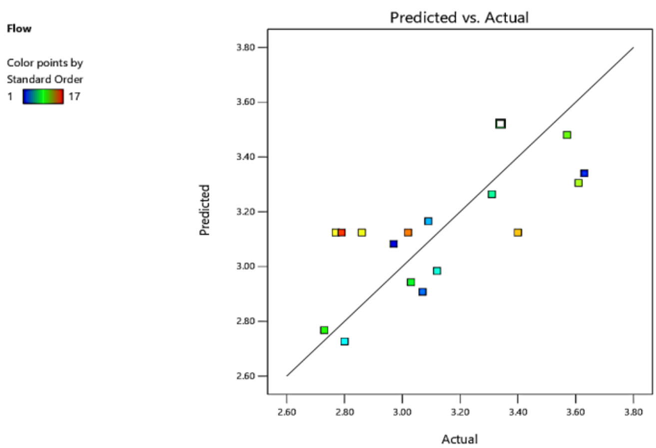


Fig. 5a. Normal probability distribution plot of flow for steel-slag and lime-modified asphalt mixtures

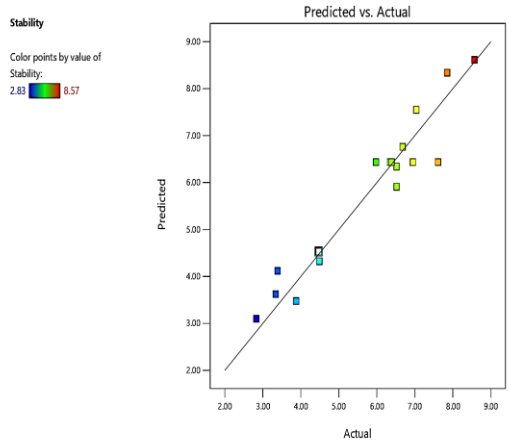


Fig. 5b. Normal probability distribution plot of stability for steel-slag and lime-modified asphalt mixtures

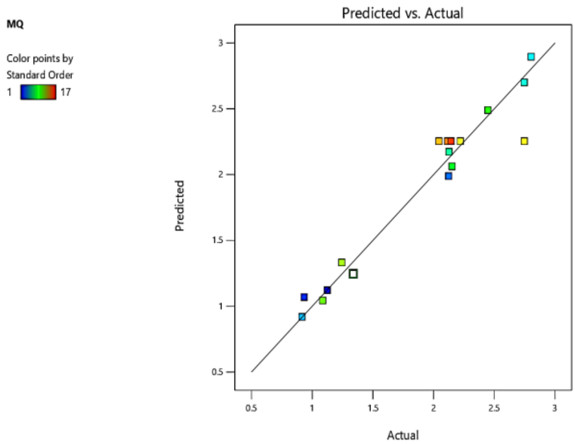


Fig. 5c. Normal probability distribution plot of MQ for steel-slag and lime-modified asphalt mixtures

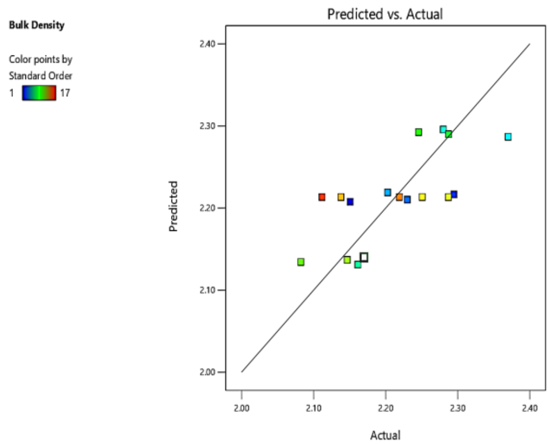


Fig. 5d. Normal probability distribution plot of Bulk Density for steel-slag and lime-modified asphalt mixtures

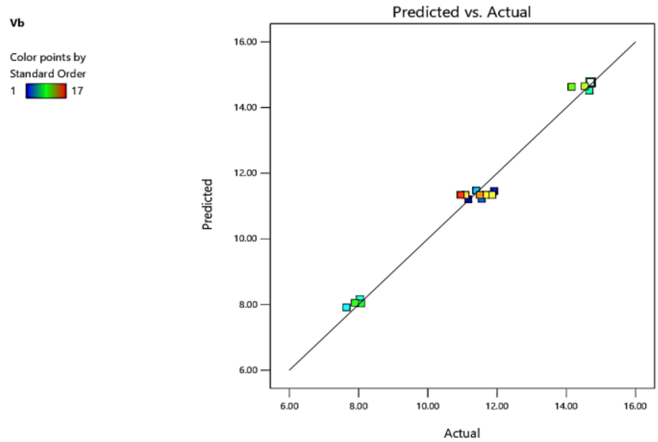


Fig. 5e. Normal probability distribution plot of Vb for steel-slag and lime-modified asphalt mixtures

