The Effect Of Compaction Temperature On Marshall Parameters Of AC-WC Asphalt Mixtures With Graphene Additives

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Abstract
This study aims to determine the effect of compaction temperature variation and graphene addition on Marshall parameters in AC-WC asphalt mixtures. The issues raised are premature damage to asphalt layers due to compaction temperatures that do not meet specifications and the lack of studies on the effect of graphene with compaction temperature variation on AC-WC. The materials used include coarse aggregate, fine aggregate, filler, Portland cement, 60/70 penetration asphalt, and graphene with variations of 0.01%–0.05% by weight of the mixture. The compaction temperatures tested were 110°C, 120°C, 130°C, 140°C, and 150°C. Testing was conducted in accordance with the 2018 Revised II General Specifications for Road Construction using the Marshall method. The results showed that adding 0.01% graphene at a compaction temperature of 140°C produced the best performance with a 19.55% increase in stability, yielding a stability value of 1711.367 kg. Density and MQ increased, while VMA, VIM, and flow decreased due to the addition of graphene, but still met the specification range. The decrease in these values demonstrates that graphene functions effectively in asphalt mixtures, improving porosity and strength compared to standard asphalt. At compaction temperatures of 110°C and 120°C, the VIM values exceeded the maximum limits of 9.67% and 7.05%, respectively. This increase could lead to excessive voids in the asphalt, making graphene a viable solution for asphalt construction.

Keywords: *AC-WC, Compaction Temperature, Graphene, Marshall, Public Works.*

Abstrak
Penelitian ini bertujuan untuk mengetahui pengaruh variasi suhu pemadatan dan penambahan *graphene* terhadap parameter *marshall* pada campuran aspal AC-WC. Permasalahan yang diangkat adalah kerusakan prematur pada lapisan aspal akibat suhu pemadatan yang tidak sesuai spesifikasi dan belum adanya kajian pengaruh *graphene* dengan variasi suhu pemadatan pada AC-WC. Bahan yang digunakan meliputi agregat kasar, agregat halus, *filler*, semen *portland*, aspal penetrasi 60/70, dan *graphene* dengan variasi 0,01%–0,05% terhadap berat campuran. Variasi suhu pemadatan yang diuji adalah 110°C, 120°C, 130°C, 140°C dan 150°C. Pengujian dilakukan sesuai Spesifikasi Umum Bina Marga Tahun 2018 Revisi II dengan metode *marshall*. Hasil penelitian menunjukkan bahwa penambahan *graphene* 0,01% pada suhu pemadatan 140°C menghasilkan kinerja terbaik dengan peningkatan stabilitas sebesar 19,55% dengan nilai stabilitas 1711,367 kg, *density* dan MQ mengalami peningkatan, sedangakan VMA, VIM dan *flow* mengalami penurunan karena adanya bahan tambah *graphene* tetapi tetap memenuhi rentang spesifikasi. Dengan adanya penurunan tersebut membuktikan bahwa *graphene* bekerja dengan baik pada campuran aspal sehingga membuat rongga dan juga kekuatan pada aspal membaik dibandingkan pada aspal normal. Pada suhu pemadatan 110°C dan 120°C nilai VIM telah melewati batas maksimum yaitu 9,67% dan 7,05% peningkatan ini akan menyebabkan rongga terlalu banyak pada aspal sehingga *graphene* dapat menjadi solusi dalam pengerjaan aspal.

Kata Kunci: *AC-WC, Suhu Pemadatan, Graphene, Marshall, Bina Marga.*

1. Introduction

Roads are an important infrastructure that supports social, economic, and cultural activities, but they are vulnerable to damage due to weather, traffic loads, and their service life. One of the road components that frequently experiences damage is the AC-WC layer, which is influenced by asphalt quality, compaction temperature, and aggregate gradation [1]; [2]; [3]. Asphalt itself is a black material primarily composed of hydrocarbons with thermoplastic and viscoelastic properties ([4]), which can be obtained from natural sources or oil [5]. LASTON or Asphalt Concrete (AC) consists of AC-WC, AC-BC, and AC-Base, and can be modified using additives [6].

Various studies have shown that the addition of additives such as polymers, fibers, and nanoparticles can improve asphalt performance [7]. One such additive is graphene, a nanostructured material that is extremely strong, lightweight, conductive, water-resistant, and possesses unique mechanical and thermal properties [8]; [9]; [10]. Graphene has also been proven to improve anti-aging properties, temperature stability, softening point, viscosity, and resistance to cracking and deformation [11]; [12]. Structurally, graphene is a carbon allotrope in the form of a thin atomic lattice with sp2 bonds, which also serves as the basis for various other carbon allotropes [13].

The performance of asphalt mixtures was evaluated using the Marshall test to determine stability, flow, VIM, VMA, VFA, and optimal asphalt content [14]. Previous studies have only examined variations in compaction temperature in asphalt concrete with anti-stripping additives [15]. Therefore, this study was conducted to investigate the effect of adding graphene to AC-WC mixtures with varying compaction temperatures.

2. Material and Methods

This research is an experimental study conducted at the Highway, Geo and Hydro Engineering Laboratory of the Civil Engineering Study Program at Malikussaleh University, Lhokseumawe City, based on the Bina Marga Specifications, Revision II (2018). The materials used to make asphalt are crushed stone, sand, Portland cement, and asphalt.

