

EFFECT OF POLYMER MODIFIED ASPHALT WITH CRUMB RUBBER ON THE AC-WC WEAR LAYER AGAINST RUTTING USES WHEEL TRACKING MACHINE (WTM)

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ABSTRACT

Premature rutting remains one of the most critical failure mechanisms in flexible pavements, particularly in tropical regions where high temperatures and increasing axle loads accelerates permanent deformation. Although polymer modified asphalt has been widely investigated to mitigate integration between laboratory rutting performance and statistical prediction models. This study aims to evaluate the effect of crumb rubber (CR) modification on the rutting resistance of Asphalt concrete wearing course (AC-WC) mixtures and to quantify its influence using regression analysis. AC-WC mixtures were prepared with crumb rubber contents of 0%, 5%, 10%, 15% and 20% by weight of asphalt binder, following Indonesian Bina Marga specifications. Rutting performance was assessed using a Wheel Tracking Machine (WTM), while Marshall properties were used to determine optimum asphalt and CR contents. The results indicate that CR contents of 5% and 10% significantly enhance dynamic stability, with the 10% CR mixture exhibiting the highest rutting resistance (1162.7 passes/mm). regression analysis confirms a very strong relationship between CR content and dynamic stability ($R^2 = 0.979$), indicating the dominant role of polymer modification in controlling permanent deformation. These findings demonstrate that crumb rubber improves asphalt elasticity and load distribution under repeated wheel loading the study provides practical implications for sustainable pavement design by promoting waste tire utilization while improving rutting performance in AC-WC layers. The novelty of this research was integrating WTM based rutting evaluation with statistical regression modeling to identify the optimal crumb rubber content for tropical pavement applications.

Keywords : Modified Asphalt, Rutting, Crumb Rubber, WTM, Dynamic Stability

1. Introduction

Roads are infrastructure that supports the pace of the economy and plays a very large role in the progress and development of a region in Indonesia. The ever-increasing flow of traffic volumes in all regions has an impact on the increasing demand for good road infrastructure, because roads are a very important means for regional growth. The increasing growth in traffic volume also makes it susceptible to damage to the pavement layer on the road surface due to excessive traffic loads or what is often called overload (Ilhamsyah, 2019; Miftahulkhair et al., 2024).

Basically, roads will experience a decline in their structural function as they age. Damage to road pavement often occurs within a relatively short period of time (early damage), both on newly built roads and on roads that have just been repaired (Sudarno et al., 2018). JRA: Japan Road Association (1989) explains that fatigue cracks and permanent deformation (rutting) are the performance that happens in flexible pavement. One of the impairments to flexible pavement brought on by issues with excessive load is permanent deformation, or rutting. As a result, the asphalt experienced rutting damage on the top layer of asphalt concrete (Laston), specifically the wear layer known as the Asphalt Concrete-Wearing Course (AC-WC), which gives the asphalt wheel traces. One effort to reduce road damage due to excessive loads is to modify the asphalt with harder asphalt or adding polymer materials to the asphalt mixture (Indriyati, 2018).

Flexible pavement systems are increasingly subjected to premature failures due to rapid traffic growth, higher axle loads, and climate induced temperature extremes. Among various distress types, rutting defined as the accumulation of permanent deformation along wheel paths poses a significant threat to road safety, ride quality, and service life (Massara et al., 2021). Globally, rutting has been reported as a dominant mode of pavement failure in hot climate regions, contributing to substantial maintenance and rehabilitation costs. In Indonesia, overloaded freight

traffic combined with high pavement temperatures accelerates rutting development, particularly in Asphalt Concrete Wearing Course (AC-WC) layers that directly experience traffic loads (Lubis et al., 2024).

Mechanistically, rutting occurs due to shears deformation of asphalt mixtures, inadequate aggregate interlock, and insufficient binder stiffness at elevated temperatures. If not properly controlled, rutting reduces structural capacity, increases hydroplaning risk, and shortens pavement service life. Consequently, improving rutting resistance has become a major focus in asphalt pavement engineering.

Modified asphalt is being developed in many countries, including Indonesia, with the aim of improving asphalt quality. Modified polymer asphalt was developed to enhance the outcomes of improved deformation resistance, crack closure, and increased damage resistance due to age, resulting in more durable road construction and reducing road maintenance or repair costs. Using a new mixture for asphalt is one way to make road pavement management more economical (Widayanti et al., 2019; Wulandari & Tjandra, 2017).

Polymers commonly used for asphalt modification can be divided into 2 types, namely plastomers and elastomers. In principle, plastomers are used to modify asphalt to make it stiffer, while elastomers are used to make asphalt elastic. Therefore, the use of plastomers and elastomers can both be intended so that asphalt has higher resistance to deformation (rutting). However, specifically for elastomers, they can also increase flexibility so that asphalt is more resistant to cracking at low temperatures (Duan et al., 2022). Crumb rubber is a type of rubber resulting from processing that goes through a crumbling stage. Rubber powder (*Crumb rubber*) is rubber that is crushed from rubber product waste such as tire rubber waste. Waste rubber tires are made from natural rubber which is an elastomer type of polymer (Bahruddin et al., 2020). Polymer modification of asphalt binders has been widely adopted to enhance high temperature performance. Conventional polymers such as Styrene – Butadiene – Styrene (SBS), Ethylene Vinyl Acetate (EVA), latex, and plastomers have demonstrated improved rutting resistance by increasing binder elasticity and stiffness (Mahmood & Kattan, 2023). However, these polymers are often associated with high material costs, complex production processes and limited sustainability benefits.

Crumb rubber (CR), derived from recycled waste tires, has emerged as an attractive alternative polymer modified due to its elastomeric properties, environmental advantages and cost effectiveness. CR modified asphalt exhibits improved elasticity, enhanced energy dissipation, and increased resistance to permanent deformation (Person, 2023). Additionally, its utilization addresses the growing environmental problem to waste tire disposal, aligning pavement engineering with sustainability goals (Bahruddin et al., 2020).

Despite extensive research on crumb rubber modified asphalt, several limitations remain (Zhou et al., 2023). Previous studies report inconsistent findings regarding optimal CR content, limited comparative analysis with rutting prediction models, and insufficient integration of laboratory rutting tests with statistical validation. Moreover, many studies focus primarily on binder level properties without explicitly linking mixture level rutting performance to regression based predictive relationships (Vigneswaran et al., 2023). Therefore, this study aims to evaluate the effect of crumb rubber modification on the rutting resistance of AC-WC mixtures using Wheel Tracking Machine (WTM) testing and to quantify the relationship between CR content and rutting performance through regression analysis. This study also seeks to identify an optimal CR dosage that balances mechanical performance, specification compliance and sustainability considerations for tropical pavement conditions.

Based on data from the Ministry of Industry, there are 14 national tire manufacturers that produce various types and sizes of tires for cars, motorbikes, trucks, buses and heavy vehicles. Production capacity for car, truck and bus tires reaches 77 million tires, while there are 64 million tires for motorbikes. Tire rubber waste is a type of waste that does not decompose easily. As the need for tire production increases, there is an increasing amount of tire rubber waste which affects the environment. Tire rubber waste is very dangerous for the environment. Meanwhile, tire rubber waste can be recycled into crumb rubber which can be used as a polymer material for flexible road pavement (Abu-Jdayil et al., 2016). Therefore, the need to recycle used rubber tire waste becomes very important. In analyzing the effect of Crumb Rubber polymer modified asphalt, the

Regression analysis method was used. The process of examining research hypotheses to see whether one variable influences another is known as regression analysis, and it is represented by a regression equation (Ghozali, 2018). The required data is obtained through stability values from the Marshall test and the number of dynamic stabilities passes from the Wheel Tracking Machine (WTM) test as a control in terms of permanent deformation (rutting) and fatigue cracks that occur in flexible pavement.

2. Literature Review

Rutting is primarily governed by asphalt mixture rheology, aggregate structure and binder viscoelastic behavior under repeated loading (Imaninasab et al., 2022). At high temperatures, asphalt binders exhibit reduced stiffness, leading to shear deformation and permanent strain accumulation. Advanced rutting studies emphasize the role of binder elasticity and aggregate skeleton integrity in controlling deformation (Massara et al., 2021).

Road pavement is a layer of pavement situated between the vehicle wheels and the subgrade layer, which serves to supply transportation amenities and is anticipated to be damage-free during its service life. Understanding the nature, sourcing, and processing of the materials that go into making up road pavement is essential to ensuring that it meets the required standards for quality (Sukirman, 2010).

Polymer modification enhances asphalt performance by altering binder rheology and improving stress recovery. SBS modified asphalt is widely recognized for superior rutting resistance, but its high-cost limits large scale adoption. EVA and plastomers increase stiffness but may reduce low temperature flexibility (Wang et al., 2021). Recent studies highlight growing interest in recycled polymers as sustainable alternatives (Seyed Ali Akbar et al., 2025).

Crumb rubber modification introduces elastomeric behavior, improves resilience and enhances energy absorption under traffic loads. Studies between 2020-2025 report that CR contents between 5-15% improve rutting resistance, though excessive CR can reduce workability and stability (Wang et al., 2025; Yan et al., 2025). Compared with SBS and EVA, CR offers superior sustainability benefits due to waste reduction and lower life cycle cost. WTM testing is widely used to stimulate field rutting behavior under controlled temperature and loading conditions. Recent research integrates WTM results with regression and mechanistic empirical models to predict rutting performance (Chen et al., 2021; Zhao et al., 2022). However, limited studies combine WTM based rutting data with statistical validation to identify optimal CR content.