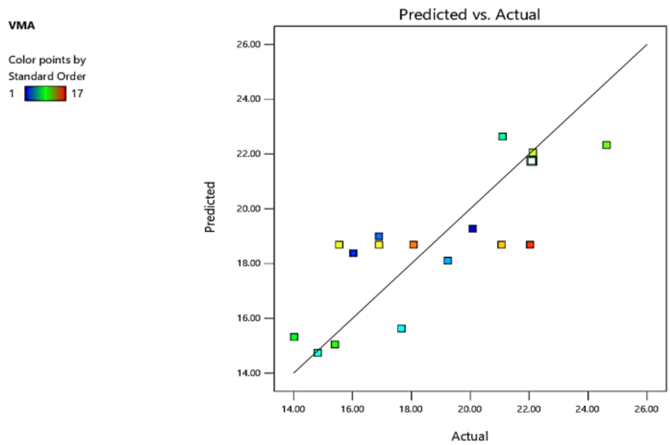


Fig. 5f. Normal probability distribution plot of VMA for steel-slag and lime-modified asphalt mixtures

From the Figures of the normal probability of students' residuals for all the properties, it can be seen that there is very less scattered along the straight line. This shows that the data is normally distributed, and almost all variations were credited to the variable factors studied. Plot predictions against actual values were used to check the model's suitability. The plot of predicted against actual indicates whether an acceptable agreement exists between the experimental results and those found from developed models. From the plots of predicted versus actual for all the properties, it can be seen that the observed points are relatively on a straight line. This justified that adequate agreement exists between the experimental results and those obtained from the model. Thus, it was evident that, in general, a normal distribution plot was a useful option for assessing the interested responses.

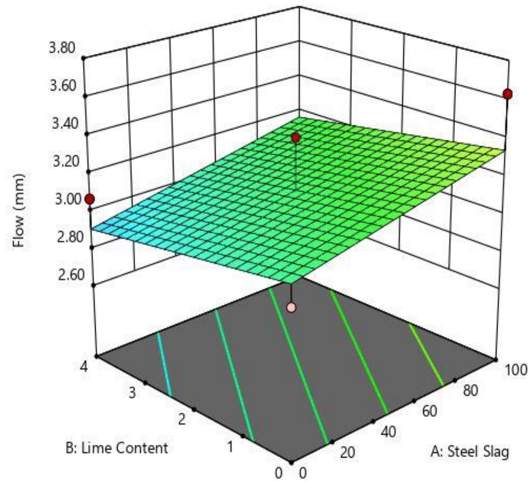
3.2.3 Surface Plots of the Marshall Properties of Steel-slag and lime-modified Asphalt mixtures

To examine the interactive relationship between the parameters and the properties of the asphalt mixtures modified with lime and steel slag under optimal conditions, response surface plots are utilized. The three-dimensional surface views (3D surface plots) show the detailed behavior of the independent variables within the experiment.

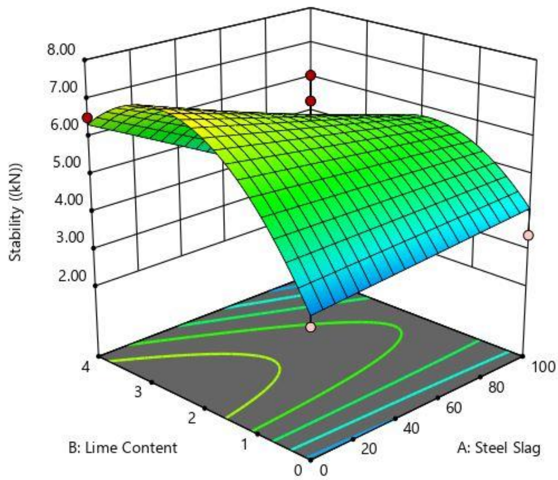
The 3D response surfaces plots for the Marshall responses based on the effects of the interactive variables, steel-slag, lime and bitumen content, as shown in Figures 6 (a-f).