1. Crushed stone
   This study used crushed stone from PT. Abad Jaya Abadi Sentosa, North Aceh. This material was obtained from crushed river rocks that were cleaned of mud and sieved to a grain size of 4.75 mm to maintain the quality and strength of the structure.
2. Sand
   Sand in flexible pavement functions as fine aggregate that fills the voids between coarse aggregates, improves gradation, increases stability, and enhances the durability of asphalt mixtures such as AC-WC (Asphalt Concrete – Wearing Course). In this study, sand was sourced from PT. Abad Jaya Abadi Sentosa, North Aceh.
3. Portland cement
   Portland cement is used as a filler in asphalt mixtures, particularly in AC-WC, to improve stability, hardness, and adhesion between aggregates and asphalt. The filler itself serves to fill the gaps between aggregates while improving the performance of the mixture.
4. Asphalt
   Asphalt serves to fill the voids between aggregates, and in this study, 60/70 asphalt from the Civil Engineering Laboratory of Malikussaleh University was used.
5. Graphene
   Graphene is an additive used in this study that also serves to improve the aging performance and temperature stability of asphalt. The graphene used was sourced from Maxlab.

The equipment used in this study includes various tools for testing the physical properties of materials, preparing asphalt samples, and testing the mechanical properties of asphalt. The following are the main pieces of equipment used in this study:

Main equipment for physical properties of materials

1. A sieve set measuring 3/4 inch, 1/2 inch, 3/8 inch, No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200, equipped with a PAN.
2. Sieve shaker
3. Scales
4. Measuring cups
5. Bowls and trays
6. Cones and pestles
7. Dunagen test
8. Oven
9. Molds and pestles

Main equipment for asphalt sample preparation

1. Stove
2. Frying pan and stirring utensils
3. Thermometer
4. Asphalt mold and Marshall hammer
5. Soaking tub
6. Calipers

Main equipment for testing the mechanical properties of asphalt

1. Marshall test
2. Water bath

Physical testing of asphalt materials is conducted to ensure the quality of the aggregates used in the mixture. The testing stages include aggregate sieve analysis in accordance with (SNI ASTM C136-2012) [16] to determine the particle size distribution, bulk density, and loose density of the aggregates in accordance with (SNI 03-4804-1998) [17] to determine the density of the aggregate, as well as the specific gravity and water absorption of coarse and fine aggregates in accordance with (SNI 1969-2016) [18] and (SNI 1970-2016)[19] to calculate the volume, absorption capacity, and surface saturated dry condition (SSD). The results of these tests form the basis for mix design planning, which includes determining the target gradation, Optimum Asphalt Content (OAC), and the number of test specimens. The mix design is based on the cumulative pass percentage for each aggregate fraction (coarse, fine, and filler), resulting in a mixture composition that meets technical specifications.

The production of AC-WC asphalt samples using a graded mix is based on the analysis of the proportions of coarse, medium, fine, and filler aggregates, as well as the asphalt and graphene content. The process includes material and equipment preparation, weighing according to calculations, heating the aggregates and asphalt to 150°C, mixing the asphalt with graphene, and mixing the aggregates into the hot asphalt before compaction. The sample is compacted using a rammer with 75 blows on each side, then cooled, removed from the mold, weighed, measured for dimensions, and soaked for 24 hours before testing.

Sample testing is conducted using the Marshall test in accordance with RSNI M-01 (2003) to determine the stability and flow of the mixture. The process involved weighing the samples after soaking, re-soaking them in a water bath at 60°C for 30–40 minutes, and then testing them using a Marshall machine with a loading rate of 50 mm/minute until the maximum load was reached. The stability value was obtained from the maximum load, while the flow value was measured from the deformation when the peak load was reached.

3. Results and Discussion

Based on the results of the research and data obtained covering several stages in this study, starting from the examination of coarse and fine aggregates, the manufacture of test specimens, and the testing of test specimens, the optimum asphalt content (OAC) was obtained. The results of the standard Marshall test of AC-WC asphalt concrete mixtures are in accordance with the 2018 Revision 2 of the Bina Marga Specifications.

Physical properties testing of materials

Coarse aggregate testing is conducted to determine specific gravity (bulk, SSD, apparent) and water absorption. The data used to calculate the specific gravity and water absorption of 3/4 coarse aggregate can be seen in Table 1 below.

Table 1. Results of specific gravity and absorption tests on 3/4 coarse aggregate.

No	Aggregate Properties	Requirements		Result
		Min	Max	
1	Bulk Specific Gravity	2,5	-	2,64
2	SSD Specific Gravity	2,5	-	2,68
3	Apparent Specific Gravity	2,5	-	2,77
4	Water Absorption (%)		3	1,78

The test results show that the 3/4 coarse aggregate meets the 2018 Revised Bina Marga Specifications, with a bulk density of 2.64 g/cm³, SSD of 2.68 g/cm³, apparent density of 2.77 g/cm³, and water absorption of 1.78%. Next, tests were conducted on the 3/8 coarse aggregate, as shown in Table 2 below.

Table 2. Results of specific gravity and absorption tests on 3/8 coarse aggregate

No	Aggregate Properties	Requirements		Result
		Min	Max	
1	Bulk Specific Gravity	2,5	-	2,65
2	SSD Specific Gravity	2,5	-	2,71
3	Apparent Specific Gravity	2,5	-	2,83
4	Water Absorption (%)		3	2,4

The test results show that the 3/8 coarse aggregate meets the 2018 Revised Bina Marga Specifications with a bulk density of 2.65 g/cm³, SSD of 2.71 g/cm³, apparent density of 2.83 g/cm³, and water absorption of 2.4%.

Table 3. Results of specific gravity and absorption tests on sand

No	Aggregate Properties	Requirements		Result
		Min	Max	
1	Bulk Specific Gravity	2,5	-	2,61
2	SSD Specific Gravity	2,5	-	2,68
3	Apparent Specific Gravity	2,5	-	2,81
4	Water Absorption (%)		3	2,60

The fine aggregate test shows that the sand meets the 2018 Revised Bina Marga Specifications 2 (BJ bulk 2.61 g/cm³; SSD 2.68 g/cm³; apparent 2.81 g/cm³; absorption 2.60%), making it suitable for use in asphalt concrete mixtures, while the fine aggregate dust data is listed in Table 4 below.

