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RESEARCH ARTICLE

Response Surface Modelling and Multi-Objective Optimisation of Asphalt Binder and Mixture Properties Modified with Reclaimed Automotive Lubricants and Waste Glass Bottle Powder

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ABSTRACT

Large volumes of reclaimed automotive lubricant (RAL) and waste glass bottle powder (WGBP) are disposed of inappropriately, causing serious environmental concerns. Furthermore, the paradigm shift towards sustainability in the pavement industry has prompted academics to investigate alternatives to conventional materials. As a result, one possible approach is to use these waste products as alternative materials in the asphalt pavement sector. This study investigated the combined use of RAL and WGBP as complementary modifiers, extending beyond the conventional single-modifier approaches reported in previous studies. Thus, in this study, response surface methodology (RSM) was utilised to optimise and predict the synergistic effects of RAL as an asphalt binder replacement (0–10%) and WGBP (0–4%) as sustainable modifiers incorporated into 60/70 penetration grade asphalt binders. The responses evaluated were the binder's penetration, softening point, and specific gravity. Additionally, the mixture performance indicators include Marshall stability, flow, indirect tensile strength, the indirect tensile strength ratio, and Cantabro loss. The results demonstrate that the synergy of RAL and WGBP improves both conventional asphalt binder properties and asphalt mixture performance properties. The RSM developed statistically significant models, with key responses exhibiting high coefficients of determination ($R^2 > 0.93$), indicating strong predictive capability and low variance. Additionally, the RSM multi-objective optimisation revealed that the contents for performance improvement and optimal workability were 1.39% RAL and 3.6% WGBP. This shows the feasibility of using both liquid and solid wastes as complementary modifiers and providing a statistically sustainable developed asphalt pavement.

Keywords: Asphalt mixture, Recycled automotive lubricant, Waste glass bottle powder, Optimisation, Sustainable asphalt pavement materials

1. Introduction

Asphalt pavements account for more than 90% of the world's road pavements, are critically short of materials, face sharply increasing costs for binders, and are negatively impacted by the adverse effects of climate change on the pavement life span [1, 2]. Additionally, there is a growing need for sustainable paving materials that yield greater performance efficiency and impose lower negative environmental footprints [2–4]. Therefore, the incorporation of waste materials and byproducts into asphalt

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pavements has received considerable attention as a dual-purpose solution that improves pavement performance and addresses the need for the closing of the loop in a circular economy [5, 6]. Globally, more than 100 million tonnes of waste glass are produced annually [6–8]. This waste is largely composed of single-use beverages, container glass, flat glass, windows, and electronic products [5, 8, 9]. Although less than 50% of waste glass is recycled, the remainder often contains hard-to-recycle glasses [8, 10]. These types of glass also accumulate in landfills and pose environmental challenges because of their nonbiodegradable nature [7, 10]. To mitigate the environmental challenges of landfilled glass, waste glass is increasingly being repurposed using what is known as 'open-loop' systems through incorporation as a surrogate material in the construction industry [9, 11]. Waste glass bottle powder (WGBP) has an angular, fine, high surface area and pozzolanic properties.

Additionally, at a global scale, as of 2017, the generation of recycled automotive lubricants (RALs) was approximately 3.8 billion gallons, while only 27% of this total volume was re-refined into base oils and other higher-value products [12, 13]. The remainder are largely discarded or used for other low-value purposes, reflecting lubricant waste management inefficiencies [12, 14]. This finding is also an indication of the prospect of incorporating lubricant waste into asphalt binders as a sustainable waste valorisation option [15]. RAL is a degraded hydrocarbon that liquefies and can improve the lower temperature flexibility and elasticity of aged asphalt binders, thus allowing the binder to be rejuvenated [15]. According to previous studies, a larger quantity of waste oil softens the asphalt binder, affecting the conventional properties, as well as decreasing the stiffness and load-bearing capacity, which affects the mechanical properties [15–17]. As a result, various modifiers are used to balance and stiffen the asphalt binder. Thus, in this study, WGBP was utilised as a modifier for the waste oil-modified binder. While these materials have been studied independently in the context of asphalt modification, studies on the synergistic effects of the two materials from the perspective of the asphalt binder and mixture performance properties are limited [18]. The components of the asphalt mixture behave nonlinearly and interdependently, making the performance of the mixture under different traffic and climatic conditions difficult to evaluate [19, 20]. This encourages the use of mathematical functions where multiple variables are expressed and a need for predictive value [19, 21]. More traditional approaches, for example, one-variable-at-a-time (OVAT), do not capture such interactions and are inadequate, leading to inaccurate conclusions and suboptimal results, resulting in excessive resource waste (in terms of time, effort, cost, and experimentation) [18, 20]. This encourages the use of complex statistical techniques such as response surface methodology (RSM) [21, 22].

RSM is a statistical tool that provides a framework for the modelling and optimisation of multifactor systems by offering the ability to conduct a reasonable volume of experimental runs while providing the means to analyse the separate and combined effects of a number of factors [22, 23]. Additionally, owing to the complexity and synergistic properties of the modifiers and fillers incorporated into asphalt pavement, the applicability of RSM is at its peak when mixtures of asphalt are combined with these waste fillers/modifiers [18, 22]. RSM, in conjunction with actual experimental results, is a hybrid of statistical models and designs of experimental approaches and provides a combination of theoretical and empirical analyses for evaluating the interactions among the components of a mixture, leading to the construction of improved and more informative predictive models, especially for pavement performance [23]. Several previous works have used response surface methodology (RSM) in asphalt research for the optimisation of binder and mixture properties in systems with single modifiers such as waste oils and mineral fillers [18, 22]. The RSM has been shown to be very useful for modelling and predicting factor interactions as well as performance characteristics in these studies [19, 21]. However, the number of studies that have focused on its application in systems utilising both liquid and solid waste modifiers, especially with regard to their combined effects on the binder and mixture performance, remains limited.

There is a gap in the literature concerning the synergetic application of RAL as an asphalt binder replacement and WGBP as a modifier to improve the performance of asphalt binders and mixtures, as well as the application of the RSM approach to model and optimise the optimal content to improve performance. Thus, to support research on sustainable asphalt binder modification and the engineering properties of asphalt pavements, the primary aim of this research is to employ RSM to evaluate the synergetic effect of incorporating RAL as an asphalt binder replacement at varying contents of 0 to 10% and utilising WGBP at varying contents of 0 to 4% as a modifier for asphalt binder penetration, softening point, specific gravity, and asphalt mixture volume, Marshall properties, indirect tensile strength, indirect tensile strength ratio, and Cantabro loss and to use RSM to model, describe and predict the performance interactions and establish a comprehensive framework driven by circular economy principles.

Table 1. Physicochemical properties of the constituent materials.

