Optimizing Asphalt Mixture Performance with Modified Buton Asphalt and Recycled PET using the Response Surface Methodology

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ABSTRACT

In order to enhance asphalt-concrete mixtures, additives are used to improve durability and resilience to repeated road loads. The present study uses plastic waste as an additive and aims to find the optimal parameters for blending asphalt with additives made from Plastic Bottle Waste (PET) using Response Surface Methodology (RSM). The RSM approach, guided by the Design-Expert 8.0.6 software (Stat-Ease, Inc., Minneapolis, MN, USA), involved the design and analysis of a series of 17 experiments, employing a three-factorial Box-Behnken Design. The experimental design incorporated three primary independent variables, with the first (*X1*) being the ratio of PET to Modified Buton Asphalt (MBA), and the dependent variable (*Y*) corresponded to the Marshall characteristic, which serves as a measure of the reaction output. The results indicate that the incorporation of PET-based additives significantly enhances the stability, flow, and void characteristics of the asphalt mixture. The optimal mixture was achieved at an *X1* of 2.0%:6.25%, which resulted in an improvement of Marshall stability by 47.89% compared to conventional asphalt mixtures. Furthermore, the addition of PET improved asphalt resistance to deformation and fatigue cracking. Consequently, it is recommended that further investigation be conducted into the potential of PET-based additives for large-scale applications in road construction, with a focus on long-term performance and environmental impacts.

Keywords-Response Surface Methodology (RSM); plastic waste; Marshall characteristics

I. INTRODUCTION

The usage of plastic waste as an additive in asphalt mixtures has emerged as a promising solution to address environmental concerns stemming from plastic pollution, while concurrently enhancing road durability [1]. Employing a Life Cycle Assessment (LCA) approach ensures that the environmental impact of asphalt production, encompassing the extraction of raw materials and the end-of-life disposal phase, is minimized. The incorporation of locally available materials, such as MBA, not only mitigates transportation-related emissions, but also fosters sustainable resource usage in road construction [2]. This approach has the potential to enhance labor efficiency by streamlining the asphalt production process, reducing the need for complex handling, and ensuring cost-effective infrastructure development [3]. The high rate of damage to road pavement in Indonesia is attributable to various factors, including environmental conditions, such as the tropical climate, as well as an increase in traffic load, both in terms of volume and axle weight [4]. The quality of road pavement is continuously improved through upgrades to the asphalt grade or the incorporation of additional materials into the asphalt mixture [5, 6]. These strategies aim to increase the durability and lifespan of pavement under challenging conditions. Polymers are among the most widely used additives in asphalt mixtures, while plastics commonly utilized in daily life contain polymers, also known as elastomers. These polymers have the potential to be used as additional materials in road pavement [7]. Consequently, this study examined the performance of asphalt mixtures incorporating additives derived from plastic waste through laboratory trials. Numerous experiments have been conducted by researchers to evaluate asphalt mixtures with plastic additives, with the aim of enhancing pavement performance and promoting sustainable practices.

Authors in [8] examined the impact of incorporating PET on the engineering properties of crushed stone in Stone Mastic Asphalt (SMA) mixtures. The results demonstrated that the inclusion of PET has a positive effect on the performance of asphalt mixtures. Authors in [8] examined the usage of waste tires and plastic in asphalt mixtures, with the aim of addressing the environmental concerns stemming from non-biodegradable materials. Authors in [9] evaluated the effects of incorporating various types of polymers into asphalt concrete. It was found that, under optimal conditions, the addition of polymers enhances penetration, stability, kinematic viscosity, and indirect tensile strength. Authors in [10] examined the use of plastic waste in flexible pavement. The findings of this research indicated that incorporating plastic waste into flexible pavement improves its strength, reduces the risk of damage, such as potholes and rutting, increases load-bearing capacity, and decreases asphalt consumption, resulting in cost savings and an extended service life for the road. Indonesian natural asphalt, commonly known as asbuton (Buton natural asphalt), is sourced from the asbuton deposit located on Buton Island in Southeast Sulawesi [11]. Asbuton is a naturally occurring hydrocarbon material with a bitumen content ranging from 10% to 40%, while the remaining composition consists of minerals. The estimated size of the asbuton deposit is approximately 600 million tons, with a projected bitumen content of around 24 million metric tons [6, 12]. The Indonesian Minister of Public Works enacted Ministerial Regulation Number 35/PRT/M/2006, which promotes the increased usage of Buton asphalt in road maintenance and construction. This regulation underscores the technical and financial viability of Buton asphalt, as evidenced by laboratory and field testing, and asserts its potential to enhance the strength and durability of roads. The technology for Buton asphalt remains a subject of ongoing development. Retona, a modified form of Buton asphalt, is a blend of natural and oil-based asphalt, processed using machinery that meets the requisite standards to produce high-quality modified asphalt. In comparison to conventional asphalt, MBA exhibits superior stability, durability, workability, and service life [13, 14]. When there is no discernible change in shape over its service life, the surface layer of the road pavement can function as a wear layer. The increasing traffic density is a primary cause of road damage or premature failure. Authors in [15, 16] noted that repeated traffic loads, resulting from traffic density, induce permanent deformation in the asphalt concrete mixture, thereby reducing road performance over time. The addition of chemicals to the mixture is a proposed solution to this problem. RSM is a collection of problem-solving techniques that use mathematics and statistics in the form of mathematical models or functions to analyze a problem and determine the desired response. RSM has been widely developed in optimization research, which is influenced by several factors to achieve the best possible solution. This statistical technique can account for the involvement of two or more variables in an investigation. Additionally, the interactions between the observed components can be estimated using this method. The objective of the present study is to use RSM to ascertain the optimal parameters for blending asphalt with additives derived from PET plastic waste in a model system.