Table 4. Results of specific gravity and water absorption tests on dust

No	Aggregate Properties	Requirements		Result
		Min	Max	
1	Bulk Specific Gravity	2,5	-	2,50
2	SSD Specific Gravity	2,5	-	2,56
3	Apparent Specific Gravity	2,5	-	2,65
4	Water Absorption (%)		3	2,21

The test results showed that the dust met the 2018 Revised Bina Marga Specifications with a bulk density of 2.50 g/cm³; SSD of 2.56 g/cm³; apparent density of 2.65 g/cm³; and absorption of 2.21%, making it suitable for use in this study.

3.1.3 Aggregate weight inspection

Table 5. Results of aggregate weight inspection

Aggregate Type	**Aggregate Weight (gram/cm³)**	
	Loose	**Dense**
Coarse Aggregate (3/4)	1,315	1,390
Coarse Aggregate (3/8)	1,290	1,349
Fine Aggregate (Sand)	1,580	1,685
Fine Aggregate (*Dust*)	1,338	1,431

Based on laboratory test results, coarse aggregate size 3/4 has a bulk density of 1.315 g/cm³ in loose condition and 1.390 g/cm³ in compacted condition. Coarse aggregate size 3/8 shows a bulk density of 1.290 g/cm³ in loose condition and 1.349 g/cm³ in compacted condition. For fine aggregate, sand has a bulk density of 1.580 g/cm³ in loose condition and 1.685 g/cm³ in compacted condition, while rock dust or dust has a bulk density of 1.338 g/cm³ in loose condition and 1.431 g/cm³ in compacted condition.

Sieve analysis was conducted to determine the gradation of aggregates as asphalt mix materials, including fine aggregates in the form of sand and dust, as well as coarse aggregates in the form of crushed stone measuring 3/4 inch and 3/8 inch. The results of the examination are shown in Table 6 below.

Table 6. Results of sieve analysis.

Sieve Number	Cumulative Pass%				Cumulative Retained%			
	Aggregate Type				Aggregate Type			
	3/4	3/8	Dust	Pasir	3/4	3/8	Dust	Pasir
3/4"	100,00	100,00	100,00	100,00	0,00	0,00	0,00	0,00
1/2"	62,64	100,00	100,00	100,00	37,36	0,00	0,00	0,00
3/8”	25,80	100,00	100,00	100,00	74,20	0,00	0,00	0,00
No.4	9,98	13,64	100,00	100,00	90,02	86,36	0,00	0,00
No. 8	0,98	2,12	77,14	86,31	99,02	97,88	22,86	13,69
No. 16	0,98	1,89	51,60	57,25	99,02	98,11	48,40	42,75
No. 30	0,97	1,88	34,66	14,78	99,03	98,12	65,34	85,22
No. 50	0,97	1,85	21,90	10,09	99,03	98,15	78,10	89,91
No.100	0,95	1,62	12,60	3,20	99,05	98,38	87,40	96,80
No. 200	0,92	1,51	4,35	2,76	99,08	98,49	95,65	97,24

Determination of mixture gradation and mix design

The gradation of the mixture of coarse aggregates 3/4 and 3/8, fine aggregates of sand and dust, and filler must comply with the 2018 Revised General Specifications for Highways. The gradation must not exceed the specified maximum and minimum limits, so that the aggregates are deemed suitable for use in AC-WC asphalt mixtures. The mix design results are shown in Table 7 below.

Table 7. AC-WC asphalt mix design

Sieve		% Pass					% Mix Design					Total mix	Spek Revisi 2	
		CA (3/4")	MA (3/8")	Dust	Sand	filler	CA	MA	Dust	Sand	filler			
No	(mm)						16	24	45	13	2	100	Min	Max
3/4"	19.1	100.00	100.00	100.00	100.00	100	16.00	24.00	45.00	13.00	2.0	100.00	100	100
1/2"	12.7	62.64	100.00	100.00	100.00	100	10.02	24.00	45.00	13.00	2.0	94.02	90	100
3/8"	9.52	25.80	100.00	100.00	100.00	100	4.13	24.00	45.00	13.00	2.0	88.13	77	90
No. 4	4.75	9.98	13.64	100.00	100.00	100	1.60	3.27	45.00	13.00	2.0	64.87	53	69
No .8	2.36	0.98	2.12	77.14	86.31	100	0.16	0.51	34.71	11.22	2.0	48.60	33	53
No. 16	1.16	0.98	1.89	51.60	57.25	100	0.16	0.45	23.22	7.44	2.0	33.27	21	40
No. 30	0.5	0.97	1.88	34.66	19.44	100	0.16	0.45	15.60	2.53	2.0	20.73	14	30
No. 50	0.3	0.97	1.85	21.90	6.76	100	0.15	0.44	9.85	0.88	2.0	13.33	9	22
No.100	0.15	0.95	1.62	12.60	2.20	100	0.15	0.39	5.67	0.29	2.0	8.50	6	15
No. 200	0.075	0.92	1.51	4.35	1.76	100	0.15	0.36	1.96	0.23	2.0	4.69	4	9

Table 7 shows the proportion of aggregate mixture, namely coarse fraction (CA) 16%, medium fraction (MA) 24%, fine fraction in the form of dust 45% and sand 13%, and filler 2%. This composition meets the 2018 Revised Bina Marga Specifications. The mix gradation graph is shown in Figure 1 below.