Properties	Standard	Units	Test values	Limits
Asphalt binder				
Specific gravity	ASTMD70-18	-	1.05	1.0–1.06
Ductility at 25 °C	ASTM D113-07	cm	119	> 100
Mass loss	ASTM D2872	%	0.03	< 0.1
Softening point	ASTMD36-12	°C	51.8	47–52
Penetration	ASTMD5-13	dmm	63	60–70
Coarse aggregate				
Bulk specific gravity	ASTM C 127	g/cm^3	2.71	2.60–2.75
Aggregate crushing value	BS 812- 110	%	19.95	< 30
Elongation	BS 812 Part 105.2	%	13.02	< 20
Absorption	ASTM C 127	%	0.37	< 2
L.A. abrasion loss	ASTM C 131	%	21.43	< 30
Flakiness	BS 812 Part 105.1	%	6.9	< 20
Fine aggregate				
Flat and elongated tests	ASTM D 4791	%	15.94	< 20
Absorption	ASTM C 127	%	1.08	< 2
Bulk specific gravity	ASTM C 128	g/cm^3	2.64	2.60–2.75
Waste glass bottle powder				
Colour	Visual	-	Grey	-
Form			Powder	-
Percentage passing 75 μm	ASTM D242M -19	%	94.7	70–100
Density	ASTM C188-17	g/cm^3	2.56	2.5–2.6
Fineness modulus	ASTM C136	-	2.14	-
Absorption	ASTM C128	%	0.28	< 1
Blaine surface area	ASTM C204	m^2/kg	402	300–450
Loss of ignition (LOI)	ASTM C311-17	%	0.63	< 1
SiO_2 content	ASTM C114-15	%	73.08	70–75
Na_2O content	ASTM C114-15	%	8.56	0–10
CaO content	ASTM C114-15	%	8.64	5–10
Recycled automotive oil				
Colour	Visual	-	-	Black
Form	-	-	-	Liquid
Density	ASTM D4052	(g/cm3)	0.87	0.85–0.88
Viscosity at 40 °C	ASTM D445	Pa·s	0.041	0.03–0.05
Flash point	ASTM D92	°C	213	200–220
H content	ASTM D5291	%	12–13	12.75
C content	ASTM D5291	%	83.18	80–85
S content	ASTM D4294	%	0.79	< 1

2. Materials and methodology

The materials used in this investigation were purchased and sourced locally, and the supply chain was kept consistent throughout the experiment to reduce unpredictability. Each material's characteristics and requirements are explained in the subsequent subsections.

2.1. Asphalt binder

For this study, the control (unmodified) binder was a 60–70 penetration grade asphalt. This binder was utilised as the basis for developing the modified asphalt binder and mixtures. The physicochemical characteristics of the binder were carefully assessed to ensure that it complied with the standards. Table 1 summarises the test results for the control binder, demonstrating that it is suitable for use in the investigation.

2.2. Aggregate

The Public Works Department's Standard Specification for Road Works was followed in the selection of the coarse and fine aggregates. The asphalt concrete wearing course was used in the study, and crushed granite with a nominal maximum aggregate size (NMAS) of 14 mm, in addition to natural fine aggregates, was used. To encourage sufficient interlocking and weight distribution within the mixture, a dense grade of aggregate was used. Fig. 1 displays the aggregate gradation curve employed in this investigation, and Table 1 summarises the physical characteristics of both coarse and fine aggregates.

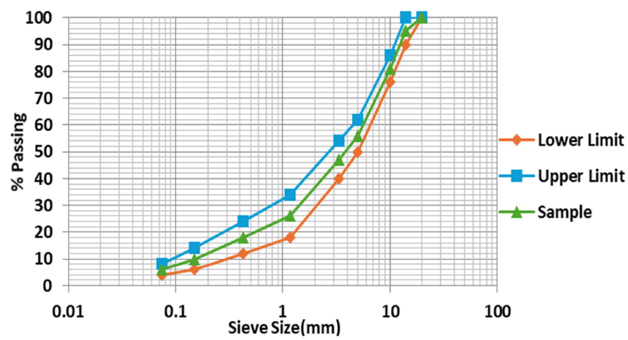


Fig. 1. AC 14 aggregate gradation used in the study.

Table 2. Chemical composition of WGBP.

Composition	% wt
Al_2O_3	2.35
Fe_2O_3	3.01
SiO_2	73.08
CaO	8.64
SO_3	0.46
MgO	2.93
Na_2O	8.56
K_2O	0.96

2.3. Waste glass bottle powder

Waste glass bottle power (WGBP) of different colours and sizes was sourced within the province and then collected and sorted to remove labels, dust, and other debris. To remove moisture, the glass was placed in an oven at a temperature of 100 °C. Next, the glass was placed in a jaw crusher for 10 minutes to create granules. The granules were placed in a ball mill for 7 hours, with 200 rotations each minute, to create a glass powder. Previous studies have reported shorter grinding durations, such as 5–15 and 45–120 minutes, depending on the equipment and required particle fineness [24, 25]. Then, the ground WGBP was placed and sieved through a BS No. 200 sieve, and the filtrate powder was obtained and termed WGBP to be utilised as an asphalt binder modifier. Table 2 shows the chemical composition of WGBP. The high SiO_2 content (73.08%) indicates that WGBP is predominantly silica-based, which contributes to increased stiffness and improved stability when it is incorporated into asphalt mixtures.

2.4. Recycled automobile lubricant (RAL)

Recycled automotive lubricants (RALs) were sourced from a local vehicle repair workshop. The collected RAL was sieved to remove potentially suspended substances, and the RAL was stored in airtight and opaque containers to avoid contamination from potential contaminant sources

Table 3. RAL chemical composition.

Element	% wt
Hydrogen	12.75
Carbon	83.18
Oxygen	2.73
Sulphur	0.95
Nitrogen	0.29

and oxidation. This study evaluated the effects of RAL on asphalt binder replacement at various contents ranging from 0 to 10% by weight. The RALs used in this study were assessed for their physicochemical characteristics according to the ASTM guidelines to determine their suitability for use in modifying asphalt binder. The chemical constituents of the RAL and their weight percentages are shown in Table 3. Because of its hydrocarbon nature, which permits efficient chemical interaction with asphalt binder constituents, RAL was selected for this investigation.

2.5. Modified asphalt binder preparation

The RSM design of experiments (DoE) was employed in the preparation of the modified asphalt binder RAL-WGBP. To prepare the RAL-modified binder, the virgin asphalt binder was heated to approximately 120 °C to facilitate mixing, and the RAL was preheated at 50 °C to increase its viscosity (Fig. 2). The RAL was measured by the weight of the asphalt binder replaced as per the DoE and mixed for 45 minutes at 1200 rpm with the temperature regulated at 145 °C to achieve a homogenous blend. Then, WGBP was added as a modifier based on the DoE, and the mixture was stirred in an advanced multitasking laboratory mixing machine for 45 minutes at 1200 rpm with the temperature regulated at 145 °C to retain homogeneity and consistency during the study. The study mixing methodology was consistent

Fig. 2. High-shear multimix mixer used for blending modified asphalt binders.

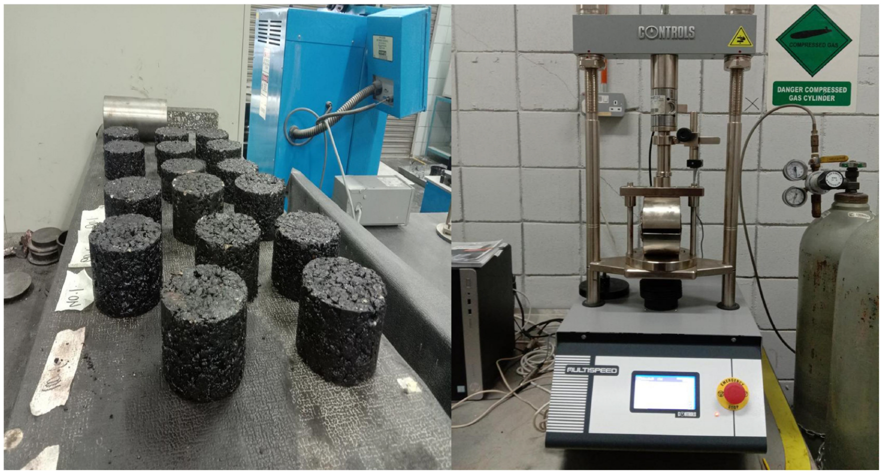


Fig. 3. (a) Marshall samples and (b) Marshall testing machine.

with the accepted methodology for modifier mixing to minimise any level of thermal degradation of the asphalt during the mixing process.