II. MATERIALS AND METHODS

A. Physical Properties of the Aggregates

Tables I-III present the properties of the coarse aggregate, filler made from stone ash, and fine aggregate (stone ash), respectively. The test results for the stone ash, filler, and coarse aggregate (crushed stone) clearly show that the aggregates used meet the criteria for road materials as outlined in the 2018 General Specifications for Bina Marga, Indonesia. Given that aggregates constitute the majority of an asphalt mixture, particularly the Asphalt Concrete Wearing Course (AC-WC) combination, their properties were evaluated to ascertain their suitability for this study. The aggregates employed in this investigation are classified as coarse, fine, and filler, contingent on their particle size distribution: coarse aggregates are those retained on sieve No. 8 (2.36 mm), fine aggregates are those that pass-through sieve No. 8 but are retained on sieve No. 200 (0.075 mm), and filler aggregates are those that pass-through sieve No. 200. The coarse aggregate, fine aggregate, and filler materials utilized in this study comply with the road construction material specifications delineated in the 2018 General Specifications for Bina Marga, Indonesia. These materials were selected to ensure that the asphalt mixture attains the requisite strength, durability, and performance standards for road pavement applications.

TABLE I. PHYSICAL PROPERTIES OF FINE AGGREGATE

No.	Properties	Results	Specification		Unit
			Min	Max	
1	Water absorption	2.67	-	3.0	%
2	Bulk specific gravity	2.39	2.5	-	-
	Saturated Surface Dry (SSD) specific gravity	2.49	2.5	-	-
	Apparent specific gravity	2.51	2.5	-	-
3	Sand equivalent	90.16	50	-	%

TABLE II. PHYSICAL PROPERTIES OF FILLER

No.	Properties	Results	Specification		Unit
			Min	Max	
1	Water absorption	2.31	-	3.0	%
2	Bulk specific gravity	2.71	2.5	-	-
	SSD specific gravity	2.78	2.5	-	-
	Apparent specific gravity	2.85	2.5	-	-
3	Sand equivalent	79.75	50	-	%

B. Physical Properties of Modified Buton Asphalt

The binder used in this study is a modified asphalt. The physical properties of the asphalt, which are associated with its performance, were determined by examining its characteristics. The properties of the MBA, as outlined in Table IV, demonstrate that the asphalt employed in this study meets the requirements of Indonesia's 2018 General Specifications Revision 2, Section 6, for asphalt pavement.

TABLE III. PHYSICAL PROPERTIES OF COARSE AGGREGATE

No.	Properties	Results	Specification Min	Specification Max	Unit
1	Water absorption				
	Crushed stone 5 - 10 mm	2.18	-	3.0	%
	Crushed stone 10 - 20 mm	2.19	-	3.0	%
2	Specific gravity				
	Crushed stone 5 - 10 mm				
	Bulk specific gravity	2.72	2.5	-	-
	SSD specific gravity	2.77	2.5	-	-
	Apparent specific gravity	2.87	2.5	-	-
	Crushed stone 10 - 20 mm				
	Bulk specific gravity	2.72	2.5	-	-
	SSD specific gravity	2.78	2.5	-	-
	Apparent specific gravity	2.87	2.5	-	-
3	Flatness index				
	Crushed stone 5 - 10 mm	21.21	-	25	%
	Crushed stone 10 - 20 mm	10.47	-	25	%
4	Abrasion in Los Angeles Machine				
	Crushed stone 5 - 10 mm	26.83	-	40	%
	Crushed stone 10 - 20 mm	25.55	-	40	%

TABLE IV. PHYSICAL PROPERTIES OF MODIFIED BUTON ASPHALT

No.	Properties	Results	Specification Min	Specification Max
1	Penetration before losing weight (mm)	82.7	60	79
2	Soft Point (°C)	51.9	48	58
3	Ductility at 25°C, 5 cm/min (cm)	123	100	-
4	Flash point (°C)	279	200	-
5	Specific gravity	1.14	1	-
6	Weight loss (%)	0.23	-	0.8
7	Penetration after losing weight (mm)	87.5	54	-

C. Physical Properties of Plastic Waste

PET, a polymer composed of long chains of ethylene monomers (IUPAC: ethene), is the type of plastic bottle used in this study. The molecular structure of ethene, C_2H_4, is represented as CH_2—CH_2—n, where two CH_2 units are connected by a single bond. The polymerization of ethene results in the formation of polyethylene. Polyethylene's chemical properties are such that it can dissolve in aromatic hydrocarbons at high temperatures [20]. Figure 1 shows the thin surface structure of polyethylene. PET is a type of plastic that is derived from petroleum and is recognized for its favorable mechanical properties, slightly translucent appearance, high flexibility, and slightly greasy surface. It exhibits excellent chemical resistance at temperatures up to 60 °C and has a specific gravity of 0.91 g/cm³–0.94 g/cm³. Additionally, it is easy to process, dissolves readily in mixtures, and provides good resistance to water vapor. Low-density PET is a thermoplastic polymer with a melting point of 115 °C, which is produced through free radical polymerization under high pressure and temperature (200 °C). PET-type plastic has a wide range of applications, including plastic bottles, toys, molding materials, buckets, drums, pipelines, wire and cable insulation, and plastic bags.

D. Asphalt Concrete Wearing Course Design

The aggregate used in this study comprises two distinct types: filler, which is retained on sieve number 200, and coarse aggregate, which consists of crushed stones measuring 1cm–2 cm and 0.5 cm–1 cm, respectively. The preparation of Marshall test specimens is based on the produced mix design. Table V presents the gradation of the wear layer in accordance with the requirements outlined in Indonesia's 2018 General Specifications Revision 2.

Fig. 1. Polyethylene thin surface.