In highway construction, an asphalt concrete layer is made up of aggregate and hard asphalt that has been continually graded (well graded), mixed, spread, and heated to a specific temperature. To provide a surface layer or intermediate layer (binder) on road pavement that may provide measured bearing capacity and serve as a waterproof barrier to shield the construction underneath, Asphalt Concrete Layers (Laston) was created (JRA: Japan Road Association, 1989).

Laston consists of 3 types of layers, namely Wear Layer Laston (AC-WC), Intermediate Layer Laston (AC-BC) and Foundation Layer Laston (AC-Base) (Department of Public Works, 2018, Sudarno et al., 2018) Table 1 presents the technical requirements for modified Asphalt Concrete (Laston Mod) mixtures according to the Bina Marga 2018 specifications for three pavement layers: Wear Layer (AC-WC), intermediate layer (AC-BC) and foundation layer (AC-base). The table 1 outlines key performance parameters such as Marshall compactions blows, Voids in the Mix (VIM), Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), flow values, residual Marshall stability after water immersion and minimum dynamic stability. These adequate strength, durability, volumetric balance, and resistance to permanent deformation (rutting), particularly under repeated traffic loading.

Table 1 - Provisions for the Properties of Modified Laston Mixtures (AC Mod)
(Source: Bina Marga, 2018)

Properties of Mixtures	Modified Asphalt Concrete (Laston) Coating		
	Wear Layer	Intermediate Layer	Foundation Layer
Amount collision per field	75		112 ⁽³⁾

The ratio of particles passing through the sieve is 0.075mm to the effective asphalt content	Min.	0.6		
	Max.	1.6		
Voids in the mixture(%) ⁽⁴⁾	Min.	3.0		
	Max.	5.0		
Voids in Aggregate (VMA) (%)	Min.	15	14	13
Asphalt Filled Voids (%)	Min.	65	65	65
Melting (mm)	Min.	2		3
	Max.	4		6 ⁽³⁾
Residual Marshall Stability (%) after soaking for 24 hours, 60°C ⁽⁵⁾	Min.	90		
Voids in mixture (%) in Bale density(refusal) ⁽⁶⁾	Min.	2		
Dynamic Stability, track/mm ⁽⁷⁾	Min.	2500		

Table 2 provides the specification limits for hard asphalt binders, including Type I Asphalt (Penetration Grade 60-70) and Type II Modified Asphalt (performance Grade PG70 and PG76). The properties listed include penetration, softening point, ductility, specific gravity, weight loss after short term aging (TFOT/RTFOT) and dynamic shear rheometer (DSR) temperature criteria. These parameters are essential for evaluating binder performance at high temperatures, resistance to oxidation and shear deformation resistance which directly influence the rutting performance and durability of asphalt mixtures.

Table 2 - Provisions for Hard Asphalt
(Source: Bina Marga, 2018)

No.	Test Type	Test Method	Type I Asphalt	Type II Modified Asphalt	
			Pen. 60-70	PG70	PG76
1.	Penetration, at 25 (0.1 mm)°C	SNI 2456:2011	60-70	reported ⁽¹⁾	
2.	Softening Point ()°C	SNI 2434:2011	≥ 48	reported ⁽²⁾	
3.	Ductility at 25, (cm)°C	SNI 2432:2011	≥ 100	-	
4.	Specific gravity	SNI 2441:2011	≥ 1,0	-	
Residue Testing TFOT (SNI-06-2440-1991) or RTFOT (SNI-036835-2002) results:					
5.	Weight Lost (%)	SNI 06-2441-1991	≤ 0,8	≤ 0,8	
6.	Temperature that produces Dynamic Shear (/sin) at an oscillation of 10 rad/sec, ()G*δ ≥ 2,2 kPa°C	SNI 06-6442-2000	-	70	76
7.	Penetration at 25 (% original)°C	SNI 2456:2011	≥ 54	≥ 54	≥ 54
8.	Ductility at 25 (cm)°C	SNI 2432:2011	≥ 50	≥ 50	≥ 25

Table 3 describes the quality requirements for coarse aggregates used in asphalt mixtures. The tests include sulfate soundness, Los Angeles abrasion resistance, adhesion to bitumen, percentage of crushed particles, flat and elongated particle limits and the amount of material passing the No. 200 sieve. These requirements ensure that the coarse aggregates possess adequate mechanical strength, durability and proper particle shape to form a stable aggregate skeleton that enhances load distribution and rutting resistance.

Table 3 - Coarse Aggregate Terms
(Source: Bina Marga, 2018)

Testing		Test Method	Mark
Conservation of aggregate form in solution	sodium sulfate	SNI 3407:2008	Max.12%
	magnesium sulfate		Max.18%
Abrasion with Los Angeles machines	A mixture of Modified AC and SMA	SNI 2417:2008	100 rounds
			500 rounds
	All other types of graded asphalt mixes		100 rounds
			500 rounds
Aggregate adhesiveness to bitumen		SNI 2439:2011	Min.95%
Broken Grains in Coarse Aggregate		SENIOR HIGH SCHOOL	100/90 *)
		Other	95/90 **)
Flat and Oval Particles		SENIOR HIGH SCHOOL	Max.5%
		Other	Max.10%
Material passes Sieve No.200		SNI ASTM C117:2012	Max.1%

Table 4 outlines the specifications for fine aggregates, including sand equivalent value, uncompacted void content, clay clumps and friable particles, and the percentage of material passing the No. 300 sieve. These criteria ensure the cleanliness and stability of fine aggregates, preventing excessive plastic fines or clay contamination that could negatively affect mixture cohesion, moisture susceptibility and long-term performance (Ulfah, 2023).

Table 4 - Fine Aggregate Terms
(Source: Bina Marga, 2018)

Testing	Test Method	Mark
Sand Equivalent Value	SNI 03-4428-1997	Min.50%
Void Content Test Without Compaction	SNI 03-6877-2002	Min.45%
Clay Clods and Fragile Grains in Aggregates	SNI 03-4141-1996	Max.1%
Aggregate Passes Sieve No.200	SNI ASTM C117:2012	Max.10%

Table 5 - Combined Aggregate Gradation Envelopes for Asphalt Mixes
(Source: Bina Marga, 2018)

Sieve Size	% Weight Passed to Total Aggregate								
	Stone Matrix Asphalt (SENIOR HIGH SCHOOL)			Lataston (HRS)		Laston (AIR CONDITIONING)			
ASTM	(mm)	Thin	Fine	Rough	WC	Base	WC	BC	Base
1"1/2	37.5								100
1"	25			100				100	90-100
3/4"	19		100	90-100	100	100	100	90-100	76-90
1/2"	12.5	100	90-100	50-88	90-100	90-100	90-100	75-90	60-78
3/8"	9.5	70-95	50-80	25-60	75-85	65-90	77-90	66-82	52-71
No.4	4.75	30-50	20-35	20-28			53-69	46-64	35-54
No.8	2.36	20-30	16-24	16-24	50-72	35-55	33-53	30-49	23-41
No.16	1.18	14-21					21-40	18-38	13-30

No. 30	0.600	12-18			35-60	15-35	14-30	12-28	10-22
No. 50	0.300	10-15					9-22	7-20	6-15
No. 100	0.150						6-15	5-13	4-10
No. 200	0.075	8-12	8-11	8-11	6-10	2-9	4-9	4-8	3-7

Filling material (*filler*) is material that passes sieve no. 200 or has a grain size < 0.075 mm. *Filler* can be limestone dust, *fly ash* stone ash which will later fill the space between the fine and coarse aggregate so that its density and stability will increase. *Fillers* used must be dry and clean from organic dirt. *Filler* used to modify the specific gravity of the mixture and reduce the asphalt content to be used. Use of levels *filler* Excessive amounts will make the mixture brittle and crack easily *filler* Too little will cause the mixture to become soft.

Crumb rubber is a recycled rubber product that is environmentally friendly because it is obtained from recycling used rubber. Crumb rubber has advantages such as: good adhesion, sturdy, durable and long-lasting, more resistant to gasoline and lubricating oil and resistant to weather (Pszczola & Dolzycki, 2025).

Research Hypothesis

The research hypothesis is a temporary answer to the requirements proposed in the problem formulation where the answer can be proven correct by conducting empirical fact tests collected using the regression analysis method (Ghozali, 2018). In this research used:

Variations in adding Crumb Rubber 0%, 5%, 10%, 15% and 20%.

- Null hypothesis (H_0) namely stating that there is no difference in dynamic stability trajectory values through WTM testing of AC-WC mixtures using addition of optimum polymer variations of Crumb Rubber 0%, 5%, 10%, 15% and 20%.
- Alternative hypothesis (H_a) that is, stating that it exists differences in dynamic stability trajectory values through WTM testing of AC-WC mixtures using addition of optimum polymer variations of Crumb Rubber 0%, 5%, 10%, 15% and 20%.

Existing literature lacks a comprehensive evaluation that integrates CR dosage optimization, WTM rutting performance and regression-based validation within tropical pavement contexts. This study addresses this gap by combining laboratory testing and statistical modeling to determine the optimal CR content for AC-WC mixtures.

3. Research Methods

This study was conducted experimentally to evaluate the rutting resistance of AC-WC mixtures modified with crumb rubber (CR). All materials and testing procedures complied with the Bina Marga 2018 (Revision 2, Division 6) General Specifications for Highways to ensure that the results are applicable within the Indonesian pavement design framework.

This research was carried out at the BBPJJ II laboratory located on Jl. Spark Plug No.1, Siti Rejo I, Kec. Medan Maimun, Medan City, North Sumatra 20215, Indonesia. This research was carried out in December 2023.