2.6. Asphalt binder conventional properties

The asphalt binder's conventional physical parameters, such as specific gravity, penetration, and softening point, were assessed in accordance with ASTM standards to provide a baseline for performance evaluation. The specific gravity, as determined by ASTM D70, provides details on the density of the binder and how well it works with the aggregates. The consistency or relative hardness of the binder at 25 °C is indicated by penetration, which is measured in accordance with ASTM D5 and directly affects the workability and resistance to deformation. The temperature at which the binder softens and starts to flow is known as the softening point, which is determined via the ring-and-ball method in accordance with ASTM D36. It serves as a gauge for thermal susceptibility and high-temperature performance. These conventional tests are essential for evaluating how RAL and WGBP affect binder behaviour.

2.7. Asphalt concrete mixture preparation

The Marshall mix design process was used to produce the asphalt-concrete mixtures in compliance with ASTM D6927 [26]. To ensure proper blending, approximately 1200 g of the combined aggregates and filler were weighed and heated to 157 ± 3 °C. The asphalt binder was heated separately to the same temperature. The heated constituent materials were well mixed and put into Marshall moulds that had been preheated and compacted at 140 ± 1 °C. The optimal asphalt content (OAC) was determined by producing triplicate samples with binder levels ranging from 4% to 6% by mixture weight. 75 blows per side to each sample as directed. Volumetric and Marshall properties were assessed in accordance with ASTM D1559. To determine the optimal content of WGBP and RAL, the Marshall method was combined with the RSM. To guarantee sufficient durability and structural dependability of the modified asphalt mixtures, all the volumetric parameters were evaluated within the permissible limits of the pertinent performance criteria.

2.8. Volumetric and marshall properties

Air voids (AVs), Marshall stability, and flow are among the important engineering properties of asphalt mixtures that were assessed in this study. These properties were chosen because they offer crucial details about the asphalt pavement structural performance, volumetric integrity, and compaction behaviour. The goal was to evaluate how WGBP-RAL modification affects these crucial characteristics to ascertain the overall performance, durability potential, and structural adequacy of modified asphalt mixtures.

2.9. Asphalt mixture mechanical properties

The modified Lottman test (AASHTO T283), which measures moisture-induced damage through indirect tensile strength (ITS), was used to assess the water susceptibility of the asphalt-concrete mixtures. Marshall samples that were cylindrical in shape were created and exposed to both unconditioned and moisture-conditioned samples (Fig. 3a). Eq. (1), where ITS (kPa) is the indirect tensile strength, Fmax (kN) is the maximum applied load, h is the sample thickness, and d is the average diameter, was used to compute each sample's ITS from the peak vertical load (Fig. 3b). The indirect tensile strength ratio (ITSR) is calculated as the ratio of the ITS of the conditioned samples to that of the unconditioned sample, as shown in Eq. (2). For each WGBP-RAL asphalt mixture, three unconditioned and three moisture-conditioned samples were made for ITSR evaluation, with a minimum ITSR requirement of $\geq$ 80%. These tests assess tensile strength under different moisture conditions and quantify moisture susceptibility.

$$ITS = \frac{2 \times F_{Max}}{\pi \times h \times d} \quad (1)$$

$$ITSR = \frac{ITS_{Conditioned}}{ITS_{Unconditioned}} \times 100 \quad (2)$$

2.10. Cantabro durability test

A Cantabro abrasion test was conducted to measure the ravelling resistance and durability of asphalt mixtures modified with RAL-WGBP, which is essential for evaluating the mechanical stress from traffic. For each RSM DoE mixture design, 3 Marshall samples were produced at a targeted air void of 4.5 ± 0.5%, and their weights were recorded and stored at room temperature. The samples were abraded in a Los Angeles drum with no steel balls for 300 revolutions at 33 rpm in accordance with AASHTO T331 and ASTM D7064. After the procedure, to quantify surface detachment loss per the standard, the samples were weighed, and the % mass lost was calculated via Eq. (3).

$$Cantabro\ loss = \frac{Sample\ weight\ before\ testing - Sample\ weight after\ testing}{Sample\ weight\ before\ testing} \quad (3)$$

3. Response surface approach-based design of the experiment

The study employed RSM Design-Expert®software (version 12.0.3) to generate the experimental design, investigate the synergetic influence of input factors (independent variables) on designated output factors (dependent variables), generate graphical outputs and optimise the results. The CCD was employed because it is effective in capturing the influences—linear, interaction, and quadratic—of the dependent variables [27]. This study assesses the influence of RAL and WGBP on several key engineering properties of asphalt binders and mixtures. The binder's specific gravity (S.G.), penetration (Pen), and softening point (S.P.) were evaluated to assess the binder's consistency, workability, and temperature susceptibility (thermoplastic). Additionally, the asphalt mixture parameters evaluated were air voids (AVs), Marshall stability (MS), Marshall flow (MF), indirect tensile strength (ITS), and the indirect tensile strength ratio (ITSR) for moisture susceptibility, and Cantabro loss was assessed to study the combined effects of WGBP and RAL on the structural and functional durability of the asphalt mixture. The coded and actual levels of the input factors employed in the RSM design are provided in Table 4.

Table 4. RSM actual and coded levels of the input variables.

Level	Actual values		Coded levels
	A: RAL (%)	B: WGBP (%)	
High	10	4	+1
Medium	5	2	0
Low	0	0	–1

To improve dependability across low- and high-factor levels, RSM was used in 13 experimental runs, as shown in Table 5, and the RSM software was generated for each response variable in a randomised order. To account for any random errors and improve the experiment's statistical robustness and dependability, five of these runs were classified as center-point replications [27]. An experimental design model was developed for the responses. Eq. (4) was used to calculate the coded values of the input variables:

$$a_i = \frac{(A_i - A_0)}{\Delta A} \quad b_i = \frac{(B_i - B_0)}{\Delta B} \quad (4)$$

where a_i and b_i are coded (dimensionless) variables, A_i and B_i are real values from experimentation, A_0 and B_0 are center point values, and the changes in steps are denoted by ΔA and ΔB. Analysis of variance was used to determine the response relationships of the input variables and the output. This was followed by performing a regression analysis to obtain a satisfactory polynomial model of the form in Eq. (5):

$$Y = \beta_0 + \beta_{A^a} + \beta_{B^b} + \beta_{AA^{a2}} + \beta_{BB^{b2}} + \beta_{AB^{ab}} + \varepsilon \quad (5)$$

Here, Y denotes the response variable, and a and b represent the coded input variables corresponding to the RAL and WGBP contents, respectively. where β_0 represents the intercept term, β_A and β_B represent the coefficients, β_{AA} and β_{BB} are the quadratic coefficients, β_{AB} represents the interaction coefficient, and ε represents the error.

The experimental data were entered into the RSM software programme for analysis, validation with actual responses, and then modelled for optimisation. ANOVA was used to check the adequacy of the models. The lack of fit was determined via p and F

Table 5. **RSM** design matrix for the input variables.