TABLE V. ASPHALT CONCRETE COMBINED AGGREGATE GRADING

Sieve size (mm)	% Weight passed to total aggregate in mixture								
	Sand-sheet		Hot rollet sheet				Asphalt concrete		
			Gap gradation		Semi-level gradation				
	Class A	Class B	WC	Base	WC	Base	WC	BC	Base
37.5									100
25								100	90 - 100
19	100	100	100	100	100	100	100	90 - 100	76 - 90
12.5			90 - 100	90 - 100	87 - 100	90 - 100	90 - 100	75 - 90	60 - 78
9.5	90 - 100		75 - 85	65 - 90	55 - 88	55 - 70	77 - 90	66 - 82	52 - 71
4.75							53 - 69	46 - 64	35 - 54
2.36		75 - 100	50 - 72	35 - 55	50 - 62	32 - 44	33 - 53	30 - 49	23 - 41
1.18							21 - 40	18 - 38	13 - 30
0.600			35 - 60	15 - 35	20 - 45	15 - 35	14 - 30	12 - 28	10 - 22
0.300					15 - 35	5 - 35	9 - 22	7 - 20	6 - 15
0.150							6 - 15	5 - 13	4 - 10
0.075	10 - 15	8 - 13	6 - 10	2 - 9	6 - 10	4 - 8	4 - 9	4 - 8	3 - 7

At least 80% of the aggregate passing sieve No. 8 (2.36 mm) must also pass sieve No. 30 (0.600 mm) for the HRS-WC and HRS-Base to be truly gapped. The limits for the gap-graded material in Table V are specified for passing sieve No. 8 (2.36 mm) and being retained on sieve No. 30 (0.600 mm).

E. Marshall Characteristics

The Marshall test has two objectives: determine the Optimal Asphalt Content (OAC) and evaluate the asphalt mixture. The test is conducted according to the AASHTO T 245-97 (2004) standard and the primary objective is to assess the stability and plastic deformation of the asphalt mixture. Stability testing measures the mixture's resistance to traffic loads, while plastic yield testing evaluates form changes caused by repeated traffic stresses. In the preparation stage for the Marshall test specimens, the asphalt is subjected to a heating process, with the temperature being elevated to a range of 170 ± 20 cSt to attain optimal viscosity. The compaction temperature is then set to 280 ± 30 cSt. The cylindrical specimen, with a diameter of 102 mm and a thickness of 63.5 mm, is tested at 60 °C with a consistent loading speed of 2 in/min until failure occurs. The maximum load that the specimen can withstand before failure is referred to as Marshall stability, while the deformation the specimen can endure before failure is referred to as Marshall flow (Yield). The ratio between stability and flow is known as the Marshall Quotient (MQ), which is indicative of the stiffness and performance of the asphalt mixture. Authors in [16] employed the Marshall method to assess the stability and flow of asphalt mixtures. This method utilizes a dial gauge to directly measure key parameters, including stability and flow values. The primary objective of this approach was to determine the properties of hot asphalt mixtures. The test results provide key parameters, including asphalt mixture density, Voids in the Mix (VIM), Voids in Mineral Aggregate (VMA), MQ, stability, and flow. The Marshall method is commonly applied in asphalt mixture design, particularly when evaluating the elastic modulus in concrete mixtures. The performance of an asphalt mixture is primarily influenced by its volumetric properties in a solid state, which include VIM, VMA, and VFA. In 2006, the Directorate General of Highways, under the Indonesian Department of Public Works, published Regulation No. 001–05/BM/2006, which stipulates the use of Buton asphalt, a mixture of cold asphalt combined with emulsified granular Buton asphalt. This regulation delineates the requirements for briquettes produced through compaction using 2 × 50 blows. Concurrently, the Indonesian National Standard (SNI) 06-2489-1991 provides a framework for evaluating the performance of asphalt mixtures intended for roads experiencing high traffic volume. This standard outlines a procedure that utilizes the Marshall test method, employing 2 × 75 blows, to assess the quality and durability of the asphalt mixture. The dry volume weight of the mixture, which is indicative of the density of the asphalt concrete, is denoted as the unit weight. Mixtures with high density will be capable of supporting greater loads in comparison to those with low density. VIM refers to the volume of pores in a compacted mixture, or the quantity of air VIM. Due to the porosity of the mixture, it is not possible to achieve the SSD weight of the asphalt concrete in this case. Therefore, the sample volume is not determined by submerging the sample in water. VMA denotes the volume of voids between the aggregate grains of a solid asphalt mixture, including voids containing effective asphalt and describes the proportion of the test object's overall volume. The Asphalt Institute suggests that the bulk specific gravity of the aggregate be considered during the calculation of VMA for a solid asphalt mixture. Increasing the VMA of a mixture is possible by using a lower asphalt content and slightly graded material. The proportion of pores between the aggregate grains that are filled with asphalt, Void-Filled Bitumen (VFB), is important in determining a valid VMA, thereby facilitating mix planning. The primary impact of the VFB criterion is to establish the maximum asphalt content and maximum VMA. Additionally, the maximum amounts of mixed voids that satisfy the VMA requirements may be constrained by the VFB. Regardless of the aggregate type or asphalt mixture design process, compacted cylindrical specimens can be used to study the permanent deformation characteristics of the asphalt mixtures. These specimens can be fabricated using either Superpave or a Marshall compaction device [15]. The MQ value provides the mixture's flexibility; higher values indicate greater stiffness in the hard-layer mixture, while lower values indicate greater flexibility. In order to determine the MQ value:

$$MQ = \frac{S}{R} \quad (1)$$

where S is the stability value (kg) and R is the flow value (mm).

