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MECHANICAL PERFORMANCE OF STEEL-SLAG AND LIME-MODIFIED ASPHALT MIXTURE: A RESPONSE SURFACE APPROACH

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Abstract. The Response Surface Methodology (RSM) is a collection of methods used to create various experiment designs, determine relationships between experimental variables and responses, and use these relationships to identify the ideal conditions. This study uses RSM to forecast the mechanical characteristics of mixtures modified with steel slag and lime. Using the Box Behnken Design (BBD) method for the mix proportion, steel slag (0–100%), lime (0–4%), and bitumen content (4–8%) were considered independent variables, while the responses were the resilient modulus, indirect tensile strength, flexural stiffness, and compressive strength. Analysis of variance showed that the steel slag was the most influencing factor for the flexural stiffness property of the steel-slag and lime-modified asphalt mixtures. Also, the regression

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coefficient (R^2) of 0.9214, 0.8380, 0.7412, and 0.8266 was obtained for the stiffness, *Mr*, compressive strength, and *ITS*, respectively. Some interaction effects on the responses were found between the steel slag and lime. The optimization findings show that 25.01% steel slag, 2.43% lime, and 5.51% bitumen content are the best values to satisfy the design criteria. The optimized mixture design will offer a cost-effective and environmentally friendly solution, promoting resource conservation and sustainable development in the construction industry.

Keywords: asphalt mixtures, *ITS*, lime, optimization, Resilient Modulus, RSM, steel slag, stiffness.

Introduction

In recent years, using industrial by-products as alternative construction materials has gained significant attention due to its potential for sustainable development and resource conservation (Akadiri et al., 2012; Oguntayo et al., 2023a; Oguntayo et al., 2023b; Oguntayo et al., 2023c). Steel slag, a by-product created during steel manufacture, is one such by-product (Hainin et al., 2015). According to Jiang et al. (2018), steel slag has potential engineering qualities that make it appropriate for use in various applications, including building roads, the manufacture of cement, and soil stabilization. However, the inherent variability and unknowns surrounding its mechanical behaviour hinder its use as a building material (Gao et al., 2020). Researchers have investigated various modification techniques to improve steel slag engineering qualities (Wang et al., 2021). Lime modification has been identified as a potential technology for enhancing the mechanical properties of mixes made from steel slag (Mohammed & Elsageer, 2018; Dang et al., 2022; Gu et al., 2018; Subathra Devi et al., 2015). The mechanical properties of steel-slag and lime-modified mixes must be thoroughly investigated to understand their potential for sustainable construction applications (Hainin et al., 2015; Wu et al., 2019).

Response surface methodology (RSM), a statistical modelling and optimization tool, has gained more popularity recently as a method for forecasting and enhancing complex engineering systems (Braimah et al., 2016; Doust et al., 2016; Aladegboye et al., 2022; Oguntayo et al., 2024). According to Raissi and Farsani (2009) and Hamzah and Omranian (2016), RSM provides an efficient framework for analysing how various variables affect the response of interest and developing mathematical models to predict system behaviour. While using a limited number of experimental trials, RSM enables exploring a wide range of design components and their interactions, providing valuable insights into the system behaviour under study (Doust et al., 2016). Bala et al. (2017) used RSM to investigate nano-silica and binder content optimization to improve the volumetric properties of asphalt mixtures modified with nanocomposite materials. The outcomes show that binder content and nano-silica have sizeable individual effects and that RSM optimization is highly efficient.

Additionally, Nassar et al. (2016) investigated cold bitumen emulsion mixtures (CBEM) and the optimization of the mix design parameters, such as bitumen emulsion content (BEC), pre-wetting water content (PWC), and curing temperature (CT), to establish the ideal ratios for the CBEM mechanical and volumetric properties. Nassar used RSM and central composite design (CCD). The results show that the interactions between BEC, PWC, and CT affect the mechanical properties of CBEM. However, compared to other approaches, the RSM method provides a more thorough understanding of how each mix design parameter affects the mechanical and volumetric responses of CBEMs.

Several mix factors influence performance of a bituminous mixture as a composite material. An RSM may be required to choose a mix with the desired properties if every mix variable is considered (Hoseinpour-Lonbar et al., 2020). In this study, the Box Behnken Design (BBD) method was utilized for the mix proportion of the steel slag and lime-modified asphalt mixtures. Using steel slag (A), lime (B), and bitumen (C) as the independent variables, the test responses of interest are the resilient modulus, indirect tensile strength, stiffness, and compressive strength.

1. Materials and method

1.1. Materials

i. *Aggregate*: The granite used for the coarse aggregate was 12.5 mm, and 10 mm granite was sourced from a quarry 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 µm sieve. Table 1 displays the aggregate characteristics and Figure 1 is the combined aggregate gradation for the mixture.
ii. *Steel slag:* Steel slags from Prism Steel Mills Limited in *Ikirun*, Nigeria, were used in this study. As 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. Steel slag was used to replace the coarse aggregate of size 12.5 mm.
iii. *Bitumen*: Penetration grade 60/70 of bitumen was used in this study. Table 2 displays the properties of bitumen.
iv. *Lime:* Lime used in this study is hydrated lime from the local market. The properties of the lime are shown in Table 3.

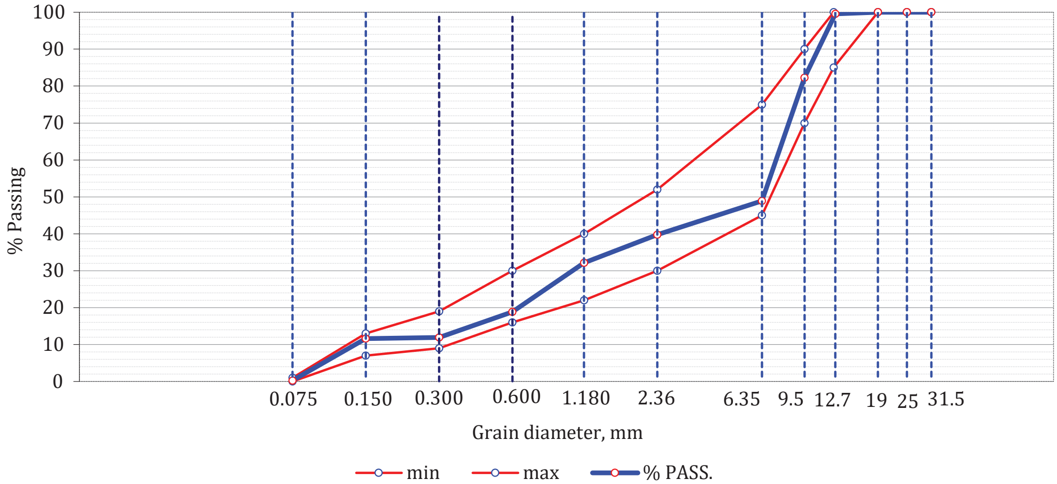

Figure 1. Combined aggregate gradation used for the asphalt production

Table 1. Aggregate properties

Parameters	Steel-slag	Granite	Specification
Aggregate impact value, %	9.5	19.44	30% max
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
Penetration @ 25 °C	60–70	66
Ductility @ 25 °C	100 MIN	121
Solubility	99.5 MIN	107.00
Viscosity	2400 MIN	2753
Flash point, C	≥ 250	287
Softening Point	55–65	56
Specific gravity @ 25 °C	1.01–1.06	1.02
Minimum loss on heat for 5 hours at 163 °C	Max. 0.2	0.08
Drop in penetration after heating	Max. 20	13.5