	Input factors		Responses								
Run	RAL (%)	WGBP (%)	S. G	Pen. (dmm)	S.P (°C)	AV (%)	MS (kN)	MF (mm)	ITS (kPa)	ITSR (%)	CL (%)
1	6	0	1.021	266	37.8	2.99	10	6.58	706	77.8	13.18
2	3	0	1.032	182	46.6	3.71	11.5	4.79	902	82.2	11.58
3	0	4	1.071	39	60.2	4.79	9.1	2.23	1271	87.6	9.49
4	3	2	1.042	130	48.8	3.88	13.5	4.38	934	85.2	11.24
5	3	2	1.037	132	49.8	3.96	13.3	4.41	927	85.8	11.21
6	3	2	1.043	129	47.9	3.81	13.2	4.39	930	85.3	11.22
7	3	4	1.052	78	52.4	4.17	12.1	3.99	992	89.1	10.52
8	3	2	1.039	130	49.1	3.89	13.4	4.42	928	85.4	11.19
9	3	2	1.041	128	49.2	3.91	13.2	4.38	926	85.7	11.17
10	0	2	1.062	44	56.7	4.47	10.6	2.63	1243	85.8	10.02
11	6	4	1.041	176	42.1	3.35	10.5	5.78	802	86.2	12.03
12	0	0	1.049	63	51.8	4.12	9.1	2.98	1207	84.5	10.5
13	6	2	1.031	216	40.3	3.21	11.5	6.18	737	82.2	13.04

values at the 95% confidence level. Measurements of Adequate Precision (AP), Standard Deviation (SD), Coefficient of Variation (CV), and F tests were used to evaluate the precision and reliability of the models [23, 27]. The best set of inputs was obtained through numerical optimisation, and the interaction of the factors was presented through 3D response surface graphs. The experimental validation of the predicted optimum parameters validated the RSM method as precise, reliable, and robust for predicting and improving the performance of RAL-WGBP-modified asphalt mixtures.

4. Results

4.1. RSM fit statistical analysis

Table 6 shows the results of the ANOVA performed on the dataset, and the models obtained reflect adequacy and reliability. The models have low SDs and C.V.s for all the responses, indicating that the models are reliable and precise with nominal variability. The coefficient of determination (R^2) showed a strong correlation between the predicted and actual values for all the responses evaluated in the study [27, 28]. Additionally, the closeness to the R^2 of the actual values to the predicted R^2 values and adjusted R^2 also serves to indicate that the model is predictive in nature, as the difference between them was less than 0.2 [20, 27]. The models' adequacy was also examined by the ratios of the adequacy of the models' adequate precision (A.P.), which also confirmed the models' precision by exhibiting separator characteristics, i.e., separating the signal from the noise, and all ratios were well above the threshold for adequate precision of 4, which is a pointer to the models' precision. Linear, quadratic and two (2) factor interaction (2FI) models were used to effectively and adequately describe the relationships between the input factors and the responses [23, 28]. The findings from this study validate the reliability, precision, and consistency of the RSM-based models, validating the empirical evidence needed for the influence of RAL-WGBP on the optimised asphalt binder and mixture properties.

Eqs. (6) to (14) show the relationships between the input variables and their corresponding responses, where the letters A and B represent the contents of RAL and WGBP, respectively. The equations include lines A and B, interaction (AB), and quadratic (A^2 and B^2) equations. A, B, and AB are represented

Table 6. Response fit statistics, parameters, and verification summary.

	ANOVA fit statistics variables							
Responses (model)	R^2	Adj. R^2	Pred. R^2	AP	C.V	Model p value	LOF p value	Significant terms
SG (Quadratic)	0.986	0.976	0.960	36.07	0.19	< 0.0001	0.76	A, B,A^2
Pen (2FI)	0.999	0.999	0.998	259.44	1.36	< 0.0001	0.052	A, B, AB
SP (2FI	0.987	0.983	0.951	49.89	1.66	< 0.0001	0.329	A, B, AB
AV (Linear)	0.971	0.965	0.936	39.85	2.36	< 0.0001	0.099	A, B
MS (Quadratic)	0.996	0.992	0.975	43.51	1.24	< 0.0001	0.344	A, B, A^2, B^2
MF (Linear)	0.996	0.996	0.995	106.08	1.94	< 0.0001	0.981	A, B
ITS (Quadratic)	0.997	0.998	0.996	178.32	0.49	< 0.0001	0.091	A, B, AB, A^2, B^2
ITSR (Quadratic)	0.991	0.986	0.940	47.98	0.40	< 0.0001	0.189	A, B, AB, A^2
CL (Quadratic)	0.992	0.986	0.951	45.36	1.09	< 0.0001	0.345	A, B, A^2, B^2

alphabetically in terms of the ANOVA hierarchy, as these terms have primary control of the responses, and the influence of the terms is indicated by the sign of the coefficients being positive (synergistic) or negative (antagonistic). This structure allows the input variables and combined effects on the response variables to be analysed.

$$Specific\ gravity = 1.041 - 0.0148A + 0.0103B - 0.0005AB + 0.0048A^2 + 0.0004B^2 \quad (6)$$

$$Penetration = 129.385 + 85.671A - 40.667B - 16AB \quad (7)$$

$$Softening\ point = 48.67 - 8.083A + 3.083B - 1.025AB \quad (8)$$

$$Air\ void = 3.88 - 0.6217A + 0.235B \quad (9)$$

$$Marshall\ stability = 13.31 + 0.533A + 0.1833B + 0.125AB - 2.2A^2 - 1.45B^2 \quad (10)$$

$$Marshall\ flow = 4.36 + 1.773A - 0.385B \quad (11)$$

$$Cantabro\ loss = 11.258 + 1.373A - 0.5366B - 0.035AB + 0.265A^2 - 0.217B^2 \quad (12)$$

$$Indirect\ tensile\ strength = 936.276 - 232A + 57.67B + 24AB + 64.035A^2 + 21.034B^2 \quad (13)$$

$$Indirect\ tensile\ strength\ ratio = 85.5 - 1.95A + 3.0666B + 1.33AB - 1.55A^2 + 0.1B^2 \quad (14)$$

4.2. Model diagnostic graphs

Fig. 4 (a to i) shows the analysis of residuals and normal probability plotting methods to test the normality of residual values from the analysis of the WGBP-RAL-modified asphalt binder and mixtures. The residuals from the models of the responses appear to be normally distributed, and the points lie on the 45-degree line of equality. These results show that the models are statistically significant, considering how the residuals are dispersed and normally distributed [29]. The points in the plots cluster towards the line of equality, which indicates that the RSM models accurately represent the responses [23]. The scatter of the points in the plots indicates the strength of the developed models and is considered to have excellent and good predictive abilities for the WGBP-RAL asphalt binder and mixture properties.

4.3. Input variable synergistic effects on the response of asphalt binder and mixture

The RSM generates 2-dimensional (2D) contours and 3-dimensional (3D) plots to assist in visualising the interrelationships and influences of the input variables on the responses. In the graphs, the response variable is on the Z-axis, whereas the input variables are on the X-axis and Y-axis [23]. The height of the response displayed in the contour is represented by the color, with the lower response levels shown in blue, intermediate response levels in green, and the more optimised response levels in red. The graphs help to demonstrate the combined influence of WGBP and RAL with respect to the various responses and aid in demonstrating their antagonistic/synergistic relationships.