III. EXPERIMENTAL PROGRAM

In the context of a quality system, experimental design is a technique that can be deployed to enhance process performance. A frequently utilized experimental design is RSM, which uses statistical and mathematical tools to develop models and analyze responses influenced by multiple independent variables or factors. By using a mathematical model, researchers can determine the values of the independent variables that lead to the optimal value of the response variable. The integration of regression and experimentation is a critical component of the RSM analysis, wherein research data from experimental outcomes are employed to construct models. To collect experimental data, it is essential to implement an experimental design that is aligned with the objectives of the analysis. An experimental design is a test conducted across multiple phases in a predetermined manner. This design seeks to provide solutions to the issue under examination through hypothesis testing. The objective of RSM is to optimize order two as an analysis that seeks to improve the response. For order two, the Box-Behnken Design (BBD) is a suitable experimental design, developing a two-level factorial design ($2k$), which is a design study with k factors (treatments) and only two levels for each. These two levels are described as low-level (-1) and high-level (1).The BBD is a design employed in RSM to estimate second-order effects while using fewer experimental units, rendering it more efficient and cost-effective, particularly in high-cost research. The integration of multiple center points or center runs within the design unites the $2k$ and incomplete block designs, therefore formulating the BBD design. Using the RSM approach based on the BBD, experimental model testing was conducted with a quadratic model, incorporating three levels of variation for each variable. The response surfaces were plotted, and regression analysis of the experimental data was performed utilizing Design Expert 8.0.6 (Stat-Ease, Inc., Minneapolis, MN, USA). The second-order quadratic polynomial equation used to assess the main and interaction effects of each independent variable on the result, is:

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i<j}^{n} \beta_{ij} X_i X_j + \sum_{j=1}^{n} \beta_{jj} X_j^2 \quad (2)$$

where Y is the experimental response, β is the regression coefficient, n is the number of variables examined in the experiment, X_i is the factor (independent variable), and i and j are the linear and quadratic coefficients, respectively. A Marshall feature is used as the independent variable and Table VI presents the BBD experimental design.

TABLE VI. BBD EXPERIMENTAL DESIGN

Run	Independent variable			Response: Marshall characteristics						
	Factor 1	Factor 2	Factor 3							
	A: PET to asbuton ratio	B: Mixing temperature (°C)	C: Mixing time	1	2	3	4	5	6	7
1	-1	0	+1							
2	0	0	-1							
3	0	0	+1							
4	0	-1	-1							
5	0	0	0							
6	0	-1	0							
7	0	0	0							
8	-1	0	0							
9	+1	0	0							
10	+1	+1	0							
11	0	0	+1							
12	0	-1	+1							
13	0	0	0							
14	+1	0	-1							
15	0	-1	0							
16	-1	0	0							
17	-1	+1	0							

The independent variable's variation level is indicated by the numeric values -1, 0, and +1, corresponding to low (-1), medium (0), and high (+1), respectively. These values will be adjusted based on the outcomes of the preliminary experiment. The seven Marshall qualities that will be examined are: (1) stability, (2) flow, (3) MQ, (4) VIM, (5) VMA, (6) VFB, and (7) density.

IV. RESULTS AND DISCUSSION

A. Aggregate Gradation

According to the General Specifications for Road Works by Bina Marga (2018), Figure 2 demonstrates that the combined aggregate design, also known as combined aggregate gradation, falls within the standard specification range and satisfies the requirements for surface layers, hence allowing for the creation of an ideal mix design. Aggregates, filler, and MBA were integrated and compacted into a 1,200-gr capacity and 101.6-mm diameter cylindrical mold. Using a Marshall compactor, the specimens were compressed with 75 blows per face. In the laboratory, the mixing and compaction procedures were conducted at room temperature (27 °C). The specimens were created using the predicted asphalt content for each variation in the amount of plastic waste utilized (0.0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%), with the objective of achieving OAC, while concurrently affecting the changes in modified asphalt content. The asphalt pavement samples were fabricated using MBA Type Retona Blend 55 as a binder. The samples were created utilizing the effective asphalt content calculation and varied bitumen contents according to the SNI. Test specimens were then made using the OAC based on the value obtained for each level of plastic waste. PET plastic waste was used, and the samples were then handled in accordance with the regulations of the SNI.

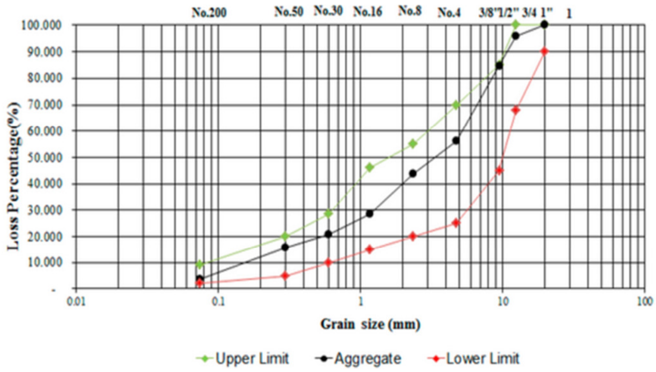

Fig. 2. Aggregate gradation.

B. Modified Buton Asphalt-Plastic Waste Mixture Design

The sieve method was applied to determine the composition of the aggregate (weighing was done according to the size of the sieve). These results were obtained from previously conducted sieve analysis tests on coarse aggregate and fine aggregate. Rather than being grouped by aggregate fraction (coarse, fine, and filler) as in the by-portion approach, this method of determining aggregate proportions is calculated by weighing based on the composition of each sieve size employed in this study. The following calculation must be utilized to obtain the estimated asphalt content necessary to create the AC-WC mixture:

$$Pb = 0.035\ (\%\ coarse\ aggregate) + 0.045\ (\%\ fine\ aggregate) + 0.18(\%\ filler) + constant = 0.035\ (53.95\%) + 0.045\ (39.05\%) + 0.18\ (7\%) = 6.12\% \quad (3)$$

Consequently, variations in asphalt content—5.0%, 5.5%, 6.0%, 6.5%, 7.0%, and 7.5%—were employed for the AC-WC combination, based on the projected asphalt content. The calculations that determine the mixture composition according to the aggregate gradation or the aggregate retained on each sieve are presented in Table VII and are used to determine the composition of the AC-WC combination without the use of PET plastic waste. Additionally, aggregate is substituted with PET plastic waste in each MBA content. Plastic waste is used at the following levels: 0.0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%. Consequently, the ideal asphalt content at each level of PET plastic waste can be determined by incorporating PET plastic waste into all variations in asphalt content.