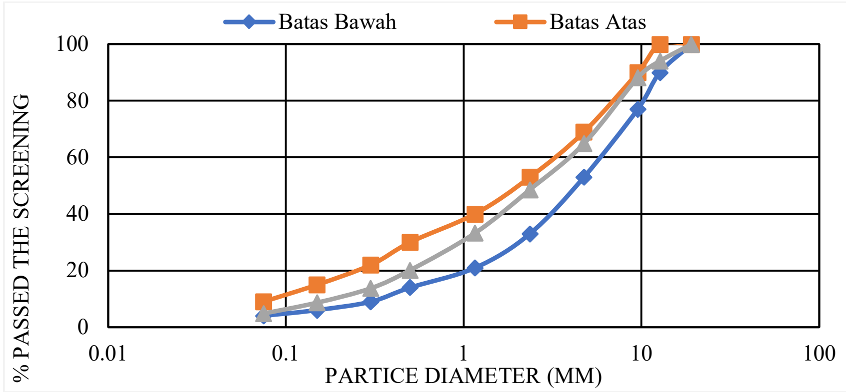

Figure 1. AC-WC asphalt mix design

Optimum asphalt content test object

Test specimens were prepared after obtaining the mix design and median asphalt content (Pb) in accordance with the 2018 Revised Road Construction Specifications. The mix composition consisted of 40% coarse aggregate, 58% fine aggregate, and 2% filler. The asphalt content (Pb) is determined from the aggregate gradation analysis and used as the basis for varying the asphalt content to obtain the optimum content. The asphalt content (Pb) is shown in Table 8 below.

Table 8. Planned asphalt content (pb)

Planned Asphalt Content				
I	**II**	**III**	**IV**	**V**
4%	4,5%	5%	5,5%	6%

The calculation results show a median asphalt content (Pb) of 5%, so asphalt contents of 4%, 4.5%, 5%, 5.5%, and 6% were used to determine the optimum asphalt content (KAO), as shown in Table 9 below.

Table 9. Results of aggregate mixture proportion testing for KAO values

No	Asphalt (%)	Material (Gr)					
		CA (3/4")	MA (3/8")	Dust	Pasir	Filler	Aspal
1	4%	184,32	276,48	518,4	149,76	23,04	48
2	4,5%	183,36	275,04	515,70	148,98	22,92	54
3	5%	182,40	273,60	513,00	148,20	22,80	60
4	5,5%	181,44	272,16	510,30	147,42	22,68	66
5	6%	180,48	270,72	507,60	146,64	22,56	72

Based on Marshall testing, the mixture parameters were met at asphalt contents of 5.5% and 6%. Therefore, the Optimum Asphalt Content (OAC) was determined by taking the average of these two values, namely 5.75%, which was then used for the manufacture of the next test specimen.

Marshall test results for optimum asphalt content

The Marshall test aims to determine the optimum asphalt content (KAO) in asphalt mixtures, based on the middle asphalt content (Pb) as a reference. The asphalt content variations used are 4%, 4.5%, 5%, 5.5%, and 6%. The determination of OAC refers to the General Specifications for Public Works 2018 Revision 2, meeting the Marshall parameter criteria, namely Void in Mineral Aggregate (VMA), Void in Mix (VIM), Void Filled with Asphalt (VFA), stability, flow, and Marshall Quotient (MQ). The Marshall parameters at the optimum asphalt content can be seen in Table 1.

Table 10. *Marshall parameter test results.*

No	Characteristics Marshall	Asphalt Content (%)				
		4%	4,5%	5%	5,5%	6%
1	*Density* (gram/cm^3)	2,34	2,35	2,36	2,37	2,38

No	Characteristics Marshall	Asphalt Content (%)				
		4%	4,5%	5%	5,5%	6%
2	VMA (%)	15,51	15,31	15,53	15,45	15,70
3	VIM (%)	8,31	7,00	6,14	4,94	4,13
4	VFA (%)	46,46	54,43	60,48	68,49	74,10
5	*Stability* (kg)	1340,83	1505,40	1549,43	1549,90	1564,57
6	*Flow* (mm)	4,04	4,27	3,44	3,90	3,77
7	MQ (kg/mm)	347,77	354,84	451,58	403,19	421,94

From the Marshall test results, the optimum asphalt content was determined to be the content that met all Marshall parameter specifications, namely at a variation of 5.75%. The Marshall parameters can be seen in Table 2.

Table 11. *Marshall parameters in determining KAO*

No	Characteristics Marshall	Asphalt Content (%)				
		4%	4,5%	5%	5,5%	6%
1	*Density* (gram/cm^3)					
2	VMA (%)					
3	VIM (%)					
4	VFA (%)					
5	*Stability* (kg)					
6	*Flow* (mm)					
7	MQ (kg/mm)					

Based on the results of Marshall parameter testing on KAO asphalt mixtures, the asphalt content that meets the criteria in accordance with the 2018 Revision 2 Bina Marga Specifications is 5.75%. A detailed explanation of all Marshall parameters is as follows:

Based on the test results, the density of the asphalt mixture was determined from variations in content of 4%, 4.5%, 5%, 5.5%, and 6% as control test objects, and the Optimum Asphalt Content (OAC) was obtained at 5.75%. The mixture density graph is shown in Figure 2.

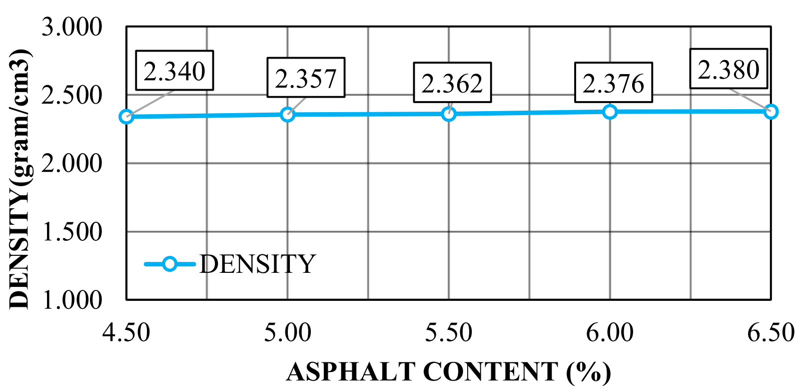

Figure 2. Density at KAO

The minimum Marshall parameter value for VMA is 15% with no maximum limit, so that asphalt content variations of 4%, 4.5%, 5%, 5.5%, and 6% meet the requirements of the 2018 Revised General Specifications for Road Construction. The results are shown in Figure 3.