The materials used in this research were obtained from the Material Company PT. Trimurti Perkasa North Sumatra Region: Jl. Patumbak IV Market Defense, District. Patumbak, Kab. Deli Serdang - North Sumatra Province and CV Tire Rubber Waste Processing Company. Kramed was founded in January 2019 in Malang, Indonesia. The material used in this study consisted of Pen 60/70 asphalt binder, crumb rubber derived from recycled waste tires, coarse and fine aggregates and limestone filler. Prior to mixture preparation, all materials were tested to verify compliance with specification requirements. Asphalt binder testing included penetration, softening point, ductility, specific gravity and weight loss after short term aging (TFOT/RTFOT). Aggregate testing included sieve analysis, Los Angeles abrasion, specific gravity, sand equivalent, and material passing sieve No. 200. Only materials that satisfied Bina Marga requirements were used in mixture production.

The AC-WC mixture design was developed using the Marshall method. To determine the Optimum Asphalt Content (OAC), five asphalt content variations were prepared (4.7%, 5.2%, 5.7%, 6.2% and 6.7%). For each asphalt content, five specimens were compacted with 75 blows per face, resulting in a total of 25 primary specimens. Additional specimens were prepared for

immersion and density verifications tests, ensuring statistical reliability. The OAC was determined based on stability, flow, VIM, VMA, VFA and density criteria in accordance with Bina Marga specifications.

The materials used in this research are as follows:

1. Asphalt Pen 60/70 obtained from PT. Mighty Trimurti.



Fig. 1. Asphalt Pen 60/70
(Source: PT. Trimurti Perkasa)

2. Coarse aggregate and fine aggregate obtained from PT. Mighty Trimurti.



Fig. 2. Coarse Aggregate and Fine Aggregate
(Source: PT. Trimurti Perkasa)

3. *Fillers* Tohor lime obtained from PT. Mighty Trimurti.



Fig. 3. Calcium oxide (Source: PT. Trimurti Perkasa)

4. *Crumb Rubber* obtained from the CV used tire processing factory. Kramed.



Fig. 4. *Crumb Rubber*
(Source: CV. Kramed)

Research Flow Chart

All research stages can be seen in the following flow diagram (Fig 5). According to the research flow diagram, the initial stage of conducting a literature study is by searching for and reading journals and books that are related to the research being carried out, this literature will later be used as a guide in completing research. Then proceed to the preparation of the materials and the materials are tested according to the 2018 Bina Marga specifications. If they do not meet the specifications, then they must be replaced with new materials and if they meet the specifications then proceed with making test objects.

The research used 5 varying levels of Crumb Rubber addition, namely 0%, 5%, 10%, 15% and 20% of the asphalt weight. Variations in levels that meet specifications are used in making test objects. To determine the Optimum Asphalt Content (KAO) 55 test specimens are required for the Marshall test and to determine the KAO test object for the Crumb Rubber Polymer Asphalt variation, it is adjusted from the results of the Crumb Rubber variation asphalt properties (JRA-Japan Road Association, 1989). In each test, 5 test objects are required to obtain accurate data. The test sample was cylindrical in shape with a diameter of 10 cm and a total weight of the mixture of materials, aggregate and filler of 1200 grams and was mixed with the planned asphalt content at a temperature of 140°C. Then Density and Marshall testing was carried out to obtain stability, flow, VIM, MQ, VMA, VFA and density values. Variations in levels that meet the Marshall characteristic values according to the 2018 Laston Mod Bina Marga specifications were tested by WTM with the aim of analyzing deformation (rutting) in Crumb Rubber polymer modified asphalt.

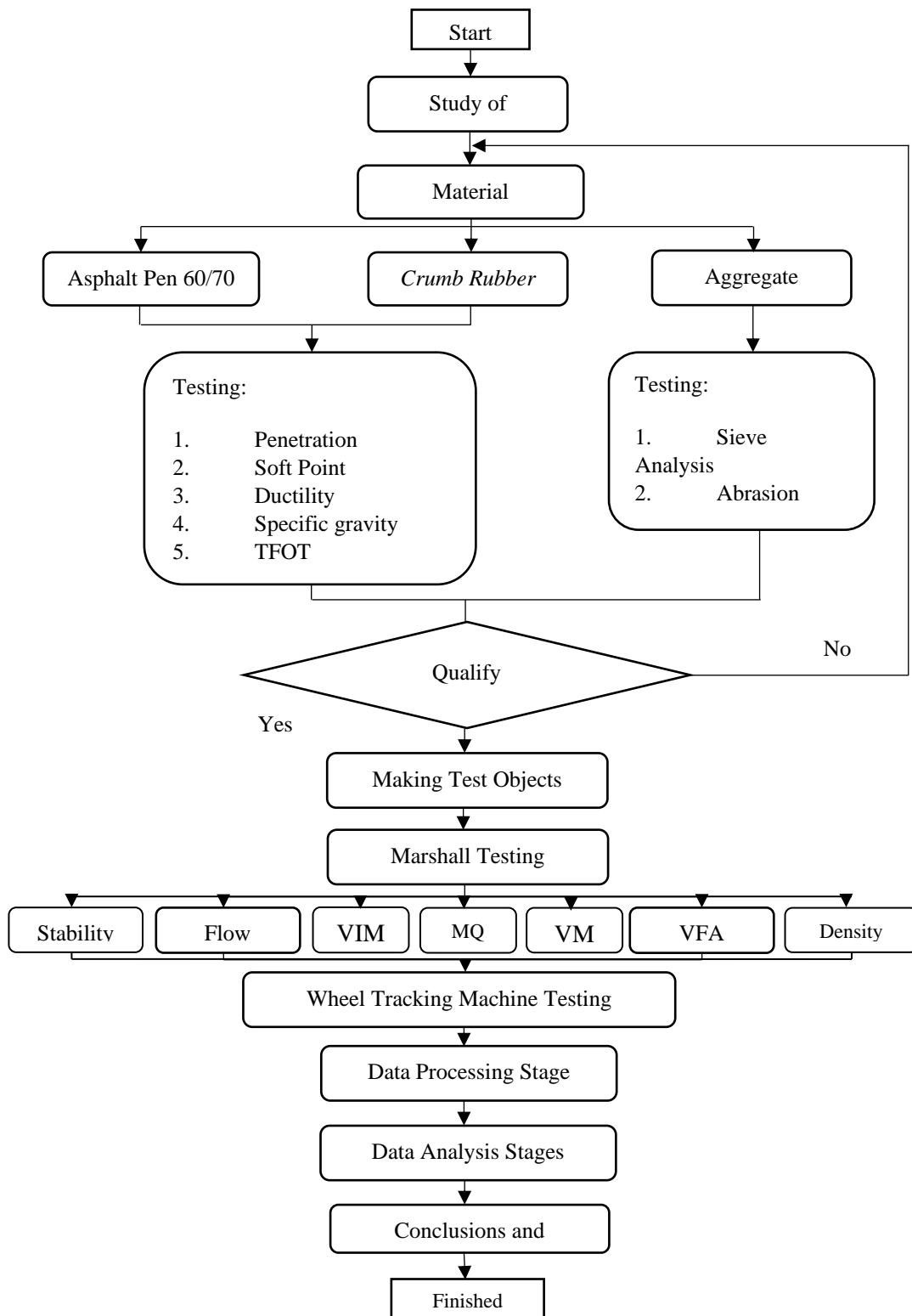


Fig. 5. Research Flow Chart

Rutting performance was evaluated using the Wheel Tracking Machine (WTM). The WTM test was conducted at a controlled temperature of 60 °C to stimulate high temperature service conditions typical of tropical climates. The test applied repeated wheel loading at a constant speed under standardized load conditions in accordance with national specifications. Rut depth was recorded continuously, and dynamic stability (passes/mm) was calculated based on the rate of deformation between specified load cycles. This configuration enables realistic simulation of traffic induced permanent deformation and provides a reliable indicator of rutting resistance.

To quantify the influence of crumb rubber on rutting resistance, statistical analysis was performed using regression modelling. Simple regression was applied to evaluate the relationship between CR content and dynamic stability. Multiple regression analysis was then conducted to verify simultaneous effects where applicable. Model validity was assessed through the coefficient of determination (R^2), analysis of variance (ANOVA), and residual diagnostics to ensure normality and homoscedasticity. A significance level of 5% was adopted for hypothesis testing. This statistical approach strengthens the reliability of the conclusions and supports performance-based mixture optimization (Hair et al., 2019).

Data Collection Techniques and Procedures

Data collection was carried out experimentally in the laboratory. Where the research carried out includes material inspection by carrying out sieve analysis, abrasion and specific gravity tests on coarse aggregate and fine aggregate. Carry out penetration, softening point, ductility, specific gravity and TFOT tests on Pen 60/70 asphalt and modified asphalt mixtures of Crumb Rubber variations.

In making Marshall test samples, this research used a total mixture planning of 1200 grams with a mold size of 4". To determine the Optimum Asphalt Content (KAO) to be used, a Marshall test is carried out with the planned asphalt content (Pb). Each test requires 5 test objects so that the accuracy of the data obtained from the test is precise and efficient (Table 6).

Table 6 - Marshall Test Objects Optimum Asphalt Content (KAO)

	4.7%	5.2%	5.7%	6.2%	6.7%
30 minutes	5 Samples	5 Samples	5 Samples	5 Samples	5 Samples
24 hours	-	5 Samples	5 Samples	5 Samples	-
PRD	-	5 Samples	5 Samples	5 Samples	-

After obtaining the Optimum Asphalt Content, then mix the Pen 60/70 asphalt with a variation of Crumb Rubber Polymer at a temperature of 170°C then properties testing is carried out. The results of modified asphalt variations of Crumb Rubber that meet the 2018 Bina Marga specifications are continued with making test specimens, while variations that do not meet specifications are not continued in making test specimens.