4.3.1. Synergetic influence of RAL and WGBP on the conventional properties of asphalt binder

4.3.1.1. Specific gravity

The 3D surface map that shows how RAL and WGBP together affect the specific gravity of the asphalt binder is shown in Fig. 5a. As the RAL content increases, a distinct decreasing trend in specific gravity is observed. The inherent properties of RAL, whose lighter hydrocarbon parts have a lower density than the pure asphalt binder, are reflected in this behavior. By altering the colloidal structure and lowering internal friction, the inclusion of RAL also improves binder fluidity, which further lowers the blend density overall [30]. Furthermore, the incorporation of WGBP results in a denser particle network, which increases the binder blend's specific gravity. As a result, the two modifiers clearly show a performance gradient: a stiffer, denser binder is produced by a greater WGBP content combined with a lower RAL content. This combined interaction emphasises how crucial it is to balance the amounts of RAL and WGBP to obtain the appropriate binder density and mechanical properties for certain pavement applications.

4.3.1.2. Penetration value

Fig. 5b depicts the 3D plots for the synergetic effect of RAL and WGBP on the asphalt binder penetration value. The plot shows that an increase in the RAL content facilitates greater penetration due to the thin oil fraction, which increases the fluidity and

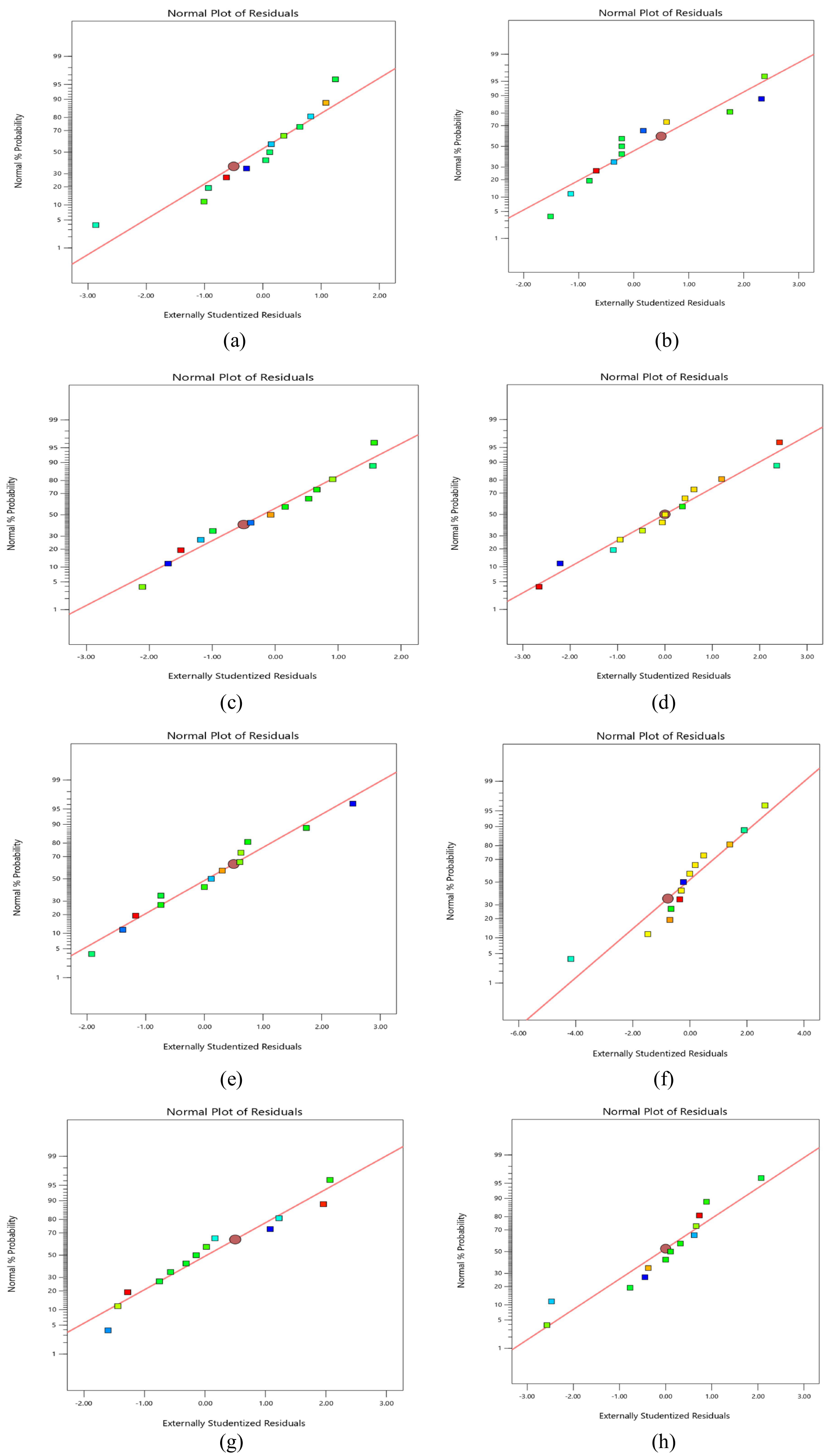
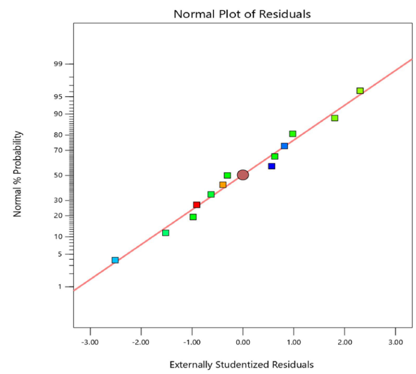


Fig. 4. Model adequacy diagnostic graphs for (a) specific gravity, (b) penetration, (c) softening point, (d) air void, (e) Marshall stability, (f) Marshall flow, (g) indirect tensile strength, (h) indirect tensile strength ratio, and (i) Cantabro loss.



(i)

Fig. 4. Continued.

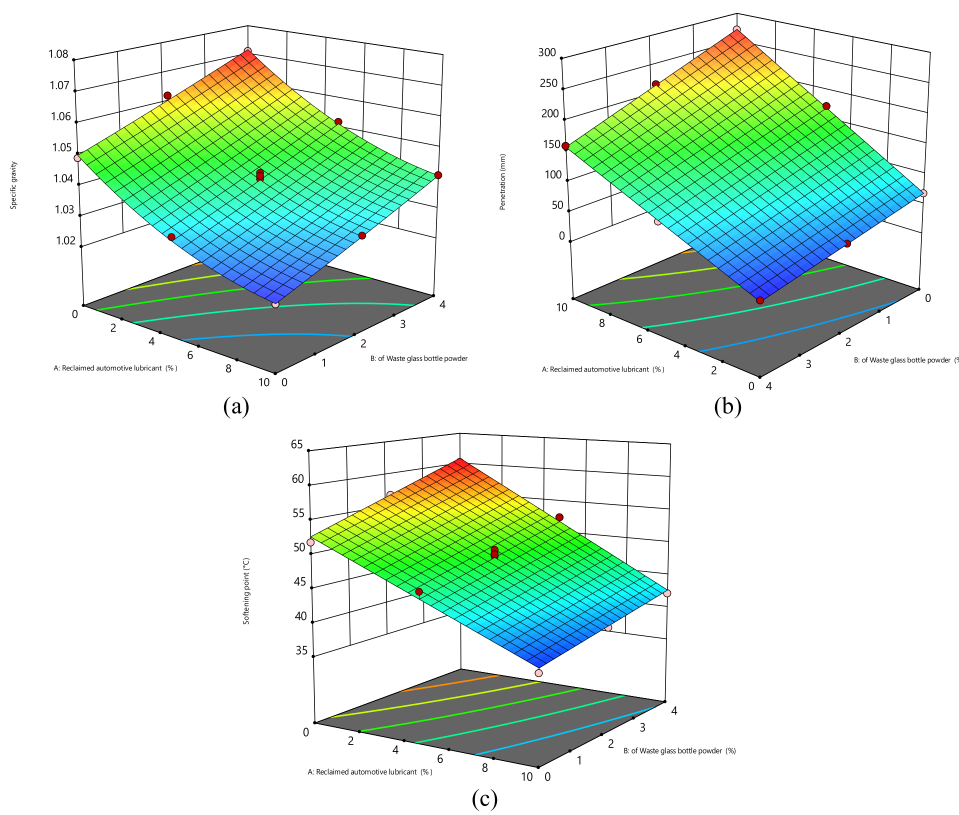


Fig. 5. Synergistic influence of RAL and WGBP on the asphalt binder (a) specific gravity, (b) penetration, and (c) softening point.