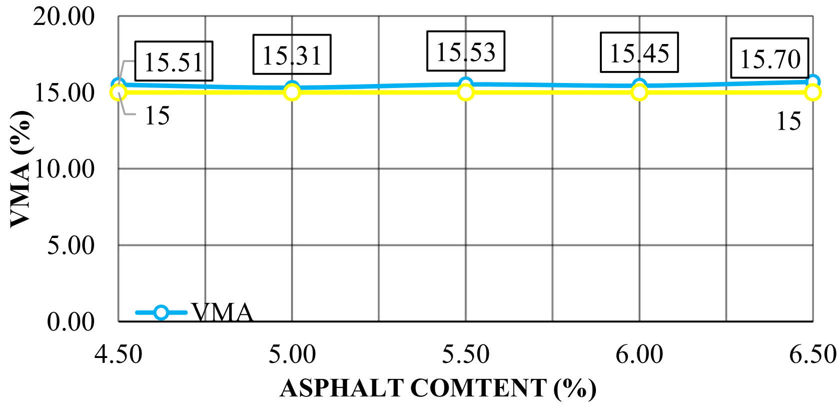

Figure 3. VMA at KAO

The minimum VIM value is 3% and the maximum is 5%. From the test specimen variations, asphalt contents of 5.5% and 6% meet the 2018 Revision 2 General Specifications for Road Construction, while contents of 4%, 4.5%, and 5% do not meet the requirements. The results are shown in Figure 4.

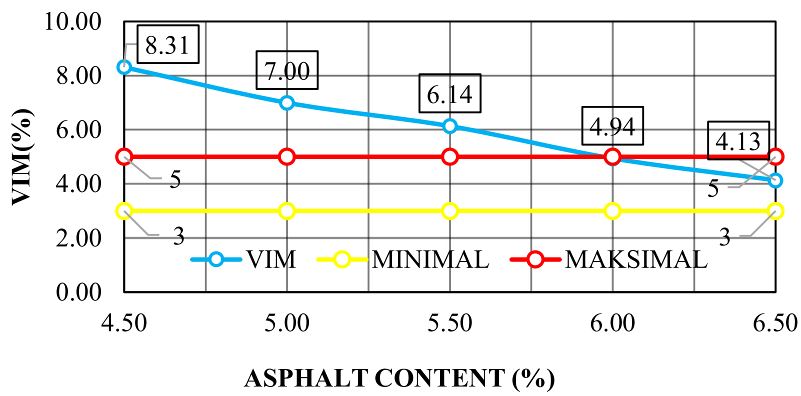

Figure 4. VIM at KAO

The minimum VFA value is 65% with no maximum limit. Asphalt content variations of 5.5% and 6% meet the specifications, while contents of 4%, 4.5%, and 5% do not meet the requirements, as shown in Figure 5.

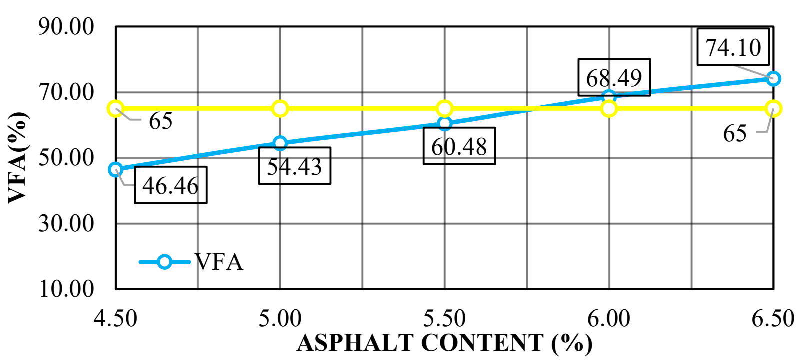

Figure 5. VFA at KAO

The minimum stability value is set at 800 kg with no maximum limit. All asphalt content variations of 4%, 4.5%, 5%, 5.5%, and 6% meet the 2018 Revised General Specifications for Road Construction, as presented in Figure 6.

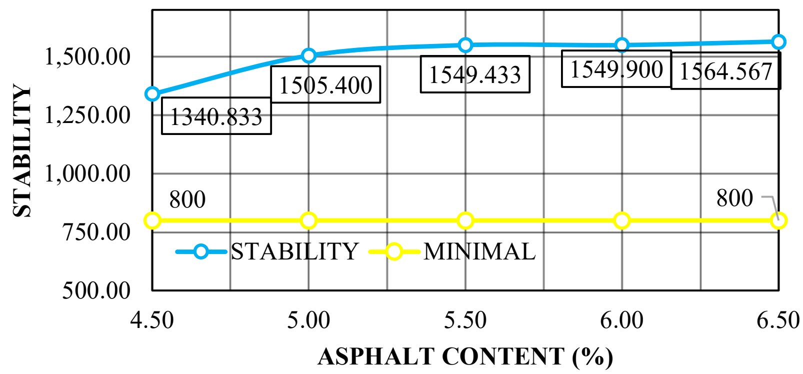

Figure 6. Stability at KAO

The minimum flow value is 2 mm and the maximum is 4 mm. The optimum asphalt content variations that meet the specifications are 5%, 5.5%, and 6%, while the 4% and 4.5% variations do not meet the specifications, as shown in Figure 7.