Table 7 - Marshall Test Objects Crumb Rubber Variations

	0%	5%	10%	15%	20%
30 minutes	5 Samples	5 Samples	5 Samples	5 Samples	5 Samples
24 hours	5 Samples	5 Samples	5 Samples	5 Samples	5 Samples
PRD	5 Samples	5 Samples	5 Samples	5 Samples	5 Samples

Test specimens for modified asphalt variations of Crumb Rubber were tested for Density and Marshall to obtain stability, flow, VIM, MQ, VMA, VFA and density values (Table 7). Variations that meet the ideal value in accordance with the Bina Marga requirements for 2018 are then tested for dynamic stability using the Wheel Tracking Machine (WTM) testing tool.

The test object used in WTM testing has dimensions. From the WTM test, it was found that the maximum number of dynamic stabilities passes until the modified asphalt experiences deformation (rutting) $40 \times 30 \times 7$ cm.

Data analysis technique

After all testing stages are completed, the WTM test data obtained is then analyzed to determine how big the effect is. Data analysis uses simple and multiple linear regression analysis methods and partial tests, specifically, assesses how two or more independent factors (also known as independent variables or X) affect the dependent variable (also known as dependent variable Y) (Hair et al., 2019). Data analysis was processed using the IBM SPSS application.

The stages for testing the magnitude of the effect in experimental research are as follows:

- a. Simple and Multiple Correlation on each variable X
 - 1) Simple Linear Regression Analysis

Simple linear regression is a method in statistics that is used to see the relationship between variables, namely the independent variable and the dependent

variable. This type of regression is also often shortened to SLR (Simple Linear Regression) and is the method used to analyze the effect of Crumb Rubber (X) on the Number of Trajectories (Y) of WTM test results.

The equation model used to calculate simple linear regression is as follows:

$$Y = a + bx$$

Information:

- Y = dependent variable / response or consequence variable
- X = independent variable / predictor variable
- a = Constant
- b = regression coefficient

2) Multiple Linear Regression Analysis

Multiple linear regression analysis is a statistical calculation that provides an explanation of the relationship pattern or model between two variables free or more. Multiple Linear Regression Analysis is used as an analysis of the influence of research data from WTM testing results and processed using the IBM SPSS application, with the following equation form:

$$Y = a + bx + cx^2.$$

Information:

- Y = dependent variable / response or consequence variable
- X = independent variable / predictor variable
- a = Constant
- b = regression coefficient X_1
- c = regression coefficient X_2

b. Simple and Multiple Regression on each variable X

To determine the percentage influence The coefficient of determination is used with the independent variable's impact on the dependent variable the following equation:

$$r^2 = \frac{(b_1 \sum x_1 y) + (b_2 \sum x_2 y)}{\sum y^2}$$

- 1) If R^2 has a value of 0, then in the regression equation model formed, the variation in the dependent variable Y cannot be explained in the slightest by the variation in the independent variables and $X_1 X_2$
- 2) If the value is 1, then in the regression equation model formed, The dependent variable The best way to describe Y is by variations in the independent variables and $R^2 X_1 X_2$

Table 8 - Value Interpretation R^2

R^2	Interpretation
0	Not correlated
0.01-0.20	Very weak
0.21-0.40	Weak
0.41-0.60	Pretty weak
0.61-0.80	Enough
0.81-0.88	Strong
0.89-1.00	Very strong

c. Partial Test Correlation

To test parameters partially, the t-test can be used. The purpose of the t-test is to ascertain if or not there is a partial (individual) influence given by the independent variable (X) on the dependent variable (Y). If a confidence level of 95% or a significance level of 5% is set ($\alpha = 0.05$), then the decisions that can be made are as follows.

- 1) If the sig value is < 0.05 then it is rejected and accepted, so there is an influence of the independent variable on the dependent variable. $H_0 H_a$
- 2) If the sig value is > 0.05 then it is accepted and $H_0 H_a$ rejected, so there is no influence of the independent variable on the dependent variable.

4. Results and Discussions

Pen 60/70 Asphalt Testing

The asphalt used in this research was Pen 60/70 asphalt obtained from PT. Mighty Trimurti. The asphalt properties are presented in Table 9 and meet the requirements according to the 2018 Bina Marga Revision 2 Division 6 specifications. The Pen 60/70 asphalt binder satisfies all Bina Marga 2018 specification value of 64.2 (0.1 mm) lies within the required range of 60-70, indicating medium stiffness suitable for tropical pavement conditions. The softening point of 48.4 °C meets the minimum threshold ($\geq 48^\circ\text{C}$), suggesting acceptable high temperature performance under Indonesian climatic conditions. Ductility of 145 cm exceeds the minimum requirement (≥ 100 cm), indicating sufficient flexibility and crack resistance at intermediate temperatures. The specific gravity of 1.0287 (>1.0) confirms standard binder density characteristics. Furthermore, the TOFT weight loss of 0.22% is well below the 0.8% limit, demonstrating good short term aging resistance. Overall, the base binder provides a stable rheological platform for crumb rubber modification without premature oxidation or excessive volatilization.

Table 9 - Asphalt Pen 60/70 Test Results

Test Type	Test Method	Test result	Specification	Unit	Information
Penetration at 25°C	SNI 2456:2011	64.2	60-70	0.1mm	Fulfil
Soft Point	SNI 2434:2011	48.4	≥ 48	°C	Fulfil
Ductility at 25°C	SNI 2432:2011	145	≥ 100	cm	Fulfil
Specific gravity Weight	SNI 2441:2011	1.02873	$\geq 1,0$	gr	Fulfil
Loss (TFOT)	SNI 06-2441-1991	0.22	$\leq 0,8$	%	Fulfil

Testing of Modified Crumb Rubber Asphalt

Mixing Crumb Rubber modified asphalt begins at a temperature of 170°C with a mixing time of 60 minutes. The variations in the Crumb Rubber mixture are 0%, 5%, 10%, 15% and 20%. Data on the properties of Crumb Rubber modified asphalt from the five variations, all meet specifications (Table 10). The incorporation of crumb rubber (CR) significantly alters binder rheological properties. Penetration decreases progressively from 64.2 (0%) to 39.6 (20%), indicating substantial stiffening. This reduction reflects rubber swelling and absorption of light aromatic fractions, increased binder viscosity and formation of elastic network structures. This stiffening effect enhances rutting resistance but may increase brittleness at higher dosages ($>15\%$). Softening point increases from 48.4 °C to > 60 °C at 20% CR. This improvement indicates enhanced high temperature resistance and susceptibility to permanent deformation. Such behavior is typical in elastomer modified asphalt, where increased softening temperature reflects improved thermal stability and load bearing capacity. Ductility decreases sharply from 145 cm to 38 cm at 20% CR. While increased stiffness improves rutting resistance, reduced ductility may compromise fatigue resistance. This confirms the stiffness flexibility trade off. Moderate CR contents (5-10%) maintain better balance between stiffness and flexibility. Specific gravity slightly fluctuates, reflecting rubber dispersion within the binder matrix. The changes are minimal, suggesting good compatibility and homogeneous blending. Weight loss increases gradually (0.22% to 0.77%) but remains below 0.8% specification. This indicates that CR modified binders remain stable under short term aging conditions. However, high rubber content increases oxidation susceptibility due to greater exposed surface area of rubber particles.

Table 10 - Crumb Rubber Modified Asphalt Test Results

Test Type	Test result					Specification	Unit
	Mixed Variation (%)						
	0%	5%	10%	15%	20%		
Penetration, at 25 (0.1 mm)°C	64.2	53.15	51.05	42.65	39.6	Reported	0.1mm

Softening Point (°C)	48.4	51.5	52.7	55.9	>60	Reported	°C
Ductility at 25, (cm)°C	145	62	54	45	38	-	cm
Specific gravity	1.02873	1.03722	1.00216	1.03447	1.04421	-	gr
Weight Loss (TFOT)	0.22	0.29	0.4	0.54	0.77	≤ 0,8	%

Aggregate Testing

Aggregate testing is carried out to ensure that the aggregate used to make test objects is suitable for use. Tests carried out on aggregates include sieve analysis testing, abrasion testing and specific gravity testing (Table 11). The sieve analysis confirms that aggregate gradation is within the designed envelope for AC-WC mixtures. Based on key observations, coarse aggregate show strong dominance at 19-25 mm sizes, sand fraction ensures adequate fine matrix formation and calcium oxide, and stone ash provide filler stability. The distribution indicates dense-graded structure, suitable for surface wearing course. Proper gradation ensures the effective load distribution, adequate interlocking and reduced susceptibility to rutting. The presence of sufficient material passing 0.075 mm contributes to mastic stability.

a. Sieve Analysis

The results of the sieve analysis test can be seen in table 11.

Table 11 - Aggregate Sieve Analysis Test Results

No. Filter	Agg 3/4"	Agg 1/2"	Batu Ash	Sand	Calcium oxide
	Get away (%)	Get away (%)	Get away (%)	Get away (%)	Get away (%)
37.5	100	100	100	100	100
25.4	100	100	100	100	100
19	100	100	100	100	100
12.5	54.59	100	100	100	100
9.5	16.49	96.21	100	100	100
4.75	4.22	44.77	91.25	99.20	100
2.36	2.42	13.97	60.31	96.81	99.05
1.18	1.58	5.86	37.09	77.30	97.39
0.6	1.32	2.48	23.30	34.29	90.19
0.3	0.81	1.24	15.85	8.59	75.12
0.15	0.41	0.46	14.85	1.87	21.48
0.075	0.08	0.01	11.30	0.44	6.74

b. Abrasion Testing

The abrasion test results can be seen in table 12. The Los Angeles abrasion results showed that 100 rounds for 4.13% (< 6 %) and 500 rounds for 15.77% (<30%). These results confirm high aggregate durability and resistance to fragmentation. Low abrasion loss indicates strong mechanical integrity, which supports rutting resistance and long-term structural performance. Durable aggregates are essential in rubber modified mixtures to ensure that improvements in binder properties are not offset by weak aggregate skeleton behavior.