Table 3. Lime (hydrated lime) properties

Parameters	Value
Specific gravity	2.56
Fineness, %	6.00
CaO, %	85.78
MgO, %	3.52
SO_3, %	1.47
CO_2, %	3.89

1.2. Mix design

The Box Behnken Design (BBD) experimental runs were produced using the Response Surface Methodology (RSM), a feature of the Design Expert software version 13, available for download. Steel slag (A), lime (B), and bitumen (C) are three parameters, or independent variables, that are varied over three (3) levels as +1 (high level), −1 (low level), and centre point (mid-level), as given in Table 4. Table 5 displays the experimental run created for the steel-slag and lime-modified asphalt mixtures.

Table 4. 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 5. Experimental design for steel-slag and lime modified asphalt mixtures

S/N	Steel Slag: A, %	Lime content: B, %	Bitumen content: C, %	Steel slag: A, g	CA: 12.5 mm, g	CA: 10 mm, g	FA, g	Filler, g
1	0	2	4	0	480	240	360	120
2	0	4	6	0	480	240	360	120
3	100	2	4	480	0	240	360	120
4	100	2	8	480	0	240	360	120
5	0	0	6	0	480	240	360	120
6	50	0	4	240	240	240	360	120
7	50	2	6	240	240	240	360	120
8	50	0	8	240	240	240	360	120
9	100	4	6	480	0	240	360	120
10	50	2	6	240	240	240	360	120
11	50	2	6	240	240	240	360	120
12	50	2	6	240	240	240	360	120
13	50	2	6	240	240	240	360	120
14	0	2	8	0	480	240	360	120
15	100	0	6	480	0	240	360	120
16	50	4	4	240	240	240	360	120
17	50	4	8	240	240	240	360	120

1.3. Mixture preparation and testing

The asphalt mixtures were made in compliance with ASTM D 1559-89 standards using Table 5. Dry sieving was used to divide the aggregates into the required gradation and 150 °C preheating followed. Typically, 1200 g of each fraction would be needed to create a specimen with a height of 63.5±3 mm. The pan is heated to a mixing temperature of 150 °C in the oven. To produce a combination with a uniform asphalt distribution, the grade 60/70 bitumen was manually mixed with aggregate at 150 °C while being prepared for that temperature. The compaction hammer is cleaned, the sample moulds are assembled, and the mould is preheated to 150 °C. After thoroughly mixing, the asphalt mixtures were put into a Marshall mould and compacted with 75 blows (top and bottom) of the Marshall hammer.

1.4. Flexure beam test (Flexural Stiffness)

The flexural beam test shows similarities to the field loading experienced by pavements in real life. The fatigue resistance of asphalt mixtures was determined using the three-point bending beam method (AASHTO T 321) in a universal testing machine. The asphalt mixtures were compacted to prepare the fatigue test specimens with a dimension of 400×100×100 mm. The fatigue test was conducted by placing the beams of asphalt mixtures in repetitive three-point loading (using the setup shown in Figure 2). Four clamps held the beams in place during

Figure 2. Beams test setup for three-point load

the test, and a repeated haversine load was applied to the two inner clamps using the loading frequency rate of 10 Hz at 20 °C (because fatigue cracking is usually considered an asphalt mixture distress at intermediate temperatures). The deflection due to the loading was measured at the centre of the specimen. Equations (1) and (2) were used to calculate the maximum bending stress, which occurred at the centre of the beam for the concentrated load applied at the midpoint. The maximum bending stress to maximum bending strain ratio represents the mixture stiffness.

$$\sigma = \frac{3PL}{2bh^2}, \tag{1}$$

where: σ – maximum bending stress in the beam, Mpa;
L – span length, mm;
H – thickness of the beam, mm;
B – width of the beam, mm;
P – load, N.

The maximum bending strain is calculated as follows:

$$\in = \frac{6\delta h}{L^2}, \tag{2}$$

where: $\in$ – maximum bending strain in the beam;
L – span length, mm;
δ – deflection of beam, mm;
H – thickness of the beam, mm.

1.5. Resilient modulus test

The triaxial testing apparatus was used to perform the resilient modulus test. The triaxial test apparatus shown in Figure 3 repeatedly applied axial cyclic stress to a cylindrical specimen of 38 mm diameter and 76 mm high at 25 °C (the most common room temperature in Nigeria). A triaxial pressure chamber provided a static confining stress in addition to the dynamic cyclic stress applied to the specimen.

1.6. Indirect tensile strength test

In line with AASHTO T 322, the test method has been used to evaluate the concrete tensile strength. The test was conducted at 25 °C (the most common room temperature in Nigeria). The test setup can be seen in Figure 4. The measured load value at failure (P), the specimen thickness (H), and the specimen diameter (D), all measured in millimeters, are utilized to calculate the *ITS* values (S_t).

$$S_t = \frac{2P}{\pi \cdot H \cdot D}\left(\frac{\text{N}}{\text{mm}^2}\right) \quad (3)$$

Figure 3. Specimen failure in the triaxial testing machine

Figure 4. Specimen under Indirect Tensile Strength test (a) and (b)

1.7. Direct compression test

Direct compression (DC) test determines the behaviour of materials and deformation under crushing statics loads. The test was carried out in accordance with ASTM D 1074 (2017). This test was conducted using the universal compression apparatus, as depicted in Figure 5. Marshall test specimens with a diameter of roughly 100 mm and a height ranging from 62 to 69 mm were also used for this test. Before testing, test specimens were submerged in a 60 °C water bath for 30 min. Marshall specimen was put through a compression test in which the strain rate was constant at 10 mm/min (10 mm/min) until failure occurred. The maximum load identifies the specimen point of failure. The load needed to cause the specimen to fail at 60 °C is noted. The (DC) test values (S_c) are calculated using the following equation, which takes into account the measured load value at failure (P) in Newton and the specimen diameter (D) in mm.