decreases the rigidity of the binder. Additionally, the findings indicate that penetration decreases when the WGBP in the asphalt binder increases at different percentages [30]. As the WGBP content increased, penetration generally decreased. The impact can be explained by the stiffening effect of the WGBP modifier, which limits the penetration depth. These results could also be explained by the POCF particle surface, which facilitates interaction with the asphalt and increases the viscosity of the modified binder. As WGBP surface spaces absorb the binder and RAL light components, more motion is needed to overcome frictional resistance. Additionally, elements included in the WGBP, such as calcium oxide and ferric oxide, tend to absorb extra oil from the asphalt binder and RAL, making it stiffer.

4.3.1.3. Softening point

Fig. 5c depicts the 3D plots for the synergetic effect of RAL and WGBP on the asphalt binder softening point. The addition of RAL decreased the binder stiffness and increased the thermal instability. This can be attributed to the disturbance of the colloidal stability, and the dispersion of the d-asphaltene-rich network acted to produce a softening binder [31]. RAL works by partially dissolving the heavier, stiffer asphaltene molecules into lighter aromatic fractions while increasing the percentage of low-molecular-weight maltenes, and RAL alters the asphalt colloidal structure, with the goal of increasing binder mobility [30, 31]. The softening point has an inverse relationship with the RAL when WGBP is added, as an increase in the WGBP content improves the softening point. The improvement in the softening point can be attributed to an increase in the modified asphalt binder stiffness. WGBP increases viscosity by preventing movement due to the resistance of the binder matrix particles to motion. This can also be explained by the WGBP silica content absorbing the light component of the binder. The improvement in the softening point enhances the ability of the asphalt binder blend to resist high temperatures and deterioration of the pavement from rutting. When WGBP is combined with WGBP, it significantly enhances the workability and flexibility of the binder while maintaining the required stiffness.

4.3.2. Synergistic influence of RAL and WGBP on the volume and Marshall properties of the asphalt mixture

4.3.2.1. Air voids

The synergistic influence of RAL and WGBP on the void space of the asphalt mixture is shown in Fig. 6a. The addition of RAL to the mixtures caused a considerable reduction in the number of air voids, whereas the addition of WGBP slightly increased the number of air voids. As a viscous liquid modifier, the RAL increases the fluidity of the asphalt binder, increasing the coating of the aggregates and increasing the efficiency of rearranging more of the aggregates during the compaction of the mixture. This also lowers the number of air voids, which encourages workability and a reduction in compaction. However, WGBP has a high specific gravity with stiff, angular particles that act as fillers, which increases the void content via microvoids and interlattice restrictions that prevent overall densification (predominate) [32]. The study air void content ratio between 3% and 5% is the optimum amount of binder expected to prevent the mix from overall cracking, and the accommodating voids are designed to permit thermal expansion and bleeding of the pavement.

4.3.2.2. Marshall stability

The combined effect of adding RAL and WGBP on the Marshall stability of mixtures is shown in Fig. 6b, with an elliptical contour profile showing appropriate synergy between the input variables. As the RAL content increases, the Marshall stability initially increases at low contents; however, beyond an optimal level, it begins to decrease, reflecting a reduction in the load-bearing capacity of the mixture until it reaches an optimal content and begins to decrease, indicating the need to determine an optimal content [17]. This shows that at higher contents, RALs increase the plasticising activity from lighter hydrocarbons, which lowers the binder viscosity, weakens the asphaltene and maltene equilibrium and induces overlubrication at the aggregate — binder interface. This lowers aggregate interlock and reduces Marshall stability. Conversely, WGBP greatly increased the Marshall stability in all the samples, and the higher the replacement level was, the greater the stability. This is due to the WGBP acting as a structural micro-filler and adding stiffness to the mixture [32]. This was due to the angular, rigid, and silica-rich particulates of WGBP, which increased the packing density and restricted the mastic flow, thus increasing internal friction. The opposing behaviours of RAL and WGBP led to notable synergistic interactions; excessive RAL further diminished structural stability, whereas the addition of WGBP altered the balance by strengthening the internal scaffold of the mixture, thus increasing frictional resistance.

4.3.2.3. Marshall flow

Fig. 6c shows the synergetic effect of incorporating RAL and WGBP on the Marshall flow of the mixtures. For the plot, with increasing RAL, the Marshall flow increased as well, which shows the RAL-modified binder's plasticising effect, which allows the mixture to resist more deformation before failure [17]. WGBP, however, decreased the flow values linearly at higher contents. WGBP decreases the mixture's susceptibility to plastic deformation due to increased rigidity, increases the mastic stiffness by decreasing the binder layer thickness, and increases the mastic stiffness [32]. The linear effects of RAL and WGBP on MF show the importance of balancing the additives to achieve a usable workability—stiffness relationship.

4.3.3. Synergistic influence of RAL and WGBP on the mechanical and durability responses of asphalt mixtures

4.3.3.1 Indirect tensile strength

Fig. 7a shows the 3D synergetic interaction response surface plots between RAL and WGBP on the ITS. The results illustrate that an increase in RAL, which has a softening and plasticising effect on the

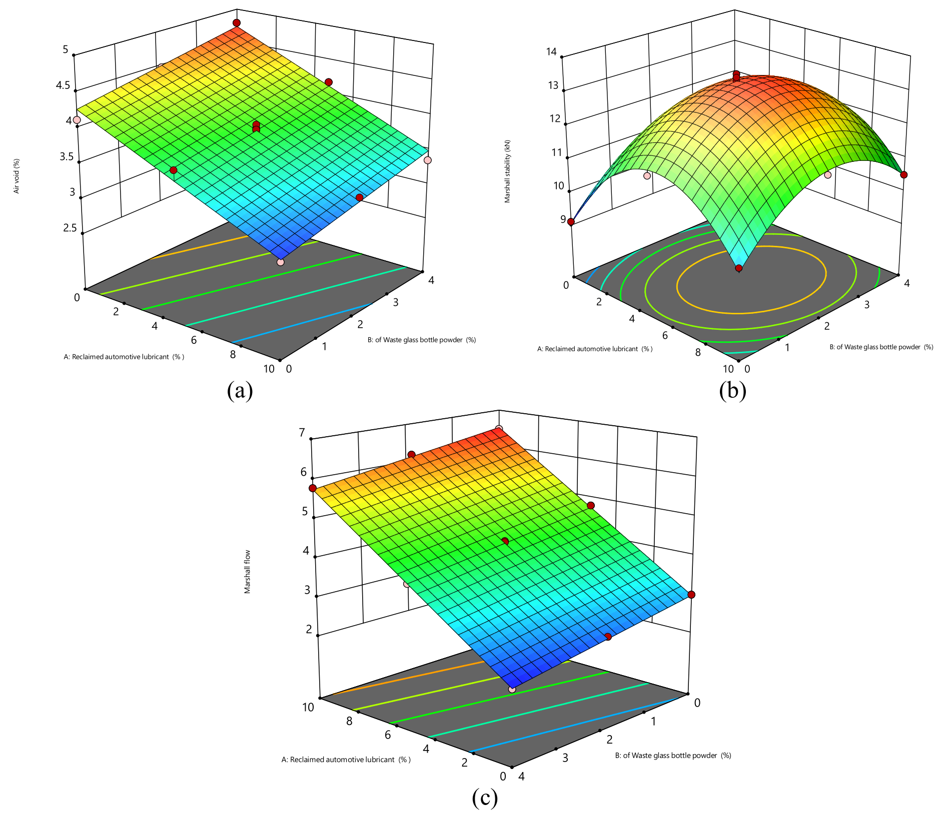


Fig. 6. Synergistic influence of RAL and WGBP on asphalt mixtures: (a) air voids, (b) Marshall stability, and (c) flow.