Table 12 - Aggregate Abrasion or Wear Test Results

	Testing	Specification	Mark	Information	
Abrasion with Los Angeles machines	Modified AC Mixture	100 Rounds	Max. 6%	4.13%	Fulfil
		500 Spins	Max. 30%	15.77%	Fulfil

c. Aggregate Specific Gravity Testing

The results of the aggregate specific gravity test can be seen in table 13 and table 14. The bulk specific gravity values fall within normal range (2.6-2.8) indicating dense mineral composition. Water absorption is extremely low (0.007-0.010%) suggesting minimal porosity. Low absorption reduces moisture susceptibility and improves binder aggregate adhesion. This supports long-term durability under wet tropical conditions. The limestone dust exhibits slightly higher absorption (0.030%), which may improve mastic bonding due to filler binder interaction. Stone ash contributes to stiffness enhancement and improved Marshall stability.

Table 13 - Coarse Aggregate Specific Gravity Test Results

TYPE OF MATERIAL	3/4 (gr)	1/2 (gr)
Oven Dry Test Object Weight (Bk)	5001	2500.2
Surface Dry Test Object Weight	5037.6	2525.5
Saturated SSD (Bj)		
Weight of Test Object in Water (Ba)	3165.8	1579.1
Specific Gravity (Bulk)	2,672	2,642
Saturated Surface Dry Specific Gravity	2,691	2,669
Apparent Specific Gravity (Apprentice)	2,725	2,714
Absorption Percentage Water	0.007	0.010

Table 14 - Fine Aggregate Specific Gravity Test Results

TYPE OF MATERIAL	Stone Ash (gr)	Sand (gr)	Limestone Dust (gr)
Pycnometer Weight	171.6	173.5	68.1
Saturated Surface Dry Test Object Weight (SSD)	503.3	503.5	24.3
Pycnometer Weight + Water (B)	668.2	670.3	167.6
Pycnometer Weight + Test Object (SSD) + Water (Bt)	985.2	980.7	180.4
Weight of Open Dry Test Object (Bk)	498.7	498.4	23.6
Specific Gravity (Bulk)	2,677	2,581	2,052
Dry Specific Gravity	2,702	2,607	2,113
Apparent Specific Gravity	2,745	2,651	2,185
Absorption Percentage	0.009	0.010	0.030

4.1 Effect of Crumb Rubber on Asphalt Binder Properties and Rutting Resistance Mechanism

The base Pen 60/70 asphalt binder satisfied all requirements of the Bina Marga 2018 (Revision 2, Division 6) specification, with a penetration value of 64.2 (0.1 mm), softening point of 48.4 °C. and ductility of 145 cm. After modification with crumb rubber (CR), a clear and systematic trend was observed. Increasing CR content resulted in a progressive decrease in penetration and a significant increase in softening point, indicating enhanced stiffness and improved resistance to high-temperature deformation. Specifically, penetration decreased from 64.2 (0% CR) to 53.15 (5% CR) and 51.05 (10% CR), while the softening point increased from 48.4 °C to 51.5 °C and 52.7 °C, respectively.

These changes reflect a fundamental modification of asphalt rheology. The absorption of light fractions by rubber particles and the swelling of elastomeric chains creates a viscoelastic network that improves elastic recovery and reduces temperature susceptibility. This behavior has been widely reported in recent studies, where crumb rubber modification significantly enhances high-temperature performance and rutting resistance by increasing binder elasticity and shear resistance (Gui et al., 2021; Duan et al., 2022; Li et al., 2022). However, ductility decreased markedly with increasing CR content, falling from 145 cm (0% CR) to 62 cm (5% CR) and 54 cm (10% CR), and further declining at higher dosages. This reduction indicates a trade-off between stiffness and flexibility. Excessive CR content may increase brittleness and negatively cracking resistance, as reported in several recent investigations (Kazemian et al., 2025; Wang et al., 2021). Therefore, an intermediate CR dosage is expected to provide the most balanced performance (Ziari & Abdipour, 2024).

4.2 Rutting Performance Based on Wheel Tracking Machine (WTM) Test

The Wheel Tracking Machine (WTM) test results clearly demonstrate the beneficial effect of crumb rubber on rutting resistance. The dynamic stability (DS) increased from 590.2 passes/mm for the 5% CR mixture to 1162.7 passes/mm for the 10% CR mixture, indicating a substantial reduction in rutting susceptibility with higher CR content within this range. Dynamic stability is a direct indicator of a mixture's resistance to permanent deformation under repeated wheel loading. Therefore, higher DS values represent improved rutting performance.

For a mechanistic perspective, rutting in asphalt mixtures arises primarily from two phenomena: densification under repeated loads and shear flow at elevated temperatures. Crumb rubber modification effectively mitigates both mechanisms. The increased binder stiffness limits shear deformation, while the enhanced elastic recovery enables partial strain recovery after each load cycle. At 10% CR, these effects appear to be optimally balanced, resulting in significantly lower rut depth accumulation compared with 5% CR.

This finding consistent with international studies conducted, which report that CR contents in the range of 8-12% provide optimal rutting resistance in asphalt mixtures tested using WTM or Hamburg Wheel Tracking devices (Lee et al., 2023; Lv et al., 2022; Phan et al., 2025; Pszczola & Dolzycki, 2025). At lower dosages, the rubber acts mainly as a filler or modifier with limited interaction, while at moderate dosages a continuous elastomeric network is formed within the binder-aggregate system, significantly improving shear resistance. Conversely, higher CR contents (>15%) may cause excessive viscosity, poor workability, and reduced ductility, which can adversely affect mixture performance (Duan et al., 2022; Z. Wang et al., 2025).

Table 15 - Aggregate Percentage

Sieve Size													
Inch	1 1/2"	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200	
Mmm	37.5	25.4	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
Material Data													
AGG. 3/4"	100	100	100	54.5851	16.4888	4.2192	2.4195	1.5777	1.3197	0.8098	0.4119	0.082	
AGG. Medium	100	100	100	99.8249	96.2111	44.7662	13.9668	5.8631	2.4751	1.2425	0.4625	0.0114	
Batu Ash	100	100	100	100	100	91.2494	60.3098	37.0865	23.3033	15.8471	14.8475	11.3048	
Sand	100	100	100	100	100	99,2002	96,811	77.3018	34.2947	8.5924	1.8694	0.4399	
Limestone Dust	100	100	100	100	100	100	99.05	97.79	90.19	75.12	21.48	6.74	
Mixture Composition													
AGG. 3/4"	20%	20	20	20	10.91702	3.29776	0.84383	0.4839	0.31554	0.26395	0.16197	0.08238	0.0164
AGG. Medium	23%	23	23	23	22.95974	22.12855	10.29623	3.21237	1.3485	0.56928	0.28578	0.10638	0.00262
Batu Ash	45%	45	45	45	45	45	41.06222	27.13943	16.6889	10.4865	7.13118	6.68138	5.08714
Sand	10%	10	10	10	10	10	9.92002	9.6811	7.73018	3.42947	0.85924	0.18694	0.04399
Limestone Dust	2%	2	2	2	2	2	2	1,981	1.9558	1.8038	1.5024	0.4296	0.1348
Total Mix	100%	100	100	100	90.8768	82.4263	64.1223	42.4978	28.0389	16.5530	9.9406	7.4867	5.2849
Spec. Gradation													
Max.	100	100	100	100	90	69	53	40	30	22	15	9	
Min.	100	100	100	90	77	53	33	21	14	9	6	4	

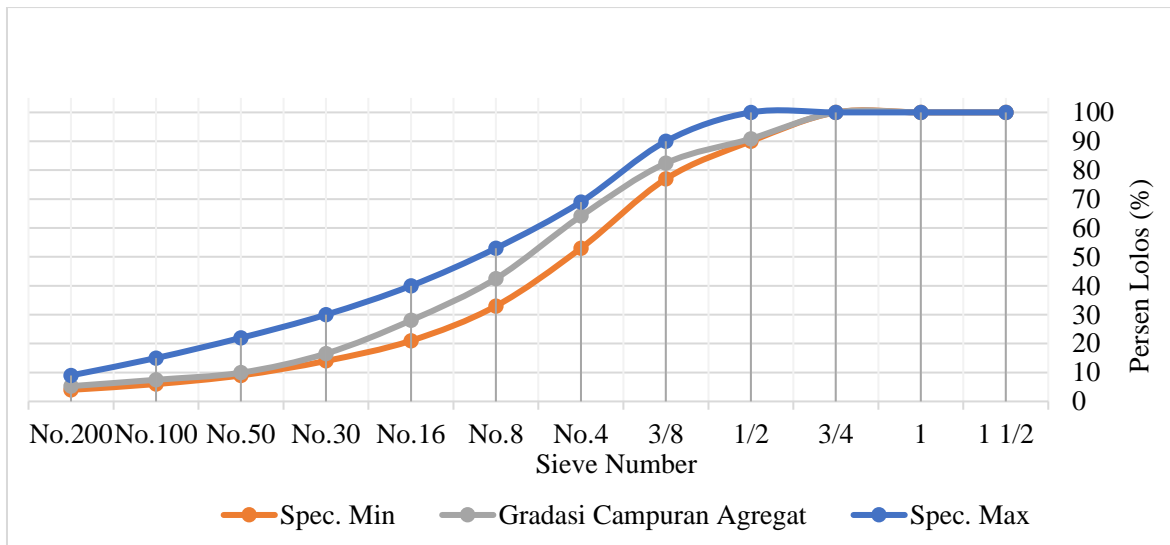


Fig. 6. Aggregate Mixture Gradation Chart

The aforementioned graph demonstrates that the aggregate mix planning satisfies the 2018 Bina Marga requirements' limit levels. The 2018 Bina Marga specs state that, According to the 2018 Bina Marga specifications, there is a threshold percentage value that must be met when planning aggregate composition. Each layer of pavement has a different threshold value. The percentage of aggregate used in making Marshall test specimens can be seen in table 15 and figure 6.