C. Optimum Modified Buton Asphalt Content in Asphalt Concrete Wearing Course Mixture

A Marshall compactor was used in the experimental phase, with each variant of the adjusted MBA content having been subjected to a total of 75 impacts for each face. The factors derived from the analysis of the Marshall test include stability and flexibility, or flow, which indicate the test object's resistance to stress. The volumetric values of the VIM, the VFB, and the VMA are additional Marshall characteristics.

TABLE VII. MIXTURE DESIGN

No	Description			Unit	MBA content (%)					
					5.0	5.5	6.0	6.5	7.0	7.5
A	MBA weight			gr	60.00	66.00	72.00	78.00	84.00	90.00
B	Combined aggregate gradation				Aggregate weight according to sieve size					
	Sieve	% Passed	% Restrained							
1	3/4"	100.00	0.00	gr	-	-	-	-	-	
2	1/2"	96.00	4.00	gr	45.63	45.39	45.15	44.91	44.67	44.43
3	3/8"	86.93	9.07	gr	103.39	102.85	102.31	101.76	101.22	100.67
4	No. 4	63.90	23.03	gr	262.49	261.11	259.73	258.35	256.97	255.58
5	No. 8	43.56	20.34	gr	231.85	230.62	229.40	228.18	226.96	225.74
6	No. 16	28.62	14.94	gr	170.34	169.44	168.54	167.65	166.75	165.85
7	No. 30	20.76	7.87	gr	89.68	89.21	88.74	88.27	87.79	87.32
8	No. 50	15.60	5.16	gr	58.82	58.51	58.20	57.89	57.58	57.27
9	No. 100	10.79	4.80	gr	54.74	54.45	54.16	53.87	53.58	53.30
9	No. 200	8.43	2.37	gr	27.00	26.86	26.72	26.58	26.44	26.29
10	PAN	0.00	8.43	gr	96.05	95.55	95.04	94.54	94.03	93.53
	Total		100.00	gr	1,140	1,134	1,128	1,122	1,116	1,100
C	Specimen weight			gr	1,200	1,200	1,200	1,200	1,200	1,200

As shown in Table VIII, the asphalt content design is found to be in accordance with the requirements for hot asphalt mixtures, with an asphalt concentration ranging from 6.0% to 6.5%, as indicated by both the stability value and the volumetric value of the mixture. It is noteworthy that, in accordance with the 2018 General Bina Marga Specifications for Indonesia, not all test results are incorporated into the AC-WC mixture characteristic specifications.

TABLE VIII. MARSHALL CHARACTERISTICS OF MBA MIXTURE

No	MBA content (%)	VMA (%)	VIM (%)	VFB (%)	Stability (kg)	Flow (mm)	MQ (kg/mm)
1	5.00	26.71	9.03	66.44	1,278.27	2.37	544.86
2	5.50	25.76	6.86	73.40	1,647.00	2.48	674.01
3	6.00	24.27	3.95	83.72	1,741.81	3.00	585.38
4	6.50	24.54	3.27	86.75	1,847.16	3.72	516.85
5	7.00	24.02	1.54	93.59	1,344.99	3.05	523.77
6	7.50	24.35	0.92	96.29	993.82	3.48	362.33
7	Specification	15% >	3-5%	65 % >	800 kg >	2-4 mm	Min.250

The test results indicate that the stability value increases with an increase in the asphalt content until it reaches an optimal level. The mixture's stability value is highest when the asphalt content is at its optimal level; when the asphalt content exceeds that level, the stability value gradually decreases. The mixture containing 7.5% MBA exhibited the lowest stability value, measuring 993.82 kg, while the mixture containing 6.5% MBA demonstrated the highest stability value, measuring 1,847.16 kg. A mixture containing 5.5% MBA had a stability value of 1647 kg, which was nearly identical to the mixtures containing 6.0% MBA, which had stability values of 1741.8. The mixture containing 5.0% MBA exhibited the lowest flow value of 2.37 mm, while the mixtures containing 5.5% and 6.0% MBA demonstrated the highest flow values of 2.48 mm and 3.00 mm, respectively. A mixture with 6.5% MBA exhibited a flow value of 3.72 mm, which is comparatively higher than the flow values of 3.05 mm and 3.48 mm for mixtures with 7.0% and 6.5% MBA, respectively. The plastic flow value may increase when there are more VIM and when higher concentrations of MBA are used. The MQ value obtained is consistent with the requirements of Bina Marga, which demand a minimum of 250 kg/mm. The mixture containing 7.5% MBA exhibited the lowest MQ value (362.33 kg/mm), while the mixture containing 5.5% MBA demonstrated the highest MQ value (674.01 kg/mm). The MQ value of a mixture containing 6.5% MBA is 516.85 kg/mm, while a mixture containing 6.0% MBA has an MQ value of 585.38 kg/mm. Furthermore, a mixture containing 5.0% and 7.0% MBA exhibited MQ values of 544.86 kg/mm and 523.77 kg/mm, respectively. The MBA mixture demonstrates a low MQ value due to its diminished stability, augmented flow, thickly covered aggregates, and enhanced ease of modification. These characteristics, when combined, reduce the binding force between the aggregates in the mixture when it is loaded, thereby decreasing the aggregate bond strength and leading to a less stable mixture with increased flow values. According to the 2018 General Specifications, the VIM value must be between 3% and 5%. The VIM values at adjusted MBA contents of 5.0%, 5.5%, 6.0%, 6.5%, 7.0%, and 7.5% are 9.03%, 6.86%, 3.95%, 3.27%, 1.54%, and 0.92%, respectively. The VIM values indicate that the MBA levels of 5.0%, 5.5%, 7.0%, and 7.5% do not meet the established criteria. However, the VIM values that meet the 2018 specifications are found at the MBA levels of 6.0% and 6.5%. In the context of asphalt mixtures, it is critical to note that the VMA value must be maintained at a minimum of 15%. The VMA value, which is one of the volumetric parameters, is indicative of the presence of voids between the aggregate and binders. When the MBA content is set at 5.0%, the VMA value reaches 26.71%, which is comparatively higher than the VMA value of 25.76% at an