$$S_c = \frac{P}{\pi D \frac{2}{4}} \left(\frac{\text{N}}{\text{mm}^2} \right) \quad (4)$$

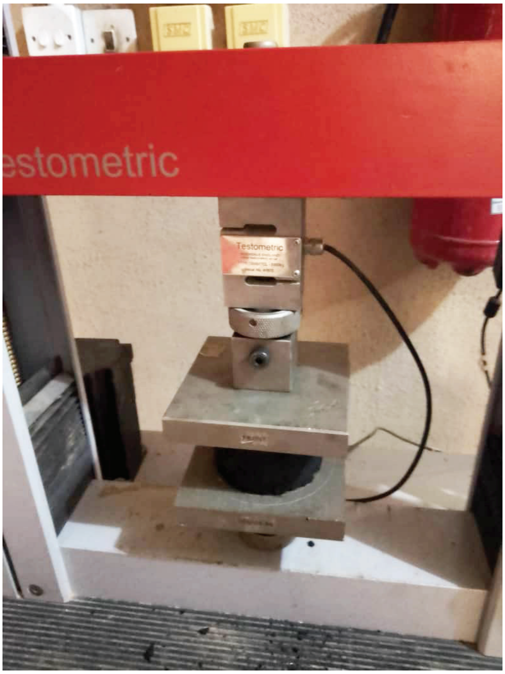

Figure 5. Specimen under Universal Testing Machine for compression test

2. Results and discussion

2.1. Mechanical properties of steel slag and lime-modified asphalt mixtures

Resilient modulus (*Mr*) and indirect tensile strength (*ITS*) of asphalt mixture materials are frequently used in pavement structural design (Zeng et al., 2020). For mechanistic design strategies for asphalt structures, *Mr* is the most crucial variable. According to Zangena (2019), it measures how asphalt reacts to dynamic stresses and related strains. Figure 6a displays the results of the *Mr* test. There was no relationship between the resilience modulus, the amount of steel slag, and the lime content. The mixture mix-5 with 0% steel slag and 0% lime had the highest *Mr* value, whereas mixture mix-7 with 50% steel slag and 2% lime had the lowest *Mr* value. This result contrasts with the study by Albayati et al. (2022). In their study, they showed an increase in *Mr* with lime addition. Furthermore, Oluwasola et al. (2015) also showed a rise in *Mr* with steel slag addition.

The indirect tensile strength test offers helpful mixture properties when describing bituminous mixes. It is frequently used to assess the cracking potential of a bituminous mixture. Mixtures that can withstand high *ITS* values are more likely to be crack-resistant. The tensile strength of lime and steel slag-modified asphalt mixes is shown in Figure 6b. The *ITS* of bituminous mixes displayed a similar pattern to *Mr*. The mix-1 with 0% steel slag and 2% lime had the greatest *ITS* value (566.62 Kpa), whereas the mix-4 with 100% steel slag and 2% lime had the lowest value (233.96 Kpa). The range of tensile strength values published by several authors (Likitlersuang & Chompoorat, 2016; Alnadish et al., 2022; Alemu et al., 2023), all of whom have reported considerably greater tensile strength values, appears to be lower than these values. The design of the mixtures can directly link to the most likely reason when it comes to material compositions.

A three-point bending fatigue test was performed to assess the fatigue performance of the steel-slag and lime-modified asphalt mixture. The results are given in Figure 6c. It is observed that the flexural stiffness tends to be the highest (2.38 GPa) in mix-1 (0% steel-slag and 2% lime), while it is the lowest in (1.08 GPa) mix-9 (100% steel-slag with 4% lime). This modified asphalt mixture could continue to withstand fatigue loading. Despite the foregoing, the trend of the stiffness relation is unclear because it is more challenging to assess the variations between mixtures. The differences in mixture design, including the amounts of lime, steel, and binders, may be the cause of the observed differences.

Figure 6d displays the compressive strength values for the asphalt mixtures made with lime and steel slag. The strength value of the modified asphalt mixtures showed some variance. Mix-4, which contained 2% lime and 100% steel slag, had the maximum compressive strength at 4.32 N/mm^2. According to Gaus et al. (2015), this greater strength value shows that the asphalt mixture is more deformation-resistant to the short-term monotonic compressive stress. Furthermore, it can be demonstrated that lime has a favourable impact on the strength of the bituminous mixtures by contrasting the compressive strength mix-4 with mix-15, which contains 100% steel slag and 0% lime. The resistance of bituminous mixes to persistent deformation depends on this effect (Iwański, 2020; Singh et al., 2021).