Figure 7 shows that the Optimum Asphalt Content (OAC/KAO) was determined at 5.7% based on the intersection of stability, flow, VIM, VMA, VFA and density criteria in accordance with Marshall mix design principles. The selection reflects the classical balance between internal shear resistance and volumetric durability. At lower asphalt contents (4.7-5.2%), the mixture exhibited insufficient binder coating, resulting in lower stability and higher air voids. Conversely, asphalt contents beyond 6.2% showed excessive flow and reduced structural stiffness due to binder dominance over aggregate interlock. This behavior aligns with the performance-based mix design theory, where OAC is selected at the condition that maximizes stability while maintaining volumetric parameters within specification limits (Chen et al., 2021). Similar optimum asphalt contents for AC-WC mixtures were reported by Duan et al. (2022), indicating that binder content around 5.5-6.0% typically ensures adequate durability in rubber modified systems.

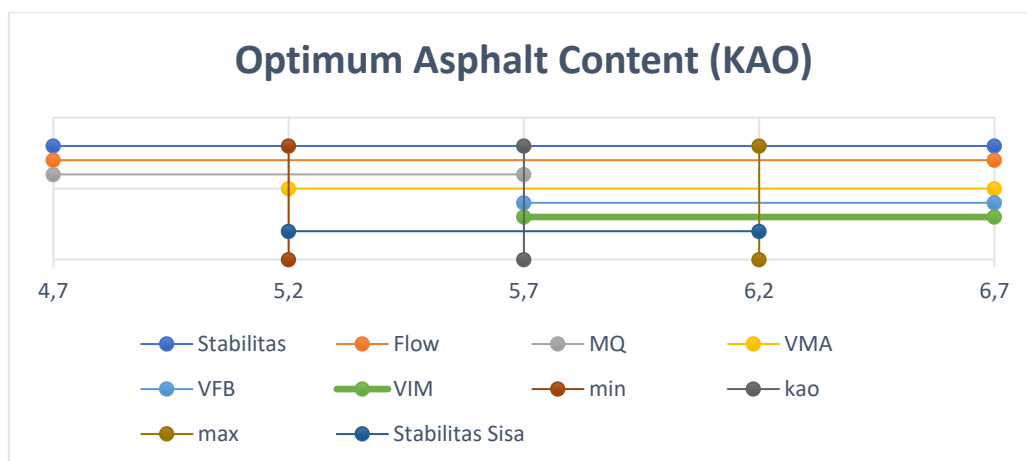


Fig. 7. Optimum Asphalt Content (KAO) Chart

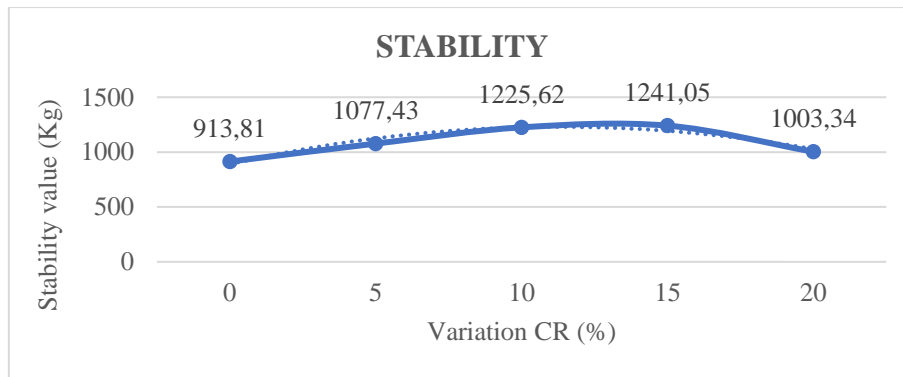


Fig. 8. Asphalt Content Graph with Stability Values

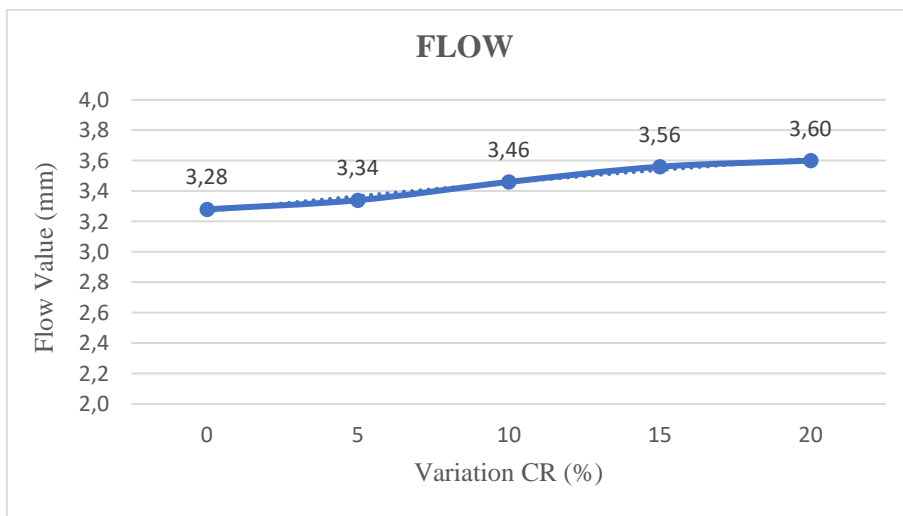


Fig. 9. Asphalt Content Graph with Flow Values

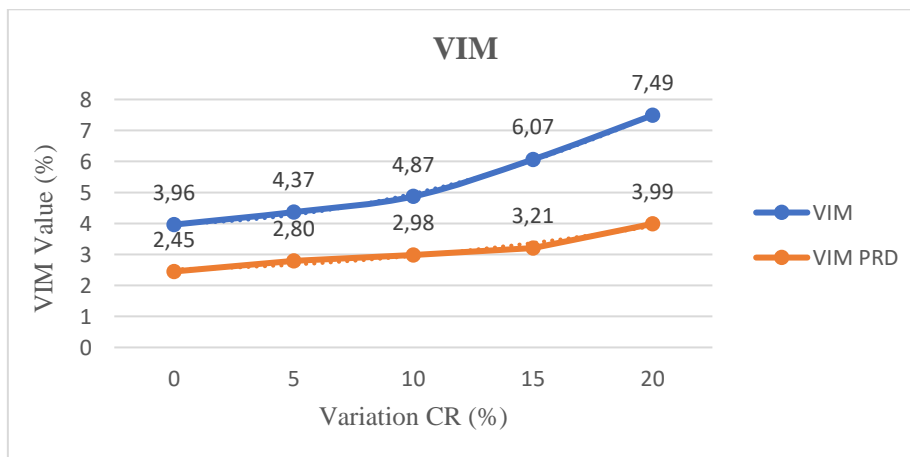


Fig. 10. Asphalt Content Graph with VIM Value

Figure 8 indicates that Marshall stability increased from 913.81 kg (0% CR_ to a peak of 1241.05 kg at 15% CR before decreasing to 1003.34 kg at 20% CR. The initial increase (0-15%) can be explained by the swelling mechanism of crumb rubber particles. Rubber absorbs light aromatic fractions from asphalt, resulting in viscosity enhancement and improved elastic recovery. This increases resistance to plastic deformation under loading. This finding is consistent with Zheng et al. (2021) who reported stability improvements between 10-20% depending on rubber particle size and mixing temperature. Similarly, Šernas et al. (2023) observed increased Marshall stability due to enhanced binder stiffness and improved stress distribution. However, the reduction at 20% CR suggests over modification. Excess rubber can cause inadequate coating,

reduced workability and micro-void formation, leading to decreased structural cohesion. (Wang et al., 2025) confirmed that excessive CR leads to brittleness and incomplete blending, reducing mechanical integrity.

Figure 9 shows a gradual increase in flow values from 3.28 mm (0%) to 3.60 mm (20% CR). Increased flow indicates greater deformation capacity before failure. This behavior reflects the elastomeric nature of rubber particles, which enhance strain tolerance. However, excessive flow may indicate reduced stiffness at higher rubber contents. According to Lee et al. (2023), crumb rubber modification increases viscoelastic flexibility, but beyond optimal levels may compromise structural rigidity. The observed trend confirms the stiffness ductility trade off widely reported in polymer modified asphalt research.

VIM increasing significantly from 3.96% (0% CR) to 7.49% (20% CR). This indicates that higher rubber content reduces compaction efficiency (Fig 10). The increase in air voids can be attributed to increased binder viscosity, rubber particle stiffness and reduced workability. Zhao et al. (2022) noted that crumb rubber mixtures often require higher compaction energy due to viscosity increase. Excess VIM reduces durability and increases moisture susceptibility. The VIM PRD curve indicates that values beyond 15% CR exceed specification limits, confirming that 20% CR may not be suitable for AC-WC applications under standard compaction conditions.