binder, reduced the ITS. This is because RAL improves viscosity, softens the asphalt binder matrix, and weakens aggregate–binder cohesion by disturbing the asphaltene–maltene network. Thus, asphalt mixtures with RAL exhibit lower tensile strength and greater susceptibility to cracking and breaking as a result of exposure to environmental and traffic loading. A similar study reported that the application of waste engine oil decreases the mixture tensile strength [16]. However, WGBP was observed to increase the ITS as the content increased. This can be attributed to the effect of the WGBP stiff micro-fillers, which improves the binder–aggregate interfacial region, increases the density of the mastic, and facilitates load transfer in the matrix. Thus, this stiffening effect improves the tensile strength, moisture damage resistance, and performance stability under cyclic loading [33]. WGBP (approximately 2–4%) was able to counter the softening effect of RAL to provide the optimal balanced tensile performance. This aligns with the findings in the RSM matrix that, as a consequence of the diversion of RAL softening and WGBP stiffening, the peak obtainable ITS can also be achieved with increased workability. These findings indicate that the carefully planned incorporation of liquid and solid waste modifiers can produce sustainable asphalt mixtures with improved performance.

4.3.3.2 Indirect tensile strength ratio

The moisture resistance of the mixture depends on the indirect tensile strength ratio (ITSR), which is affected by the moisture damage of both RAL and WGBP because of their differing influences on the adhesion of the binder to the aggregate and the mixture performance. Fig. 7b depicts the 3D synergetic interaction response surface plots between RAL and WGBP on ITSR. With increasing RAL content, the moisture resistance decreased, which was indicated by the decrease in the ITSR. This can be attributed to the light hydrocarbon fractions from RAL, which reduce the binder polarity, affecting the physicochemical interactions necessary for strong adhesive bonding to the aggregate surface [16, 17]. Additionally, the moisture resistance was reduced because the RAL softened the binder and became a low-viscosity film, which weakened the cohesive strength of the film and led to moisture weakening. On the other hand, the increase in WGBP was reflected by a significant increase in the ITSR, which indicated that the moisture resistance of

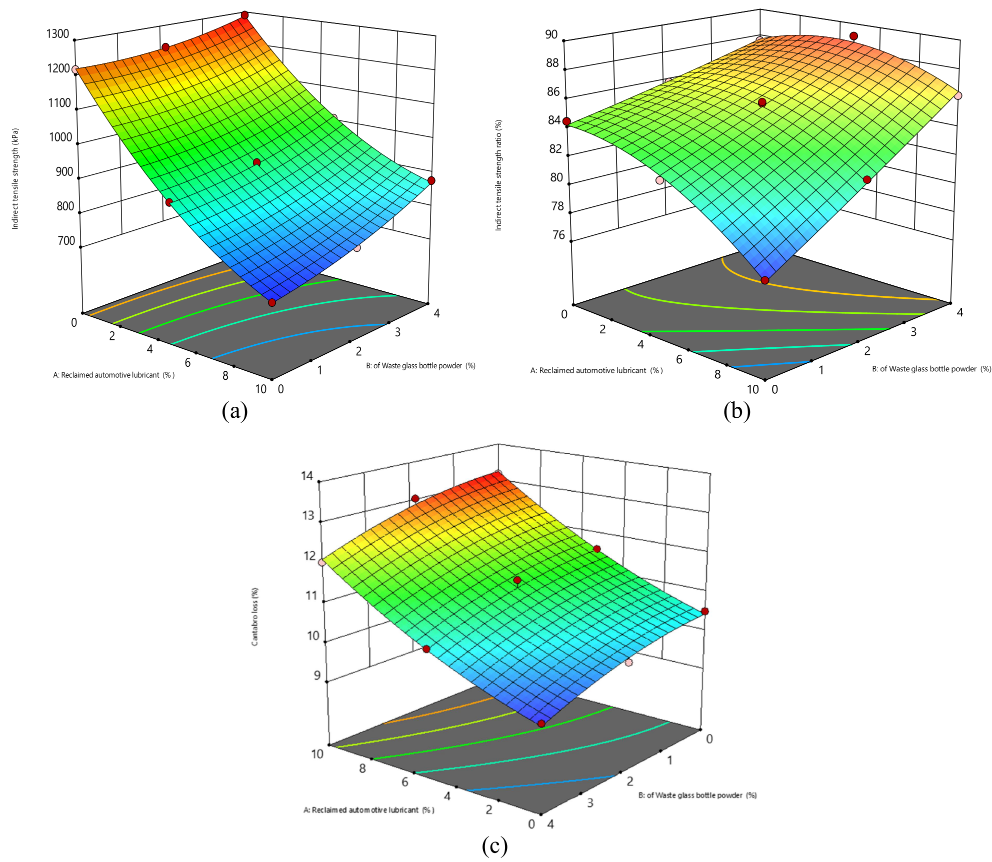


Fig. 7. Synergistic influence of RAL and WGBP on asphalt mixtures: (a) indirect tensile strength, (b) indirect tensile strength ratio, and (c) Cantabro loss.

the mixture improved. This is due to the WGBP micro-fillers, which are angular and rich in silica, increasing the cohesive strength of the binder matrix and improving the strength of the formation of a mastic that is less permeable and more cohesive, increasing the durability of the moisture [33]. This shows that WGBP has a greater ability to reduce moisture damage than RAL does. WGBP densifies and strengthens the microstructure of the mastic. The results of this study indicate that WGBP achieves a dual purpose in RAL-modified asphalt mixtures in terms of acting as a stiffening agent and effectively improving moisture resistance.

4.3.3.3 Cantabro test

Fig. 7c shows the 3D synergetic influence of integrating RAL and WGBP on the Cantabro loss value of the mixtures. The plot revealed that there was a strong correlation between the RAL content and Cantabro loss, with higher RAL contents resulting in greater Cantabro loss, which indicates greater loss of cohesiveness, weaker aggregate–binder interfacial adhesion, and greater susceptibility to ravelling. This was due to the softening effect of RAL, which lowers the viscosity of the binder, disrupts the equilibrium of the asphaltene resin within the asphalt binder, and weakens the ability of the binder to adequately hold the aggregates together [16]. This led to the high RAL mixtures being more prone to disintegration when exposed to mechanical action because of their lower structural integrity and ease of particle detachment. However, the addition of WGBP effectively increased the resistance of the mixtures to abrasion. This was due to the particle glass grinding being micro-reinforced and behaving as a filler; hence, higher WGBP contents of the mixtures led to lower Cantabro loss [33]. WGBP results in enhanced binder–aggregate interactions with lower micro voids, greater mastic densification, and free binders because micro voids are filled, mastic phase continuity is enhanced, mastic phase stiffness is increased, and mastic phase continuity is enhanced [8, 34]. Overall, the behavior of Cantabro loss showed that with RAL, the durability decreased due to oversoftening of the binder, and with WGBP, there was a stabilising countereffect through which the mastic structure was enhanced. Hence, to produce

Table 7. Multi-objective constraints for the optimisation of parameters from the RSM.