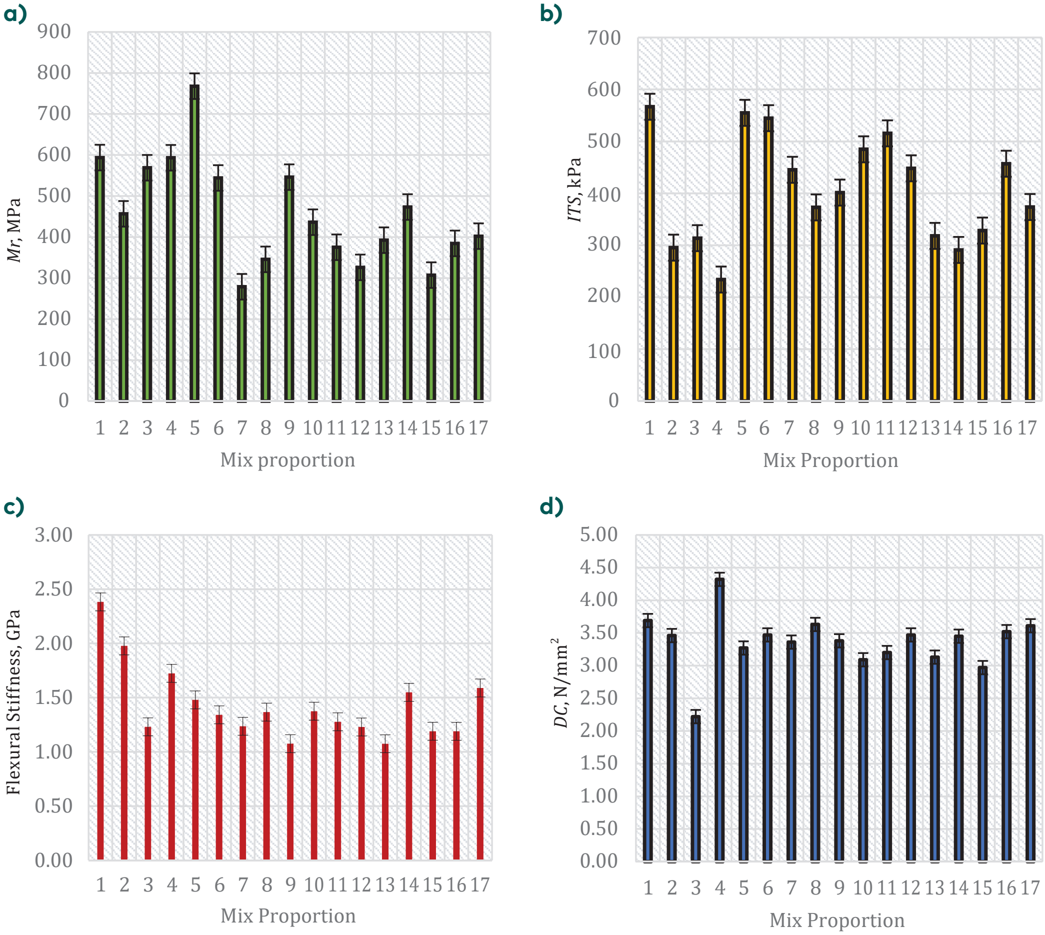

Figure 6. Mechanical properties of steel-slag and lime-modified asphalt mixtures

2.2. RSM analysis for the mechanical properties of steel-slag and lime-modified asphalt mixtures

The relationship trend obtained in the experimental result is unclear because assessing the variations between mixtures is more challenging. The differences in mixture design, including the amounts of lime, steel, and binders, may be the cause of the observed differences. Hence, to better understand the contributions of steel slag and lime on the mechanical performance of the asphalt mixtures, the RSM analysis was conducted, and the results are discussed in the following sections.

2.2.1. The ANOVA and regression model equations for the mechanical properties of steel-slag and lime-modified asphalt mixtures

The findings of the analysis of variance (ANOVA) for the characteristics of mixes made of steel slag and lime-modified asphalt are shown in Table 6. Steel-slag was the independent variable with the greatest influence and significance on the stiffness property of the steel-slag and lime-modified asphalt mixtures, with an F-value of 28.43. The bitumen content, on the other hand, was discovered to be the most significant and influencing factor among the independent variables for the other properties, including the resilient modulus, compressive strength, and indirect tensile strength, after showing the F-values of 1.56, 7.63, and 11.01, respectively. Consecutively, the model F-value of 9.12, 4.02, 4.77, and 3.71 for stiffness, resilient modulus, compressive strength, and indirect tensile strength, respectively, prove the model significance. According to Bala et al. (2018), a $P>F$ value of 0.05 typically indicates that the model terms are highly significant. The results of the stiffness property reveal the significance of factors A, B, and C. It shows that the model terms are insignificant for values greater than 0.1. An adequate correlation coefficient (R^2) of 0.9214, 0.8380, 0.7412, and 0.8266 was obtained for the responses. The predicted and experimental findings exhibit an excellent correlation, as indicated by the high correlation coefficient. Additional evidence that the models are significant and that the models chosen better suit the experimental data is provided by the difference between the adjusted and anticipated R^2 for the models, which is less than 0.2. In addition, the AP ratios of 11.4614, 6.0037, 9.7491, and 6.0041 were obtained for all the responses. As stated earlier, an *AP* ratio higher than 4 is acceptable. The second-order polynomial model coefficients were generated to suit the experimental data (pertaining to mechanical properties). Equations (5)–(8) provide the final regression model equations for essential factors. The stiffness, resilient modulus, compressive strength, and indirect tensile strength parameters of the model equation have *SD* values of 2.91, 78.38, 0.2715, and 65.03, respectively. Positive and negative signs precede the equation terms to indicate the interactions between the various variables and how they positively and negatively affect the responses.

Table 6. ANOVA results for mechanical properties of steel-slag and lime modified asphalt mixtures

SoD	***SoS***	***DoF***	***MS***	**F-value**	**P-value**	**Comment**
			Flexural Stiffness			
Model	695.19	9	77.24	9.12	0.0041	*SD* = 2.91
A	240.69	1	240.69	28.43	0.0011	*Mean* = 28.48
B	7.25	1	7.25	0.8565	0.3855	R^2 = 0.9214
C	0.0242	1	0.0242	0.0029	0.9588	Adj. R^2 = 0.8204
AB	38.45	1	38.45	4.54	0.0706	*AP* = 11.4614
AC	177.70	1	177.70	20.99	0.0025	
BC	12.68	1	12.68	1.50	0.2606	
A^2	127.19	1	127.19	15.02	0.0061	
B^2	11.04	1	11.04	1.30	0.2911	
C^2	75.38	1	75.38	8.90	0.0204	
Residual	59.27	7	8.47			
Lack of Fit	38.20	3	12.73	2.42	0.2067	
Pure Error	21.07	4	5.27			
			Resilient Modulus (*Mr*)			
Model	2.224E+05	9	24705.72	4.02	0.0400	*SD* = 78.38
A	9516.48	1	9516.48	1.55	0.2533	*Mean* = 458.36
B	3837.76	1	3837.76	0.6248	0.4552	R^2 = 0.8380
C	9584.20	1	9584.20	1.56	0.2518	Adj. R^2 = 0.6296
AB	75605.75	1	75605.75	12.31	0.0099	*AP* = 6.0043
AC	5246.83	1	5246.83	0.8542	0.3861	
BC	11682.37	1	11682.37	1.90	0.2103	
A^2	92116.79	1	92116.79	15.00	0.0061	
B^2	400.37	1	400.37	0.0652	0.8058	
C^2	9548.56	1	9548.56	1.55	0.2526	
Residual	42996.58	7	6142.37			
Lack of Fit	28192.23	3	9397.41	2.54	0.1948	
Pure Error	14808.17	4	3702.04			

$$\text{Stiffness} = 24.6674 - 5.48506A + 0.952109B + 0.0550533C - 3.10039AB + 6.66528AC + 1.78039BC + 5.49618A^2 - 1.61893B^2 + 4.23118C^2 \quad (5)$$

$$M_r = 2361.76 - 34.49A - 21.9025B - 34.6125C + 137.482AB + 36.2175AC + 54.0425BC + 147.911A^2 + 9.75125B^2 + 47.6213C^2 \quad (6)$$

$$DC = 3.3672 - 0.123458A + 0.0779166B + 0.265042C + 0.054AB + 0.584083AC - 0.0191668C \quad (7)$$

$$ITS = 442.325 - 53.8288A - 34.1802B - 76.3109C + 83.1661AB + 48.9854AC + 22.1152BC - 66.5312A^2 + 19.1919B^2 - 24.4938C^2 \quad (8)$$