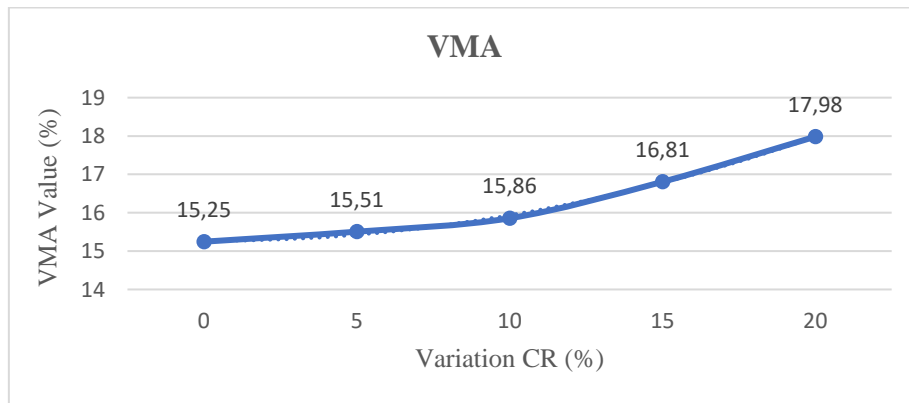


Fig. 11. Asphalt Content Graph with VMA Value

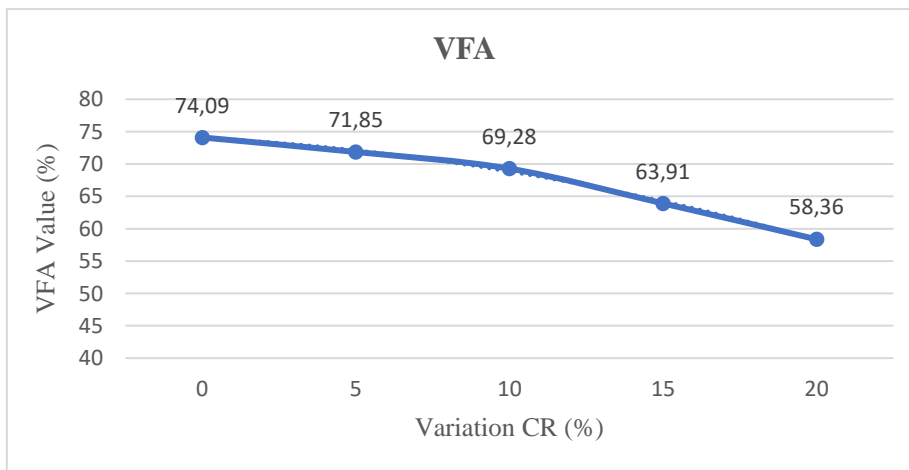


Fig. 12. Asphalt Content Graph with VFA Value

Figure 11 shows VMA increasing with CR content, while Figure 12 indicates decreasing VFA. This inverse relationship suggests that although total void space increases, less of it is filled with asphalt binder at higher rubber contents. This phenomenon is typical in rubberized mixtures, as reported by (Riekstins et al., 2021). Higher VMA improves binder film thickness but excessive reduction in VFA may reduce mixture cohesion.

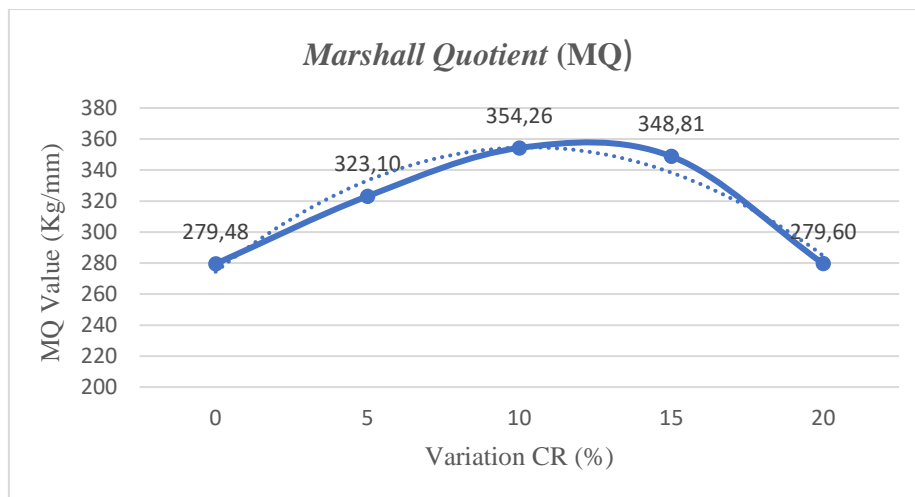


Fig. 13. Asphalt Content Graph with MQ Value

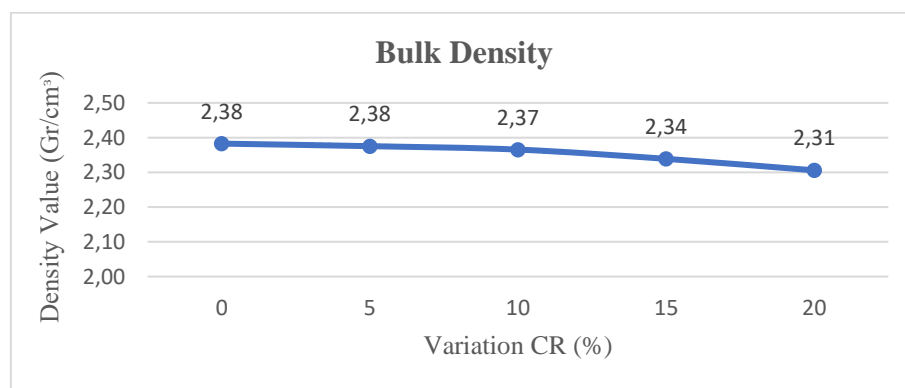


Fig. 14. Asphalt Content Graph with Density Values

Figure 13 shows MQ increasing up to 10-15% CR and decreasing at 20% CR represents stiffness index (stability/flow). The peak at 10-15% indicates optimal balance between rigidity and deformation capacity. Duan et al. (2022) reported similar parabolic MQ behavior, confirming existence of optimal rubber dosage threshold. Figure 14 indicates gradual reduction in bulk density with increasing CR content. This is due to lower specific gravity of rubber compared to mineral aggregates. Reduced density may affect structural capacity if not properly compensated.

Figure 15 synthesizes the multi criteria Marshall design check for the asphalt crumb rubber (CR) mixtures by plotting the key acceptance indicators together with the specification bounds across CR contents (0-20%). Interpreted mechanistically, this type of “envelope” plot is useful because it makes clear that the best CR content is not the one maximizes a single parameter but the one that simultaneously satisfies strength, deformability and volumetric durability. The graph indicates that the optimum decision region lies around 10% CR, where stability and MQ remain high while the volumetric indicators are still closest to the specification targets in contrast, higher CR dosages shift the volumetric balance unfavorably (especially VIM rising and VFA dropping), even if some strength indicators remain acceptable. This trade off is consistent with Marshall-based CRM mix design evidence showing that the optimum rubber content is commonly governed by a combined requirement such as adequate stability and stiffness (stability/MQ) without sacrificing compatibility and void structure (Tan et al., 2022).

From a materials perspective, the pattern shown in Figure 15 can be explained by the swelling absorption interaction between crumb rubber and asphalt binder. When CR is incorporated, rubber particles absorb maltene/light fractions and swell, increasing binder viscosity and elastic response. This can improve load bearing capacity up to an optimum dosage. However, as CR content increases further, the mixture becomes more viscous and less workable, making it harder to achieve target density under standard compaction energy, this typically manifests as

higher VIM and altered VFA/VMA balance, which is exactly the kind of volumetric drift the figure is signaling at the upper CR levels. The importance of compatibility and interaction intensity in governing these rheological and volumetric outcomes is widely emphasized in recent reviews on rubberized asphalt binders (Zheng et al., 2021).

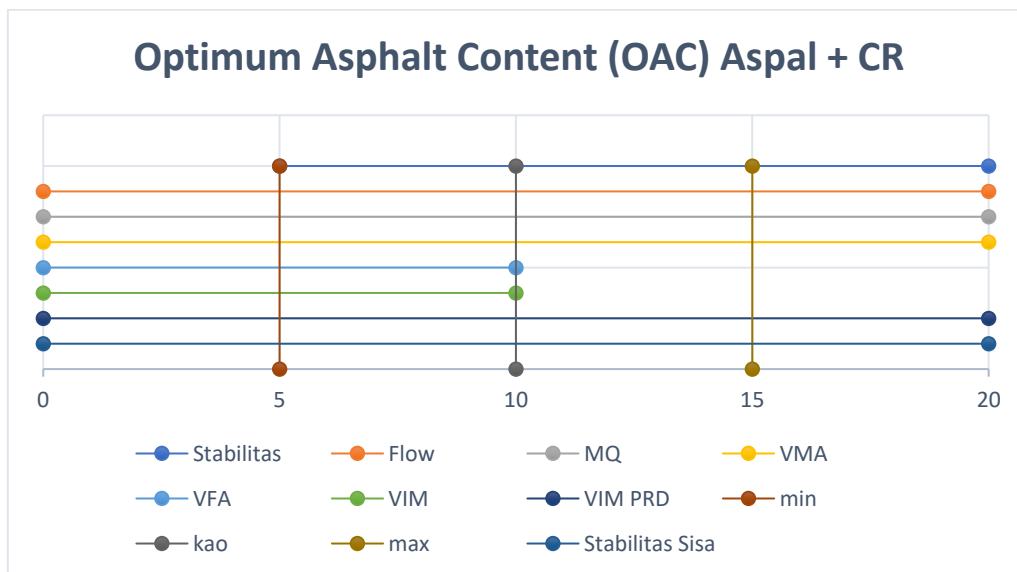


Fig. 15. Graph of Optimum Asphalt Content (KAO) Asphalt + CR

Figure 15 supports the engineering argument that CR addition may require binder content adjustment to maintain the air void target. High rubber dosages often raise air voids above specification unless additional binder is introduced, or the aggregate structure is redesigned. This phenomenon has been reported in high dosage rubber asphalt mixtures where the author explicitly note the need to increase bitumen to meet void requirements (Chegenizadeh et al., 2021). In other words, the figure does not merely report compliance. It provides evidence that the limiting factor at high CR is volumetric control, not strength alone. This also aligns with recent mixture level research indicating that improved binder rutting indices do not always translate into superior mixture rutting performance if mixture structure/volumetrics are not concurrently optimized (Wu et al., 2025).