MBA content of 5.5%. Furthermore, the VMA values were determined to be 24.27%, 24.54%, 24.02%, and 24.35%, at adjusted MBA levels of 6.0%, 6.5%, 7.0%, and 7.5%, respectively. Consequently, the MBA levels used in this study are in accordance with the stipulations outlined in the 2018 General Specifications. The asphalt mix must include at least 65% VFB. The volumetric testing results, expressed as VFB parameters, for the asphalt mixtures using MBA as a binder reveal values of 66.44%, 73.40%, 83.72%, 86.75%, 93.59%, and 96.29%, respectively, for each level of MBA. An ideal asphalt content of 6.25% is obtained by using MBA as a binder without adding PET plastic waste as an additional ingredient. The purpose of this study was to compare the ideal asphalt concentration with the addition of PET plastic waste as an extra component.

D. Modified Buton Asphalt-Plastic Waste in Marshall Characteristics

An analysis of the volumetric characteristics of VIM, VMA, and VFB, along with the density and stability characteristics of the flow, stability, and MQ, constitutes the Marshall characteristics of the AC-WC mixture with the incorporation of PET plastic waste. The performance of the asphalt mixture, particularly its flexibility, is assessed based on the obtained load using MBA that has been derived from plastic waste. The MBA-plastic waste mixture, with plastic waste content levels of 0.0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% of the aggregate weight, was tested for Marshall the properties, as depicted in Table IX. The VIM value demonstrates a negative correlation with the proportion of the plastic waste content in MBA, exhibiting a decrease in proportion to the increase in the plastic waste content. However, at MBA contents of 6.0%, 6.5%, 7.0%, and 7.5%, the VIM value increases. This phenomenon can be explained by the introduction of additional plastic waste into the existing voids, resulting in an increase in the VIM value. Conversely, the volume of the reduced plastic waste content exceeds the volume of the new plastic waste added from the aggregate's overall weight. Moreover, as the proportion increases, the absorption capacity also increases, with higher quantities of plastic waste causing the asphalt to absorb more. As the proportion of plastic waste in the mixture increases, the VMA value at all MBA levels decreases. This phenomenon occurs because an increase in the plastic waste content leads to an increase in the available space within the mixture, which can accommodate the required amount of asphalt and air voids. Conversely, as the plastic waste content rises, there is a decrease in the available space to hold the necessary asphalt and air voids. The quality of the aggregate used, which must meet Indonesian and Bina Marga standards, exerts a substantial influence on the VMA value. The VFB percentage value at each stage of MBA undergoes variation as the amount of plastic waste increases. The plastic waste absorbs a greater quantity of MBA, leading to a thinner asphalt layer covering the aggregate and a higher VFB value. The high capacity of plastic waste to absorb asphalt and mix to form mastic leads to a decrease in the VFB value. The quality of the asphalt binder and aggregate exerts a substantial influence on the VFB value. The MBA used in this study is of the 60/70 penetration grade hard asphalt category. The density value of the AC-WC mixture containing PET plastic waste is lower than that of the mixture devoid of PET plastic waste, irrespective of the PET plastic waste amount. The specific gravity of the mixture decreases with each additional amount of MBA and PET plastic waste. Since PET has a lower density than mineral aggregates, the AC-WC composites containing PET plastic waste will exhibit a decrease in the specific gravity values as a result.

TABLE IX. MARSHALL CHARACTERISTICS OF MODIFIED BUTON ASPHALT-PLASTIC WASTE MIXTURE

VIM (%)						
MBA content (%)	PET plastic waste content (%)					
	0.0	0.5	1.0	1.5	2.0	2.5
5.0	9.03	2.84	2.79	2.58	2.47	2.35
5.5	6.86	3.42	3.39	3.27	3.04	2.83
6.0	3.95	4.00	4.64	4.76	4.81	4.93
6.5	3.27	4.59	5.46	5.49	5.65	5.74
7.0	1.54	5.17	5.75	5.82	5.89	5.96
7.5	0.92	5.17	6.14	6.17	6.23	6.74
VMA (%)						
5.0	25.71	24.34	24.27	23.29	22.98	21.67
5.5	25.76	24.28	24.00	23.10	22.75	21.49
6.0	25.97	24.19	23.69	23.07	22.69	21.36
6.5	25.54	24.03	23.53	22.87	21.85	20.69
7.0	25.35	23.93	23.47	22.59	21.62	20.14
7.5	25.05	23.84	23.36	22.29	21.27	19.35
VFB (%)						
5.0	66.44	88.33	89.59	90.73	92.47	93.35
5.5	73.40	87.16	89.67	93.27	94.04	95.83
6.0	86.72	87.85	89.79	97.76	97.81	95.93
6.5	86.75	88.64	90.65	98.49	98.65	98.74
7.0	93.59	94.59	95.75	98.82	98.89	98.96
7.5	96.29	98.28	98.74	99.17	99.23	99.74
Density (kg/m^3)						
5.0	2,310	2,308	2,305	2,301	2,300	2,288
5.5	2,324	2,318	2,313	2,311	2,303	2,294
6.0	2,332	2,329	2,324	2,317	2,315	2,304
6.5	2,335	2,327	2,325	2,318	2,309	2,306
7.0	2,329	2,322	2,315	2,308	2,296	2,283
7.5	2,331	2,328	2,314	2,306	2,297	2,291
Stability (kN)						
5.0	2.71	4.81	12.22	12.52	19.79	12.17
5.5	8.24	10.66	14.24	16.55	21.85	17.49
6.0	9.89	15.19	16.74	23.67	28.18	20.36
6.5	18.20	20.41	20.48	28.17	28.54	21.69
7.0	10.29	13.75	14.46	18.20	19.23	16.14
7.5	8.86	10.45	13.51	14.32	16.50	12.35
MQ (kN/mm)						
5.0	1.14	1.20	3.06	3.13	4.95	3.04
5.5	3.48	2.67	3.56	4.14	5.46	4.37
6.0	4.17	3.80	4.19	5.92	7.05	5.09
6.5	7.68	5.10	5.12	7.04	7.14	5.42
7.0	4.34	3.44	3.62	4.55	4.81	4.04
7.5	3.74	2.61	3.38	3.58	4.12	3.09