The response surfaces for flow (Figure 6a) show that the factors have significant interaction effects on the flow. It can be observed that a decrease in the lime content increased the flow. Furthermore, with an increase in the steel slag by up to 73%, the flow increased slightly.

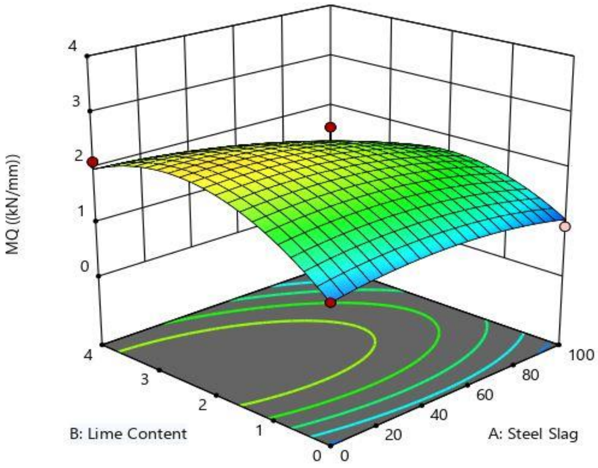
Figure 6b shows the response surfaces for the Marshall stability of the steel slag and lime-modified asphalt mixtures. The 3D plot curvature indicates that as the lime content increases up to 2%, there was an increase in the Marshall stability and a decrease afterwards. The addition of steel slag resulted in constant stability. Hence, stability is strongly influenced by lime content. It was also reported by Ogundipe [38] that the utilization of lime in asphalt mixtures resulted in an increment in stability. Furthermore, based on the plot, it is evident that all of the parameters interact well with one another.



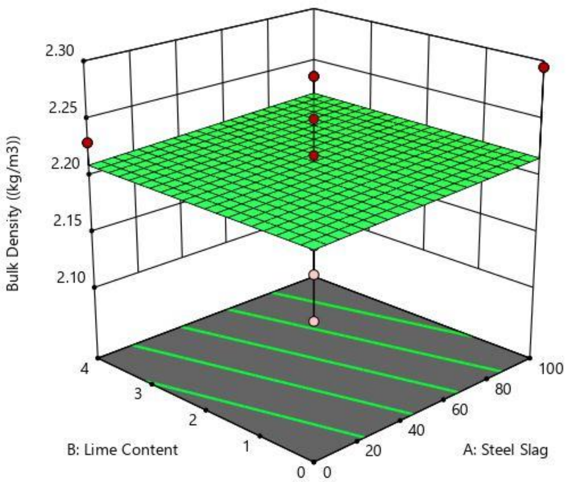
(a)



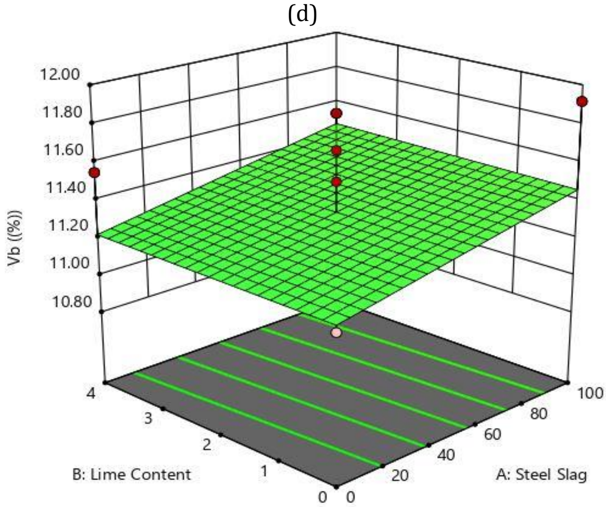
(b)


MQ ((kN/mm))
4
3
2
1
0
B: Lime Content
A: Steel Slag
0
1
2
3
4
0
20
40
60
80
100

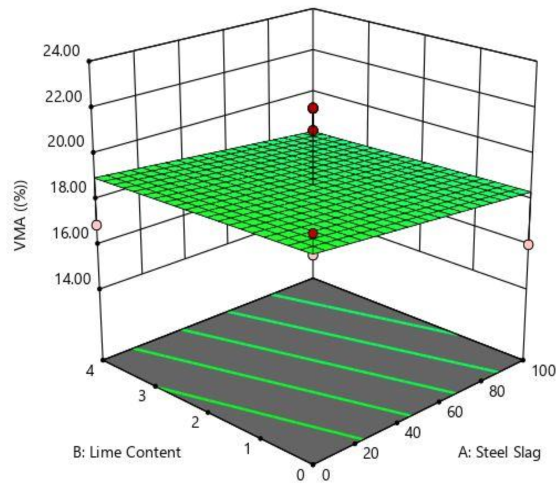
(c)