Table 6 contidued

SoD	***SoS***	***DoF***	***MS***	**F-value**	**P-value**	**Comment**
			DC			
Model	2.11	6	0.3517	4.77	0.0150	*SD* = 0.2715
A	0.1219	1	0.1219	1.65	0.2273	*Mean* = 3.37
B	0.0486	1	0.0486	0.6591	0.4358	R^2 = 0.7412
C	0.5620	1	0.5620	7.63	0.0201	Adj. R^2 = 0.5859
AB	0.0117	1	0.0117	0.1583	0.6991	*AP* = 9.7491
AC	1.36	1	1.36	18.52	0.0016	
BC	0.0015	1	0.0015	0.0199	0.8905	
Residual	0.7369	10	0.0737			
Lack of Fit	0.6339	6	0.1057	4.10	0.0965	
Pure Error	0.1030	4	0.0257			
			Indirect Tensile Strength (*ITS*)			
Model	1.411E+05	9	15680.79	3.71	0.0490	*SD* = 65.03
A	23180.28	1	23180.28	5.48	0.0518	*Mean* = 408.52
B	9346.29	1	9346.29	2.21	0.1807	R^2 = 0.8266
C	46586.77	1	46586.77	11.01	0.0128	Adj. R^2 = 0.6036
AB	27666.38	1	27666.38	6.54	0.0377	*AP* = 6.0041
AC	9598.29	1	9598.29	2.27	0.1757	
BC	1956.33	1	1956.33	0.4625	0.5183	
A^2	18637.46	1	18637.46	4.41	0.0740	
B^2	1550.86	1	1550.86	0.3667	0.5639	
C^2	2526.09	1	2526.09	0.5972	0.4649	
Residual	29606.81	7	4229.54			
Lack of Fit	6972.03	3	2324.01	0.4107	0.7547	
Pure Error	22634.78	4	5658.70			

SoD: Source of data; *SoS*: Sum of squares; *DoF*: Degree of freedom; *MS*: mean square; *SD*: standard deviation; R^2: Coefficient of determination; *AP*: Adequate precision; Adj. R^2: Adjusted coefficient of determination; A = Steel slag, B = Lime content, and C = Bitumen content.

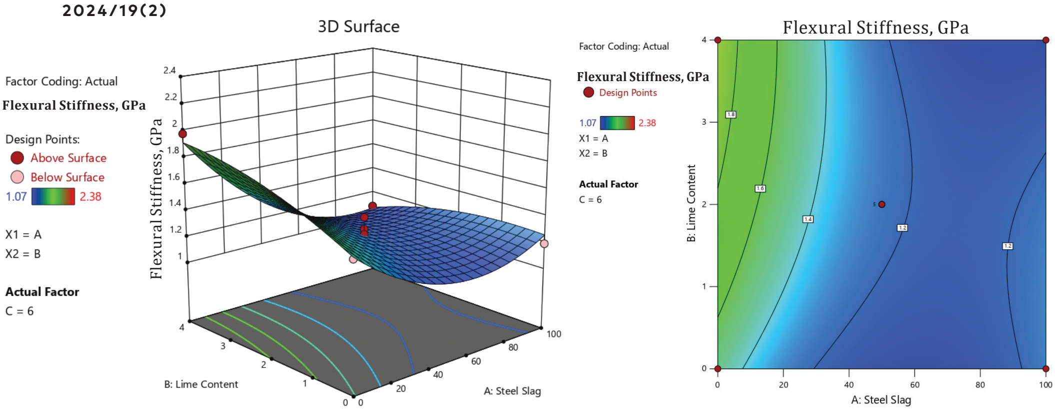

Figure 8a. Response surface plot of flexural stiffness for steel-slag and lime-modified asphalt mixtures

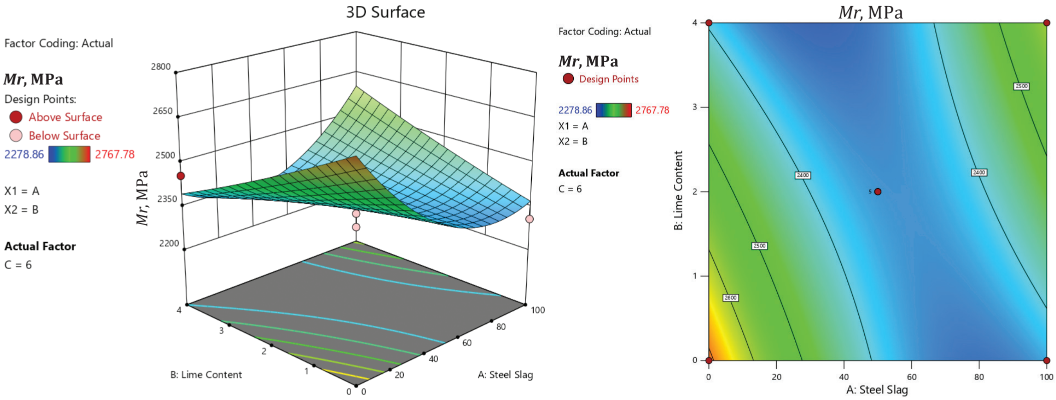

Figure 8b. Response surface plot of *Mr* for steel-slag and lime-modified asphalt mixtures

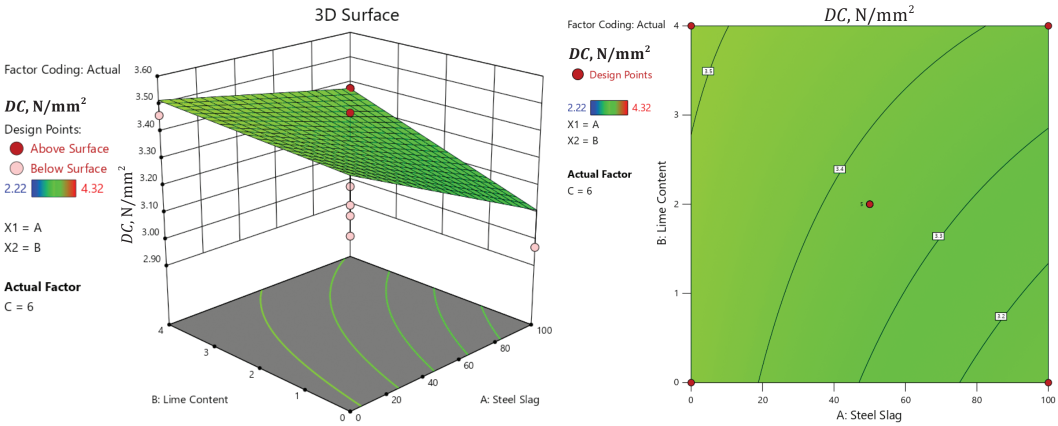

Figure 8c. Response surface plot of *DC* for steel-slag and lime-modified asphalt mixtures