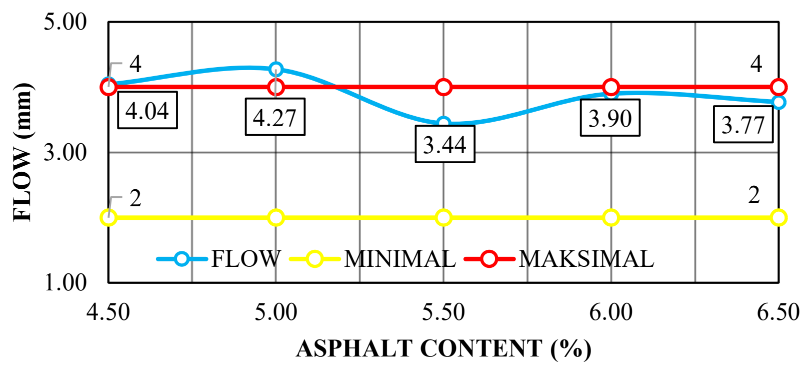

Figure 7. Flow at KAO

The Marshall Quotient has a minimum value of 250 g but no maximum value, so that all test specimens meet the specifications for asphalt content, as shown in Figure 8.

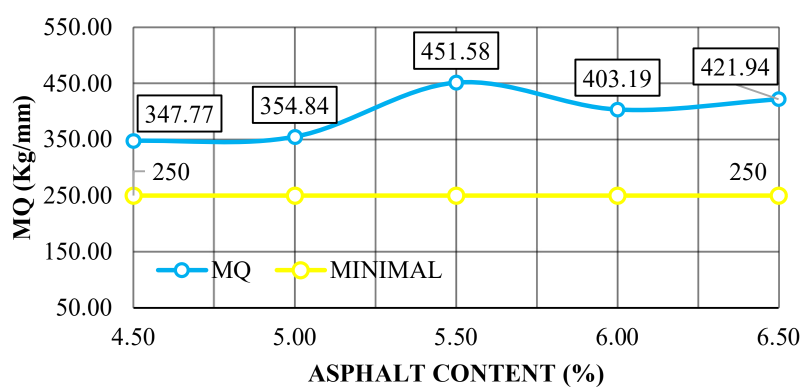

Figure 8. Marshall Quotient at KAO

Parameters for AC-WC asphalt mix with compaction temperature

After determining the optimum asphalt content of 5.75%, AC-WC asphalt testing was conducted with compaction temperatures varying at 110°, 120°, 130°, 140°, and 150°. According to the 2018 Revised Edition of the Bina Marga Specifications, the optimal compaction temperature is approximately 140°. The results of the Marshall parameter tests can be seen in Table 3.

Table 12. *Results of testing AC-WC asphalt with compaction temperature.*

No	Characteristics Marshall	Compaction Temperature				
		110°	120°	130°	140°	150°
1	*Density* (gr/cm^3)	2,192	2,255	2,315	2,306	2,313
2	VMA (%)	20,419	18,133	15,958	16,287	16,008
3	VIM (%)	9,643	7,024	4,578	4,951	4,635
4	VFA (%)	52,791	61,270	71,328	69,803	71,229
5	*Stability* (kg)	802,833	921,900	1154,633	1363,067	1308,967
6	*Flow* (mm)	3,873	3,073	3,117	3,293	3,003
7	MQ (kg/mm)	212,240	298,609	401,105	448,402	447,109

Based on the results of Marshall parameter testing on KAO asphalt mixtures, the asphalt content that meets the criteria in accordance with the 2018 Revision 2 Bina Marga Specifications is 5.75%, and the optimum temperatures obtained are 130°, 140°, and 150°. A detailed explanation of all Marshall parameters is as follows:

Based on the test results, the density value of the asphalt mixture was obtained from variations in the asphalt content of 5.75% used as a control test object. The optimum temperature was obtained at asphalt contents of 130°, 140°, and 150°, as shown in the density graph in Figure 9.

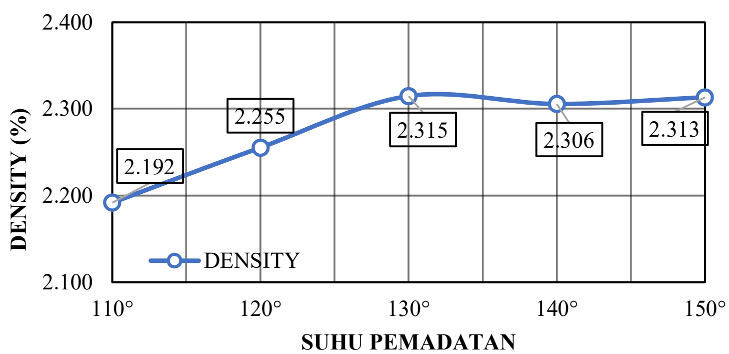

Figure 9. Density of compaction temperature

The minimum Marshall parameter value for VMA is 15%, while the maximum limit is not specified. Thus, the compaction temperature variations of 110°, 120°, 130°, 140°, and 150° meet the requirements in the 2018 Revised General Specifications for Road Construction. This is shown in Figure 10.

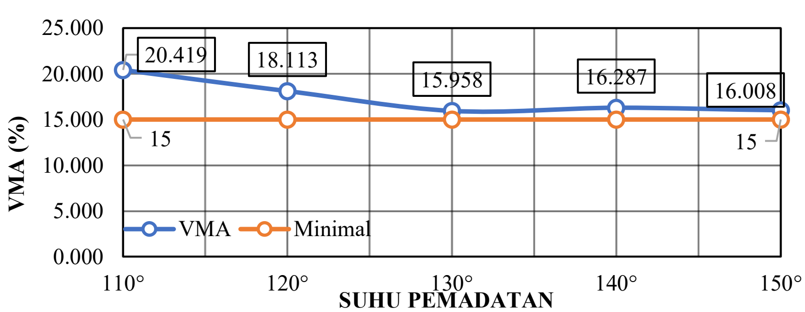

Figure 10. VMA of compaction temperature

The minimum value for VIM is 3% and the maximum is 5%. Test specimens that meet the 2018 Revision 2 General Specifications for Road Construction are those at compaction temperatures of 130°, 140°, and 150°, while those at compaction temperatures of 110° and 120° do not meet the specifications, as shown in Figure 11 below.