Parameters	Unit	Standard	Target goal	Range
A: RAL	%	-	Range	0–10
B: WGBA	%	-	Range	0–4
Specific gravity	-	-	Maximise	1.021–1.063
Penetration	dmm	-	Minimise	21–271
Softening point	°C		Maximise	37.8–60.2
Air void	%	3–5	In range	2.00–4.79
Stability	kN	> 8	Maximise	9.1–13.5
Flow	mm	2–4	Range	2.18–6.47
Indirect tensile strength	kPa	-	Maximise	708–1289
Indirect tensile strength ratio	%	>80	Maximise	77.8–89.1
Cantabro loss	%	<20	Minimise	9.49–13.18

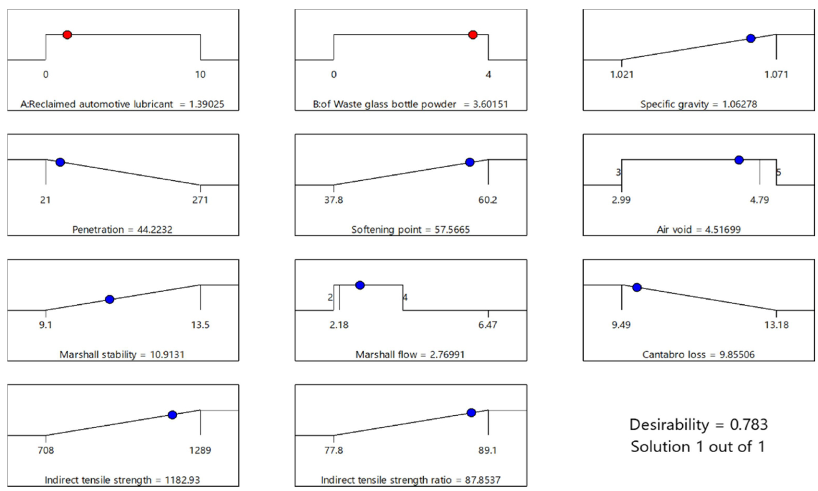


Fig. 8. Developed model multi-objective optimisation ramp.

an asphalt mixture with adequate abrasion resistance and durability over a long period of time, a balance of the optimal contents of the two modifiers is essential.

4.4. Optimisation of the asphalt binder and mixture design parameters

This study aimed to statistically determine the optimal content of RAL and WGBP to produce a sustainable and enhanced modified asphalt mixture satisfying the Marshall design specifications. Thus, this study employed a multi-objective RSM-optimisation method to evaluate the optimal content of modifiers to improve the performance of the mixture. The target and control ranges for the parameters based on the standard are summarised in Table 7. This approach ensures that the mixture of asphalt provides balanced and lasting performance due to the synergistic effect of RAL and WGBP on both the asphalt binder and the mixtures.

For RSM multi-objective optimisation, Fig. 8 shows the anticipated responses for every parameter. With a desirability level of 78.3, the ideal parameters for obtaining the required mixture properties were found to be 1.39% RAL and 3.6% WGBP. A validation run was carried out using the optimised parameter values to validate these predictions. Three sample replicates were created to acquire the average values of the responses, which were then compared to the responses that the model predicted. By confirming the RSM optimisation via the % error analysis described in Eq. (7), the model's predictive ability and precision were confirmed.

$$Error\ (\%) = \left|1 - \frac{\text{RSM model value}}{\text{Laboratory value}}\right| \times 100 \qquad (15)$$

The RSM-optimised model verification for the percentage of experimental and predicted responses is displayed in Table 8. The differences between the RSM-predicted results and the experimental data are negligible within the 5% threshold. This demonstrates the importance, precision, and dependability of the models created to forecast the performance of asphalt mixtures modified via WGBP-RAL.

Table 8. Optimised model verification for experimental and predicted responses.

Input variable	Response	RSM Model	Laboratory	Error (%)
	Specific gravity	1.063	1.098	3.29
	Penetration	44.22	45.29	2.42
RAL = 1.39	Softening point	57.57	59.38	3.14
	Air void	4.52	4.71	4.20
	Marshall stability	10.91	11.28	3.39
WGBP = 3.6	Marshall flow	2.77	2.85	2.89
	Indirect tensile strength	1182.93	1231	4.06
	Indirect tensile strength ratio	87.85	90.73	3.27
	Cantabro loss	9.86	9.59	2.74
Average error			3.27	

5. Conclusions

The objectives of this study were to examine how the combination of RAL and WGBP affect the properties of asphalt binders and mixtures and to use RSM multi-objective optimisation to determine the optimal level of each modifier to enhance performance. The study concluded with the following findings:

- The study showed that RAL-modified asphalt binders had higher penetration levels and lower softening points and specific gravities than the other binders did because of the plasticisation of the binders and manipulation of the colloidal structure. The WGBP to the asphalt binders acted as a stiffening material because the silica-rich micro-filler increased the stiffness. This optimally balanced the penetration levels, softening points, specific gravities, and thermal performance.
- Concerning the volumetric properties, the study concluded that the incorporation of RAL-modified asphalt binders resulted in a reduction in AV and an improvement in workability, whereas WGBP was concluded to slightly increase AV owing to its angularity and stiffening properties. All AVs, however, remain within the standard range of 3 to 5%.
- The durability of the asphalt mixtures and the ITS- and ITSR-modified binders was concluded to be improved because of the combined incorporation of WGBP and RAL. The modified asphalt mixtures were concluded to better resist particle detachment and water damage with and without traffic loading.
- The RSM ANOVA shows models with an R^2 value greater than or equal to 0.93, which indicates predictive adequacy and low variance. The effects of WGBP and RAL were evaluated via linear and quadratic models, with responses being evaluated via multi-objective optimisation and laboratory validation.
- The optimum value from the RSM multi-objective optimisation yielded 1.39% RAL and 3.6% WGB, which improved the output to a highly desirable value of 0.783. The validation tests performed in the study also recorded a low error value, which was less than 5%, confirming the significance and precision of the models.
- The synergistic effect of the WGBP-RAL-modified asphalt binder and mixture shows that the binder and mixture improve through enhanced particle packing, improved binder coating, and a rich silica filler mechanism with a lubricating effect.

Ethical approval

Not applicable.

Conflict of interest

The authors declare that they have no conflicts of interest to report with respect to the current study.

Authors contribution

Nura Shehu Aliyu Yaro: Conceptualization, data curation, formal analysis, investigation, methodology, software, writing - original draft. Jacob Adedayo Adedeji: Project administration, resources, writing - original draft, Luvuno Nkosinathi Jele: Project administration, resources, formal analysis. Aliyu Usman: Software, formal analysis, validation, visualization, Nasir Khan: Software, formal analysis, validation, visualization, Jacob Olumuyiwa Ikotun: Writing - review & editing, supervision. All authors reviewed and approved the final manuscript.

Availability of data and materials

All data supporting the results of this study are included within the article.

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