2.2.2. Surface plots of the mechanical properties of steel slag and lime-modified asphalt mixtures

3D and 2D response surface plots for all the responses based on the effects of the interactive variables, steel-slag, lime, and bitumen content are shown in Figures 8 (a–d). Figure 8a shows the response surfaces for the stiffness of the steel slag and lime-modified asphalt mixtures. The 3D plot curvature indicates that steel slag and lime significantly interact with the stiffness. It can be observed that the addition of steel slag decreases the stiffness by up to 40% of steel slag and a slight increase in the stiffness afterward. Also, it was observed that an increase in the lime content increased stiffness. This indicates that lime content influences stiffness more remarkably than steel slag.

Figure 8b shows the response surfaces for the resilient modulus (*Mr*) of the steel slag and lime-modified asphalt mixtures. The 3D plot curvature indicates that both steel slag and lime have a significant interaction effect on the *Mr*. It can be observed that the addition of steel slag results in a slight decrease in the *Mr*. Also, an increase in the lime content resulted in a reduction of the *Mr*.

The response surfaces for the compressive strength of steel slag and lime-modified asphalt mixtures are shown in Figure 8c. The 3D plot shows that while the strength slightly decreased as steel slag content increased, the strength increased as lime content increased. The 2D contour plot for compressive strength demonstrates good interaction between all the variables. Figure 8d shows the response surfaces for the *ITS* of the steel slag and lime-modified asphalt mixtures. The 3D plot curvature indicates that adding lime content decreases *ITS*, while

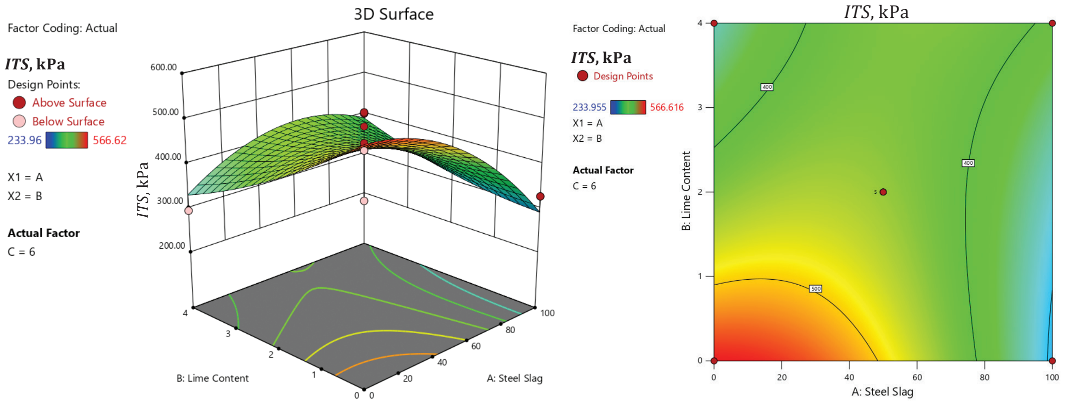

Figure 8d. Response surface plot of *ITS* for steel-slag and lime-modified asphalt mixtures

an increase in the steel slag increases *ITS* up to 60% of steel slag and decreases afterward. It was further observed that lime content strongly influenced *ITS* more than steel slag.

2.2.3. Mix design optimization

Using the RSM optimization tool, design factors were optimized in this work, and the accuracy of the created models was evaluated. The target aims for each mix design factor (A, B, and C) chosen, as given in Table 7 for steel-slag and lime modified, were established. The responses were defined as being maximal for excellent performance. The optimization findings show that 25.01% steel slag, 2.43% lime, and 5.51% bitumen contents are the best values to satisfy the design criteria. The second experiment was conducted to validate the model predictions using the ideal predicted mix design elements. Except for *Mr*, all of the response percentage error differences were less than 5%, as shown in Table 8, demonstrating that the established models predicted and experimental values agree.

Table 7. Design conditions for optimization

Responses	Units	Criteria
Flexural Stiffness	GPa	Maximum range
DC	N/mm^2	Maximum range
ITS	kPa	Maximum range
Mr	MPa	Maximum range

Table 8. Optimum conditions achieved for steel-slag and lime-modified asphalt mixtures

Response	Unit	Predicted	Observed	Error, %
Flexural Stiffness	GPa	1.24	1.21	2.48
Mr	MPa	2361.75	2621.57	9.66
DC	N/mm^2	3.37	3.45	2.31
ITS	kPa	442.33	454.26	2.63

Conclusions and recommendations

Mechanical properties are crucial in determining the structural performance of an asphalt mixture. This study evaluated the effects of steel slag and lime on the resilient modulus, flexural stiffness, compressive strength, and indirect tensile strength of asphalt mixtures. The main conclusions of the study are presented below.

- There was a variation in the experimental results. The differences in mixture design, including the amounts of lime, steel slag, and binders, may be the cause of the observed variation.
- Lime has a favourable impact on the mechanical strength of bituminous mixtures.
- Analysis of variance showed that the steel slag was the most influencing factor for the flexural stiffness property.
- The regression coefficient (R^2) of 0.9214, 0.8380, 0.7412, and 0.8266 was obtained for the flexural stiffness, *Mr*, compressive strength, and *ITS*, respectively.
- The surface plots obtained from the RSM analysis gave a better understanding of the contributions of the steel slag and lime to the mechanical performance of the asphalt mixtures.
- This study developed predictive models and identified the optimal combination of variables to design the modified asphalt mixtures as 25.01% steel slag, 2.43% lime, and 5.51% bitumen content.
- The findings of this study will aid in understanding and application of steel slag as a sustainable road construction material and offer insightful information to researchers and engineers involved in the design and development of steel slag and lime-modified mixtures.