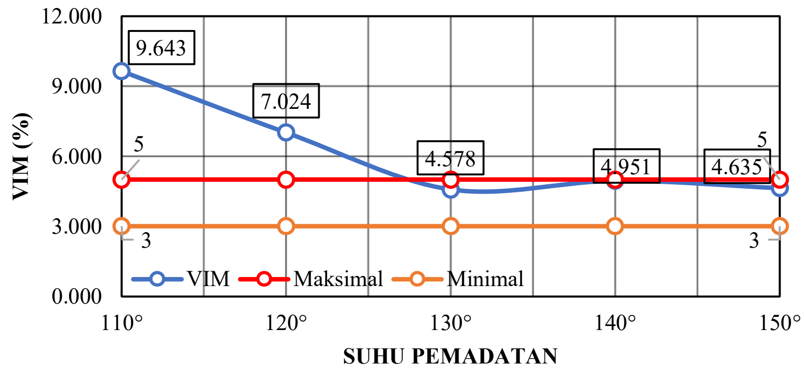

Figure 11. VIM of compaction temperature

The minimum VFA value is 65% and there is no limit value. The compaction temperature variations that meet the requirements are 130°, 140°, and 150°, while the compaction temperatures of 110° and 120° do not meet the requirements because the values obtained in these variations do not meet the specifications as shown in Figure 12.

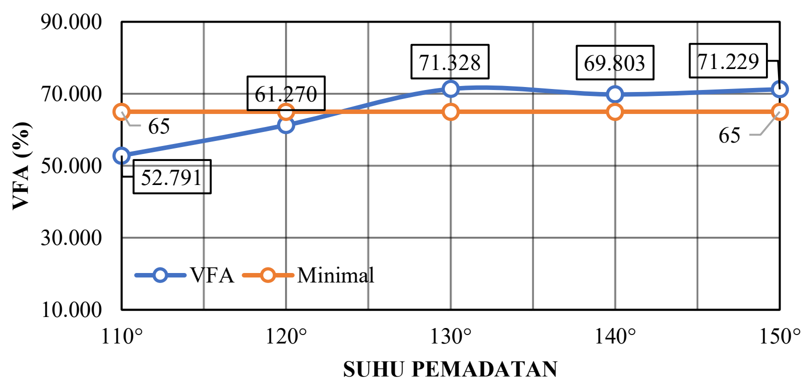

Figure 12. VFA of compaction temperature

Stability has a minimum value of 800 kg and no maximum value. The stability values for variations of 110°, 120°, 130°, 140°, and 150° meet the 2018 Revised General Specifications for Highways, as shown in Figure 13 below:

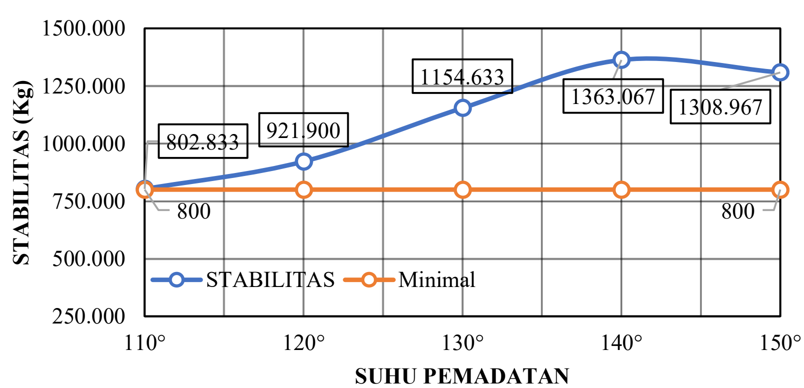

Figure 13. Stability of compaction temperature

The minimum flow value is 2 mm and the maximum is 4 mm. The optimum asphalt content variations that meet the specifications are 110°, 120°, 130°, 140°, and 150°, as shown in Figure 14.

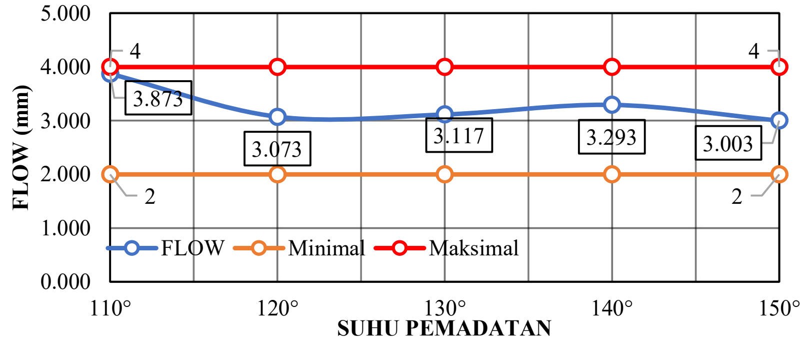

Figure 14. Flow of compaction temperature

The Marshall Quotient has a minimum value of 250 g but no maximum value. In the test specimen variation, the 110° asphalt content did not meet the specifications, as can be seen in Figure 15.