Bulk Density ((kg/m3))
2.30
2.25
2.20
2.15
2.10
B: Lime Content
A: Steel Slag
0
1
2
3
4
0
20
40
60
80
100

(d)


Vb ((%))
12.00
11.80
11.60
11.40
11.20
11.00
10.80
B: Lime Content
A: Steel Slag
0
1
2
3
4
0
20
40
60
80
100

(e)



(f)

Fig. 6. Response surface plots for the Marshall properties of steel-slag and lime-modified asphalt mixtures

3.2.4 Mix Design Optimization

In this study, design variables were optimized, and the accuracy of the developed models was assessed using the RSM optimization tool, a numerical optimization method. The target aims for each mix design factor (A, B, and C) selected, as shown in Table 6 for steel-slag and lime modified, was set to achieve this. The intended stability, MQ, and bulk density, VMA, were defined as maximal to get the greatest results. To achieve great performance, the desired flow was defined in the range. According to the optimization results, the ideal values to meet the design requirements are 24.93% steel slag, 2.43% lime and 5.51% bitumen content. A second experiment was run to verify the model's predictions based on the ideal projected mix design elements.

Table 6. Design conditions for optimisation

Responses	Units	Lower limit	Upper limit
Flow	Mm	2	4
Stability	kN	Maximum range	
MQ	kN/mm	Maximize	
Bulk Specific gravity	kg/m^3	Maximum	
VMA	%	17	
Vb	%	non	

Table 7. Optimum conditions achieved for steel-slag and lime-modified asphalt mixtures

Response	Unit	Predicted	Observed	Error (%)
Flow	mm	3.12	3.04	2.63
Stability	kN	6.67	6.58	2.13
MQ	kN/mm	2.25	2.16	4.17
Bulk density	kg/m^3	2.21	2.19	0.91
Vb	%	11.34	11.22	1.07
VMA	%	18.69	19.25	2.91

Table 7 shows the percentage error difference; It showed that the expected values for the developed models agree with the experimental values, with less than 5% for all responses. In Liu et al. [39], the error between the predicted and actual values of the asphalt indexes was also found to falls within an acceptable range.

5. Conclusions

The mix proportioning of the constituent materials is crucial to achieve the desired targeted qualities. Hence, the design of the experiment (DOE) using software tools like RSM for asphalt mix proportioning is essential. Incorporating RSM into pavement technologies, researchers can access more rapid, accurate, and reliable methods of analyzing changes in pavement performance and improved experimental matrices. In this study, the Box Behnken Design (BBD) tool in Response Surface Methodology (RSM) was used to investigate the impact of steel slag and lime on the Marshall characteristics of asphalt mixtures. The following conclusions can be made in light of the analysis in this study:

- The experimental results show that the steel-slag and lime-modified asphalt mixtures satisfy the specification limits recommended by the Asphalt Institute and the Nigeria General Specification for Roads and Bridges.
- The results of the ANOVA analysis of the models are statistically significant for all the responses.
- Lime content significantly affects Marshall stability and quotient more than the steel-slag content.
- Steel slag and lime have significant interactive effects on the flow.
- A mathematical model was successfully developed to predict the Marshall properties of steel slag and lime-modified asphalt mixtures. In all the models, the difference between the adjusted and predicted R^2 is less than 0.2, justifying that the models are significant and selected to fit the experimental data more.
- Based on the response surface plot, it is evident that all of the parameters interact well with one another
- According to the optimisation results, the ideal values to meet the design requirements are 24.93% steel slag, 2.43% lime and 5.51% bitumen content. Furthermore, a mean error of less than 5% was achieved for all the responses; this indicates that optimisation using RSM is very effective for asphalt mixture design with high-performance properties.
- In this study, steel slag of size 12.5mm was used as coarse aggregates; other sizes (for coarse and fine aggregates) should be experimented with for future works.

Acknowledgement

The authors appreciate the contribution of all technical staff of Civil Engineering Department, Landmark University, Omu-Aran, Nigeria.

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