The stability values of MBA and PET plastic waste follow a similar pattern, increasing with the addition of PET plastic waste until they reach a maximum content of approximately 2.0%, then decreasing at 2.5%. The Marshall stability values were generally higher than those of the control mixtures (mixtures containing 0% PET). The mixture containing 2.5% was the only one to show a lower stability value. The increased stability values obtained when polymers are added to hot mix asphalt can be explained by better ingredient binding.

However, the maximum temperature for admixtures in hot mix asphalt is below 180°C, even though PET has a high melting potential (its melting point is approximately 250°C). It was observed in this study that PET can be used in hot mix asphalt due to its high melting point. Authors in [16] conducted a research in which the heating temperature employed was 160 ± 5°C, which is similar to the temperature used in this experiment. Authors in [17] deployed a range of polymers as variations for the binder (i.e., PVC, PP, LDPE, HDPE, ABS, PP powder, MDPE, and PET). They concluded that the high melting points of the polymers impeded effective mixing and rendered further attempts to incorporate them into the bitumen impractical. The primary rationale for employing PET plastic waste in this study is based on its distinctive properties, as it exhibits a transition temperature (T_g) of approximately 70 °C and is a semi-crystalline resin in its native state. The characteristics of the material in question began to change with heating, becoming either a stiffer mixture with increased stability or a material with less crystalline properties. Consequently, the primary explanation for this outcome is that the asphalt mixture became stiffer due to the PET that remained semi-crystalline after being mixed in. A dry method was deployed in this study, with PET being added toward the end of the mixing process. The objective was to preserve the PET in its original form, as a semi-crystalline resin, with minimal alterations to its primary properties and structure [17]. The MQ as a measure of bitumen mixes' resistance to deformation, was used to assess the resistance to deformation of AC-WC mixed specimens containing PET plastic waste. The MQ of the 1.0%, 1.5%, 2.0%, and 2.5% PET AC-WC mixtures was higher than that of the 0% PET control mixture. Consequently, the enhanced Buton asphalt with PET mixture's high MQ produces greater stiffness and improved resistance to the significant deformations caused by heavy loads [18, 19]. Authors in [18] reached similar conclusions, finding that bitumen contents of 5–10% plastic waste could improve the bitumen properties, including fatigue life, strength, and Marshall stability. Authors in [19] observed that the addition of PET at concentrations of 5%, 5.5%, 6%, 6.5%, and 7% by bitumen weight led to a substantial enhancement in Marshall stability, with the most pronounced outcomes having been achieved at 7% PET.

E. Optimization Modified Buton Asphalt-Plastic Waste Response Surface Methodology Modeling

Two methodologies are followed to determine the optimum points simultaneously with RSM: manual experimentation with 17 different combinations of the three parameters and computations using the RSM program. The first step is to identify which parameters are expressed as $X1$, $X2$, and $X3$. Typically, temperature and time are chosen as $X1$ and $X2$ in RSM, while other factors are expressed as $X3$. Consequently, in this system, the parameters are described as: $X1$ = PET/MBA, $X2$ = mixing temperature, and $X3$ = mixing time. The lowest and highest uncoded points for each variable X are determined as the points below and above the center point, respectively, with an interval of 5. The middle point is identified as the minimum point, and the coding system developed, assigns the following values: -1 for the lowest point, 0 for the intermediate or optimal point, and 1 for the highest point, with the intention of facilitating the writing process. The BBD is a design used in RSM to estimate second-order responses. It is a combination of the 2k design and incomplete block design, and it is developed by including several center points or center runs in the design. A center run (nc) involves establishing a center point at (0, 0, ..., 0), and for distinct values of k, three center runs are obtained. The BBD design contains 12 points, in addition to the center run if there are three variables. In order to maximize the response, it is necessary to estimate the model by using regression analysis in RSM. This analysis examines the relationship between an outcome and one or more predictor variables, in addition to the usage of an identical residual assumption check trying to verify that the residual distribution satisfies the initial assumption. The purpose of the heteroscedasticity test (which checks for different distributions) is to determine whether the residuals of one observation differ in variance from those of another observation in the regression model. Table X presents the various combinations generated using the codes, with only 14 being required. However, three repetitions are conducted for the ideal combination, which is the 14th component, resulting in a total of 17 different combinations.