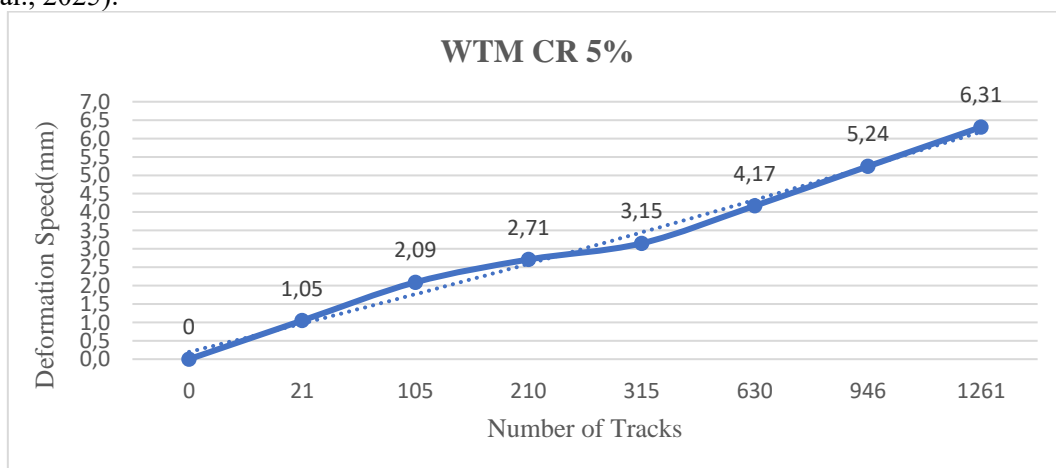


Fig. 16. WTM CR 5% Testing Chart

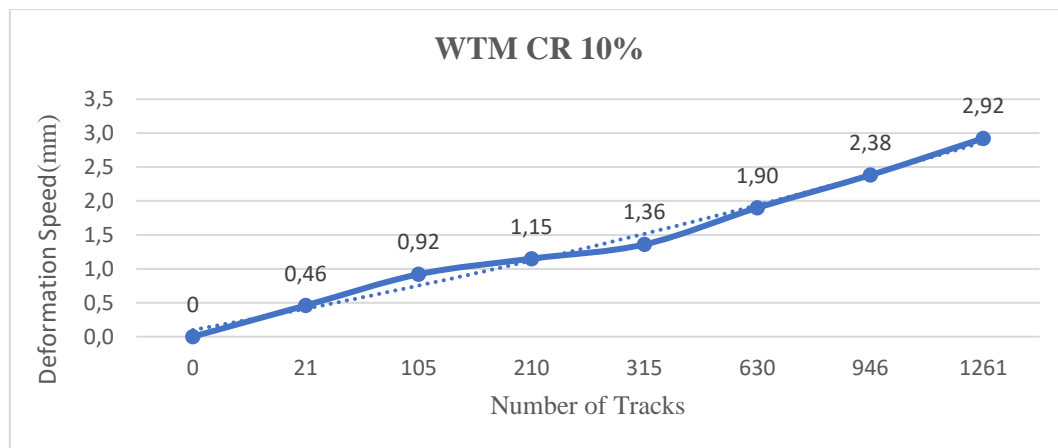


Fig. 17. WTM 10% Testing Chart

Based on the graph above, the deformation speed of CR5% is greater than CR10%. So it can be concluded that the Optimum variation of Modified Crumb Rubber Asphalt is a CR10% variation. However, the dynamic stability value is not in compliance with the Bina Marga requirements for 2018, revision 2, division 6. Figure 16 and 17 show rut depth progression under repeated loading at 60 °C, this demonstrates approximately 53-55% reduction in permanent deformation when increasing CR from 5% to 10%. Mechanistically, this improvement is due to increased binder viscosity, enhanced elastic recovery, reduced shear flow and improved resistance to aggregate rearrangement. Majidifard et al. (2021) confirmed that rutting depth is strongly influenced by binder stiffness and elastic recovery modulus. Similarly, Phan et al. (2025) demonstrated superior rutting resistance at 8-12% CR. This superior performance at 10% CR suggests optimal network formation between asphalt matrix and rubber particles. At 5%, the elastic network is insufficiently developed.

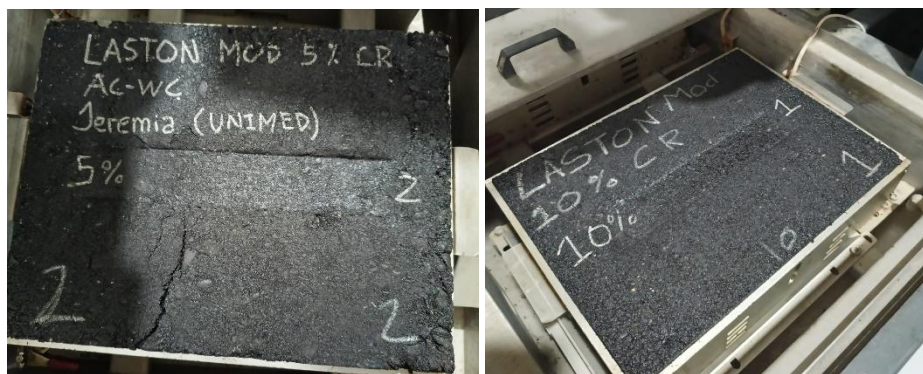


Fig. 18. WTM test results for rutting at 5% and 10% CR variations

It can be seen in Figure 18, a comparison between CR5% and CR10% variations on permanent deformation damage (rutting). In the CR5% variation, wheel grooves and cracks are clearly visible in the pavement layer, which indicates permanent deformation (rutting), whereas in the CR10% variation, slight wheel grooves are visible in the pavement layer. So, it can be concluded that the addition of Crumb Rubber can influence improving the quality of asphalt and from the results of data analysis it was found that the effect of adding Crumb Rubber on the number of dynamic stability passes was 97.9%.

4.3 Statistical Interpretation and Regression Model Validity

Regression analysis revealed a coefficient of determination ($R^2 = 0.979$), indicating that approximately 97.9% of the variation in dynamic stability can be explained by the crumb rubber content. This very strong correlation confirms that CR dosage is the dominant factor influencing rutting resistance in the tested AC-WC mixtures. Similar levels of explanatory power have been reported in recent rutting prediction studies that integrate laboratory wheel tracking data with

regression or machine learning models Majidifard et al., (2021). From an engineering standpoint, the regression model should not be interpreted merely as a statistical relationship, but as a decision support tool for mixture design. When properly validated through ANOVA and residual analysis, such models can be used to estimate expected rutting performance and to define acceptable CR dosage ranges for specific traffic and climate conditions. Performance based mix design frameworks increasingly rely on this approach to optimize materials while maintaining specification compliance (Phan et al., 2025; Šernas et al., 2023).

4.4 Comparison with Previous Studies and Engineering Sustainability Implications

The results of this study align well with contemporary international research demonstrating that crumb rubber modification significantly improves rutting resistance compared with conventional asphalt binders (Ban et al., 2025; Boom et al., 2023; Mehta et al., 2024; Zhao et al., 2022). Several comparative studies indicate that CR modified asphalt can achieve rutting performance comparable to SBS modified asphalt, particularly in hot climate applications, while offering superior environmental benefits (Šernas et al., 2023; Yan et al., 2025). From a sustainability perspective, the use of crumb rubber contributes to waste tire recycling and support circular economy principles (Khasawneh et al., 2024). Waste tires are a persistent environmental problem due to their low biodegradability and their utilization in pavement materials reduces landfill burden while enhancing pavement durability (Aboelela et al., 2025; Leandri et al., 2020; Lee et al., 2023). Longer service life and reduced maintenance frequency further improve the life cycle performance of CR modified pavements. In terms of transportation policy and engineering practice, the findings suggest that 10% crumb rubber is an optimal dosage for AC-WC mixtures exposed to high temperatures and heavy traffic loads. This dosage provides a balance between rutting resistance, workability, and binder flexibility. For broader implementation, performance-based specification incorporating WTM or Hamburg rutting criteria are recommended, along with supplementary fatigue and aging evaluations to ensure long term durability (Pszczola & Dolzycki, 2025; Seyed Ali Akbar et al., 2025)

5. Conclusion

This study investigated the effectiveness of crumb rubber modification in enhancing the rutting resistance of AC-WC asphalt mixtures. The results demonstrated that crumb rubber contents of 5% and 10% significantly improve mechanical performance, with the 10% CR mixture exhibiting the highest dynamic stability. These improvements are attributed to enhanced elasticity and stress redistribution under repeated wheel loading. Regression analysis confirms a strong statistical relationship between CR content and rutting resistance, supporting the reliability of the proposed model. CR content and rutting resistance, supporting the reliability of the proposed model. From an engineering perspective, the findings suggest that CR modified asphalt can improve pavement durability while complying with national specifications. Environmentally, the utilization of waste tires contributes to sustainable pavement construction and waste reduction. Limitations of this study include the absence of fatigue and aging tests, which should be addressed in future research to evaluate long-terms.

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