REFERENCES

AASHTO T 322. (2007). Standard method of test for determining the creep compliance and strength of hot mix asphalt (HMA) using the indirect tensile test device. American Association of State Highway and Transportation Officials (AASHTO). https://civilnode.com/download-standard/10654392138908/aashto-t-322-standard-method-of-test-for-determining-the-creep-compliance-and-strength-of-hot

AASHTO T 321. (2022). Standard method of test for determining the fatigue life of compacted asphalt mixtures subjected to repeated flexural bending. American Association of State Highway and Transportation Officials (AASHTO).

Akadiri, P. O., Chinyio, E. A., & Olomolaiye, P. O. (2012). Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. *Buildings*, *2*(2), 126–152. https://doi.org/10.3390/buildings2020126

Aladegboye, O. J., Oguntayo, O. D., Al-Ihekwaba, E., Daniel, T. E., Chiadighikaobi, P. C., & Ng'andu, P. (2022). Evaluation of volumetric properties of cassava peel ash modified asphalt mixtures. *Civil Engineering Journal*, *8*(10), 2110–2124. https://doi.org/10.28991/CEJ-2022-08-10-07

Albayati, A., Wang, Y., & Haynes, J. (2022). Size effect of hydrated lime on the mechanical performance of asphalt concrete. *Materials*, *15*(10), Article 3715. https://doi.org/10.3390/ma15103715

Alemu, G. M., Melese, D. T., Mahdi, T. W., & Negesa, A. B. (2023). Combined performance of polyethylene terephthalate waste plastic polymer and crumb rubber in modifying properties of hot mix asphalt. *Advances in Materials Science and Engineering*, *2023*, Article 6320490. https://doi.org/10.1155/2023/6320490

Alnadish, A. M., Aman, M. Y., Katman, H. Y. B., & Ibrahim, M. R. (2022). Laboratory evaluation of fiber-modified asphalt mixtures incorporating steel slag aggregates. *CMC-Computers Materials & Continua*, *70*(3), 5967–5990. https://doi.org/10.32604/cmc.2022.017387

ASTM D1074-02. (2017). Standard test method for compressive strength of bituminous mixtures. American Society for Testing and Materials.

ASTM D1559. (1989). Resistance to plastic flow of bituminous mixtures using Marshall apparatus.

Bala, N., Napiah, M., & Kamaruddin, I. (2017). Application of response surface methodology for mix design optimisation of nanocomposite modified. *International Journal of GEOMATE*, *13*(39), 237–244. https://doi.org/10.21660/2017.39.58554

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

Braimah, M. N., Anozie, A. N., & Odejobi, O. J. (2016). Utilisation of response surface methodology (RSM) in the optimisation of crude oil refinery process, New Port-Harcourt refinery, Nigeria. *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, *3*(3), 2458–9403. https://www.jmest.org/wp-content/uploads/JMESTN42351475.pdf

Dang, D. T., Nguyen, M. T., Nguyen, T. P., Isawa, T., Ta, Y., & Sato, R. (2022). Mechanical properties of steel slag replaced mineral aggregate for road base/sub-base application based Vietnam and Japan standard. *Environmental Science and Pollution Research*, *29*(28), 42067–42073. https://doi.org/10.1007/s11356-021-16706-0

Doust, A. M., Rahimi, M., & Feyzi, M. (2016). An optimisation study by response surface methodology (RSM) on viscosity reduction of residue fuel oil exposed ultrasonic waves and solvent injection. *Iranian Journal of Chemical Engineering*, *13*(1), 3–19. https://www.ijche.com/article_15369.html

Gao, D., Wang, F. P., Wang, Y. T., & Zeng, Y. N. (2020). Sustainable utilisation of steel slag from traditional industry and agriculture to catalysis. *Sustainability (Switzerland)*, *12*(21), Article 9295. https://doi.org/10.3390/su12219295

Gaus, A., Tjaronge, M. W., Ali, N., & Djamaluddin, R. (2015). Compressive strength of asphalt concrete binder course (AC-BC) mixture using buton granular asphalt (BGA). *Procedia Engineering*, *125*, 657–662. https://doi.org/10.1016/j.proeng.2015.11.097

Gu, X., Yu, B., Dong, Q., & Deng, Y. (2018). Application of secondary steel slag in subgrade: Performance evaluation and enhancement. *Journal of Cleaner Production*, *181*(1), 102–108. https://doi.org/10.1016/j.jclepro.2018.01.172

Hainin, M. R., Aziz, M. A., Ali, Z., Jaya, R. P., El-Sergany, M. M., & Yaacoba, H. (2015). Steel slag as a road construction material. *Jurnal Teknologi*, *73*(4), 33–38. https://doi.org/10.11113/jt.v73.4282

Hamzah, M. O., & Omranian, S. R. (2016). Effects of extended short-term aging duration on asphalt binder behaviour at high temperatures. The Baltic Journal of Road and Bridge Engineering, *11*(4), 302–312. https://doi.org/10.3846/bjrbe.2016.35

Harrou, A., Gharibi, E., Nasri, H., Fagel, N., & El Ouahabi, M. (2020). Physico-mechanical properties of phosphogypsum and black steel slag as aggregate for bentonite-lime based materials. *Materials Today: Proceedings*, *31*(Sup.1), S51–S55. https://doi.org/10.1016/j.matpr.2020.05.819

Hoseinpour-Lonbar, M., Alavi, M. Z., & Palassi, M. (2020). Selection of asphalt mix with optimal fracture properties at intermediate temperature using Taguchi method for design of experiment. *Construction and Building Materials*, *262*, 120601.

Iwański, M. M. (2020). Effect of hydrated lime on indirect tensile stiffness modulus of asphalt concrete produced in half-warm mix technology. *Materials*, *13*(21), Article 4731. https://doi.org/10.3390/ma13214731

Jiang, Y., Ling, T. C., Shi, C., & Pan, S. Y. (2018). Characteristics of steel slags and their use in cement and concrete – A review. *Resources, Conservation and Recycling*, *136*, 187–197. https://doi.org/10.1016/j.resconrec.2018.04.023

Likitlersuang, S., & Chompoorat, T. (2016). Laboratory investigation of the performances of cement and fly ash modified asphalt concrete mixtures. *International Journal of Pavement Research and Technology*, *9*(5), 337–344. https://doi.org/10.1016/j.ijprt.2016.08.002

Manzoor, S. O., & Yousuf, A. (2020). Stabilisation of soils with lime : A review. *Journal of Materials and Environmental Science*, *11*(9), 1538–1551. https://www.jmaterenvironsci.com/Document/vol11/vol11_N9/JMES-2020-11133-Manzoor.pdf

Mohammed, A. A., & Elsageer, M. A. A. (2018). The effect of adding steel slag and lime on the engineering properties of a sandy soil. *AIJR Proceedings 4*(23), 563–570. https://doi.org/10.21467/proceedings.4.23