TABLE X. RESULTS OF THE BBD EXPERIMENT USING RSM TO TEST OBJECTS

Run	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3
	A: PET MBA ratio	B: PET aggregate ratio	C: Mixing time	MQ (kN/mm)	VIM (%)	Density (kg/m^3)
1	0.24 (0)	0.016 (0)	20	700	2	2,200
2	0.34 (+1)	0.016 (0)	25	600	3	2,300
3	0.24 (0)	0.02 (+1)	25	650	4	2,250
4	0.24 (0)	0.016 (0)	20	550	3	2,200
5	0.24 (0)	0.009 (-1)	25	650	3.5	2,230
6	0.24 (0)	0.016 (0)	20	540	3.5	2,400
7	0.24 (0)	0.02 (+1)	15	580	4.5	2,100
8	0.34 (+1)	0.02 (+1)	20	600	3	2,300
9	0.14 (-1)	0.016 (0)	25	650	4	2,250
10	0.34 (+1)	0.016 (0)	15	550	3	2,200
11	0.14 (-1)	0.016 (0)	15	650	3.5	2,230
12	0.34 (+1)	0.009 (-1)	20	540	3.5	2,400
13	0.24 (0)	0.016 (0)	20	580	4.5	2,100
14	0.24 (0)	0.016 (0)	20	650	3.5	2,230
15	0.14 (-1)	0.009 (-1)	20	540	3.5	2,400
16	0.14 (-1)	0.02 (+1)	20	580	4.5	2,100
17	0.24 (0)	0.009 (-1)	15	600	3	2,300

This method uses statistical and mathematical tools to generate and analyze a response Y influenced by multiple independent variables, or components X, with the objective of maximizing the response. Table XI shows the fit summary analysis of variance for the response (dependent variable) as an independent variable. The usage of first- and second-order models enables the exploration of the relationship between Y and X_i, with the ideal region identified through the application of the first-order model and the optimal point determined by the second-order model. The regression coefficients of the response variable are presented in Table XII, while the interaction between three variables and the MQ value is displayed in Figure 3.

TABLE XI. FIT THE RESPONSE (DEPENDENT VARIABLE) TO THE SUMMARY ANALYSIS OF VARIANCE FOR THE INDEPENDENT FACTORS

	P-value	Predicted R^2	Adjusted R^2	Selection
Linear	0.0112	0.171	0.4605	
2FI	0.5286	-0.4542	0.4325	
Quadratic	0.0114	-0.2516	0.8177	Suggested
Cubic	0.0008		0.9933	Aliased

TABLE XII. FIT THE RESPONSE (DEPENDENT VARIABLE) TO THE SUMMARY ANALYSIS OF VARIANCE FOR THE INDEPENDENT FACTORS

Source	**Response**	
	Coefficients	*P*-value
Intercept	604.00	0.0043
A	16.25	0.0033
B	10.00	0.5728
C	21.25	0.0236
AB	5.00	0.3326
AC	12.50	0.0517
BC	5.00	0.4080
A^2	-23.25	0.0030
B^2	-5.75	0.4626
C^2	31.75	0.1112

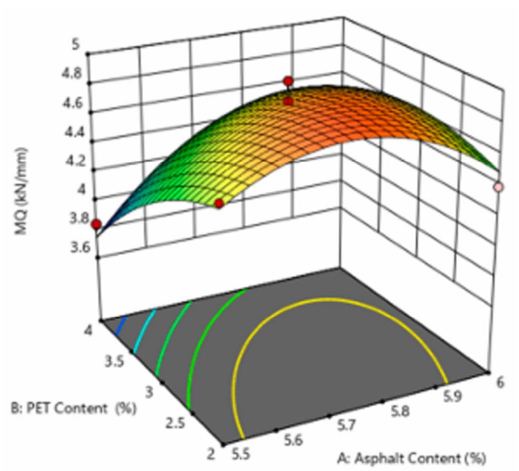

Fig. 3. A graphic model of the interaction effect of three variables on the MQ value.

The polynomial quadratic equation model for the ideal MQ value is:

$$MQ = 604.00 + 16.25^{a} + 10.00B + 21.25C + 5.00AB + 12.50AC + 5.00\,BC - 23.25A^2 - 5.75B^2 + 31.75C^2 \quad (4)$$

Figure 3 portrays a two-dimensional and a three-dimensional graph of the computed response (MQ), where two variables are varied within their experimental ranges and one variable is held constant at its center point. The objective of this display is to examine the relationships between the independent variables and ascertain the best value for each variable in relation to the suggested particular response (MQ). Through this analysis the relationships between the independent variables can be examined and the ideal value of each variable for the suggested response can be ascertained. Experiments with design points surrounding the suspected rising areas are used to determine the ideal factors and reaction points. When the asphalt content is 5.76%, the PET content is 3.46%, and the mixing time is 22.85 min, the ideal MQ of 4.91 kN/mm is reached.

V. CONCLUSIONS

- The two independent variables (factor *X*) under analysis are in response *Y*, a Marshall characteristic, and *X1*, the ratio of Plastic Bottle Waste (PET) to Modified Buton Asphalt (MBA).
- For any Asphalt Concrete Wearing Course (AC-WC) combination reaction using MBA as a binder, there are various optimal points related to the asphalt content, PET plastic waste content, and mixing time.
- The usage of asphalt content, PET plastic waste content, and optimal mixing duration at different times for each AC-WC combination reaction have been determined using MBA as a binder. Two-Factor Interaction (2FI) modeling is utilized in numerical analysis, which is the sequential sum of squares for the two parameters that need to be considered: the asphalt and the PET content.
- The present study is different from the conventional polymer-modified asphalt in its exploration of incorporating low-quality polymer PET (from plastic waste) as an asphalt modifier. Its novelty lies in optimizing the PET ratio for performance enhancement, which contributes to sustainable road construction by reducing plastic waste. The research employs Response Surface Methodology (RSM) with a Box-Behnken Design (BBD) to systematically determine the optimal blending parameters. This statistical approach enhances the precision of identifying the best formulation for improved mechanical properties.
- The majority of extant studies focus on conventional petroleum-based asphalt, whereas this research integrates PET with MBA, a naturally occurring asphalt from Buton Island, Indonesia. This combination is relatively unexplored, offering a unique approach to improving asphalt durability and sustainability. This approach is notable for its use of RSM to optimize the combination of PET waste and MBA, providing an innovative, sustainable, and locally relevant solution for asphalt mixture improvement.

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