Nassar, A., Thom, N., & Parry, T. (2016). Optimising the mix design of cold bitumen emulsion mixtures using response surface methodology. *Construction and Building Materials*, *1*(1), 1–39. https://doi.org/10.1016/j.conbuildmat.2015.12.073

Noori, G., Faqemahmood, L., Mohammed, S., & Salih, A. (2020). Modeling and statistical variations of long term of mechanical properties of concrete modified with waste steel slag. *The Journal of Duhok University*, *23*(2), 1–14. https://doi.org/10.26682/csjuod.2020.23.2.1

O'Connor, J., Nguyen, T. B. T., Honeyands, T., Monaghan, B., O'Dea, D., Rinklebe, J., Vinu, A., Hoang, S. A., Singh, G., Kirkham, M. B., & Bolan, N. (2021). Production, characterisation, utilisation, and beneficial soil application of steel slag: A review. *Journal of Hazardous Materials*, *419*, Article 126478. https://doi.org/10.1016/j.jhazmat.2021.126478

Oguntayo, D., Ogundipe, M., Aluko, O., Oguntayo, B., Rahmon, R., & Ogundipe, O. (2023a). Nigerian steel-slag for road works: Physical, mineralogy and micro-structural characterization. *2023 International Conference on Science, Engineering and Business for Sustainable Development Goals (SEB-SDG)*, *1*, Omu-Aran, Nigeria, 1–4. https://doi.org/10.1109/SEB-SDG57117.2023.10124590

Oguntayo, D., Ogundipe, M., Aladegboye, O., Ogunkunbi, G., Babatunde, Y., & Aransiola, O. (2023b). Performance evaluation of hospital waste ash-modified asphalt mixtures. *Advances in Civil Engineering*, *2023*, Article 6880766. https://doi.org/10.1155/2023/6880766

Oguntayo, D., Ogundipe, O., Daikwo, J., Adeyemi, F., & Aladegboye, O. (2023c). Moisture susceptibility of waste ceramic tiles modified asphalt mixtures. *Research on Engineering Structures and Materials*, https://doi.org/10.17515/resm2023.798ma0704tn

Oguntayo, D., Ogundipe, O., Aluko, O., & Babatunde, Y. (2024). RSM based modelling and optimization of Marshall properties of steel-slag and lime-modified asphalt mixtures. *Research on Engineering Structures and Materials*, 1–20. https://doi.org/10.17515/resm2024.83ma1117rs

Oluwasola, E. A., Hainin, M. R., Aziz, M., Maniruzzaman, A., Singh, M., & Singh, S. (2015). Effect of aging on the resilient modulus of stone mastic asphalt incorporating electric arc furnace steel slag and copper mine tailings. *InCIEC 2014*, Singapore, 1199–1208. https://doi.org/10.1007/978-981-287-290-6_106

Pasetto, M., Baliello, A., & Giacomello, G. (2023). The use of steel slags in asphalt pavements : A state-of-the-art review. *Sustainability*, *15*(11), Article 8817. https://doi.org/10.3390/su15118817

Pinheiro, C., Rios, S., Viana da Fonseca, A., Fernández-Jiménez, A., & Cristelo, N. (2020). Application of the response surface method to optimise alkali activated cements based on low-reactivity ladle furnace slag. *Construction and Building Materials*, *264*, Article 120271. https://doi.org/10.1016/j.conbuildmat.2020.120271

Raissi, S., & Farsani, R. E. (2009). Statistical process optimisation through multi-response surface methodology. *World Academy of Science, Engineering and Technology*, *3*(3), 280–284. https://www.researchgate.net/publication/289199318_Statistical_process_optimization_Through_multi-response_surface_methodology

Sas, W., Głuchowski, A., Radziemska, M., Dzieciol, J., & Szymański, A. (2015). Environmental and geotechnical assessment of the steel slags as a material for road structure. *Materials*, *8*(8), 4857–4875. https://doi.org/10.3390/ma8084857

Singh, B., Prasad, D., & Kant, R. R. (2021). Effect of lime filler on RCA incorporated bituminous mixture. *Cleaner Engineering and Technology*, *4*, Article 100166. https://doi.org/10.1016/j.clet.2021.100166

Subathra Devi, V., Gnanavel, B. K., & Murthi, P. (2015). Experimental investigation on the mechanical properties of steel slag ceramic concrete. *International Journal of ChemTech Research*, *8*(8), 152–160. https://www.sphinxsai.com/2015/ch_vol8_no8/1/(152-160)V8N8CT.pdf

Taherkhani, H., & Noorian, F. (2020). Investigating the Marshall and volumetric properties of asphalt concrete containing reclaimed asphalt pavement and waste oils using response surface methodology. *Civil Engineering Infrastructures Journal*, *53*(2), 241–258. https://doi.org/10.22059/ceij.2020.281338.1582

Wang, F. P., Liu, T. J., Cai, S., Gao, D., Yu, Q., Wang, X. M., Wang, Y. T., Zeng, Y. N., & Li, J. G. (2021). A review of modified steel slag application in catalytic pyrolysis, organic degradation, electrocatalysis, photocatalysis, transesterification and carbon capture and storage. *Applied Sciences (Switzerland)*, *11*(10), Article 4539. https://doi.org/10.3390/app11104539

Wu, J., Liu, Q., Deng, Y., Yu, X., Feng, Q., & Yan, C. (2019). Expansive soil modified by waste steel slag and its application in subbase layer of highways. *Soils and Foundations*, *59*(4), 955–965. https://doi.org/10.1016/j.sandf.2019.03.009

Zangena, S. A. (2019). Performance of asphalt mixture with nanoparticles. In *Nanotechnology in eco-efficient construction* (pp. 165–186). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102641-0.00008-6

Zeng, M., Pan, H., Tian, W., Li, J., & Zhou, J. (2020). Properties of asphalt binder and mixture containing bioasphalt derived from castor. In *Bio-Based Materials and Biotechnologies for Eco-Efficient Construction* (pp. 81–102). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-819481-2.00005-2

Zhang, L., & Zhai, J. (2020). Application of response surface methodology to optimise alkali-activated slag mortar with limestone powder and glass powder. *Structural Concrete*, *22*(S1), E430–E441. https://doi.org/10.1002/suco.202000018

Zhang, X. (2019). Study on the application and material properties of lime-soil compaction pile modified by steel slag. *IOP Conference Series: Earth and Environmental Science PAPER*, *310*(4), Article 042063. https://doi.org/10.1088/1755-1315/310/4/042063