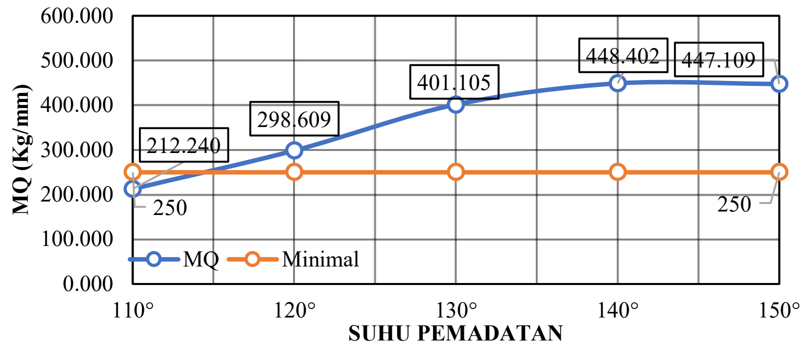

Figure 14. MQ of compaction temperature

Parameters of AC-WC asphalt mixture with graphene

After obtaining the optimum asphalt content of 5.75%, AC-WC asphalt testing was carried out with graphene variations of 0.01%, 0.02%, 0.03%, 0.04%, and 0.05%. The results of the Marshall parameter testing can be seen in Table 4 below.

Table 13. Results of testing AC-WC asphalt with graphene.

No	Characteristics Marshall	Compaction Temperature				
		0,01%	**0,02%**	**0,03%**	**0,04%**	**0,05%**
1	*Density* (gr/cm^3)	2,34	2,34	2,33	2,33	2,33
2	VMA (%)	15,13	15,18	15,28	15,29	15,43
3	VIM (%)	3,64	3,69	3,80	3,82	3,97
4	VFA (%)	76,12	76,08	75,12	75,20	74,25
5	Stability (kg)	1711,37	1611,93	1563,17	1370,03	1281,13
6	*Flow* (mm)	2,64	3,61	3,30	3,71	3,77
7	MQ (kg/mm)	659,75	636,78	483,20	385,48	341,93

4. Conclusion

Based on research into the effect of adding graphene and varying the compaction temperature on the Marshall characteristics of AC-WC asphalt mixtures, it was found that adding graphene at a concentration of 0.01%-0.05% met all Marshall parameters in accordance with the 2018 Revised General Specifications, with a 0.01% variation increasing stability by 9.38%. Density, VMA, VIM, and flow decreased, while VFA and MQ increased, indicating that graphene effectively enhances the asphalt's ability to withstand loads without deformation, prevents porosity, and ensures proper adhesion of asphalt to aggregates. Additionally, the optimal compaction temperature is at 130°C, 140°C, and 150°C, with the highest stability of 1,363.07 kg at 140°C, an increase of 19.55% from the minimum limit of 800 kg, while low temperatures of 110°C and 120°C cause VIM to exceed the limit, allowing water to enter through voids, and VFA to drop below the minimum limit, thereby reducing the mixture's resistance to damage.

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6. References

[1] D. Lagaligo, L. B. Said, and A. Alifuddin, “Pengaruh Temperatur Pemadatan pada Campuran Beton Aspal (AC-WC) dengan Bahan Tambah Karet Alam terhadap Ketahanan Deformasi dan Kuat Tarik Tidak Langsung,” *Jurnal Konstruksi: Teknik, Infrastruktur dan Sains*, vol. 1, no. 11, pp. 23–36, 2022.

[2] Y. Pane and D. S. Pasca, “Analisa Semen Portand Dan Abu Batu Sebagai Filler Dengan Marshall Dan Durabilitas Aspal Hotmix (AC–WC),” *SKYLANDSEA PROFESIONAL Jurnal Ekonomi, Bisnis dan Teknologi*, vol. 1, no. 2, pp. 86–95, 2021.

[3] V. Dotulung, L. G. Lalamentik, and S. C. N. Palenewen, “Analisis Variasi Gradasi Agregat Gabungan Terhadap Karakteristik Campuran Aspal Panas Pada Lapis Aspal Beton (AC-WC),” *TEKNO*, vol. 21, no. 85, pp. 1153–1161, 2023.

[4] M. Mesias, “Analisa Pengaruh Penggunaan Filler pada Perkerasan Jalan (Ac-Wc) terhadap Nilai Marshall,” 2022, Accessed: Mar. 19, 2025. [Online]. Available: https://repositori.uma.ac.id/jspui/handle/123456789/19844

[5] S. Sukirman, “Beton Aspal Campuran Panas. kedua,” *Bandung: Institut Teknologi Nasional*, 2016.

[6] B. Marga, “Spesifikasi umum 2018,” *Direktorat Jendral Bina Marga*, vol. 2010, pp. 1–6, 2010.

[7] S. Annura, H. Hamzani, E. Maulani, and B. Burhanuddin, “Pengaruh Penambahan Graphene Sebagai Bahan Tambah Aspal Terhadap Kinerja Campuran Ac-Wc,” *Sisfo: Jurnal Ilmiah Sistem Informasi*, vol. 8, no. 1, pp. 161–181, 2024.

[8] R. Wijaya, G. Andersan, S. Permatasari Santoso, and W. Irawaty, “Green reduction of graphene oxide using kaffir lime peel extract (Citrus hystrix) and its application as adsorbent for methylene blue,” *Scientific reports*, vol. 10, no. 1, p. 667, 2020.

[9] F. A. Shilar, S. V. Ganachari, V. B. Patil, T. M. Y. Khan, N. M. Almakayeel, and S. Alghamdi, “Review on the Relationship between Nano Modifications of Geopolymer Concrete and Their Structural Characteristics,” *Polymers*, vol. 14, no. 7, Art. no. 7, Jan. 2022, doi: 10.3390/polym14071421.

[10] M. Apriansyah, A. G. Wangsa, M. Ukkasya, F. Fadlun, and N. Anisah, “STUDY LITERATUR: GRAPHENE, NANO TEKNOLOGI SEBAGAI MATERIAL KONSTRUKSI MASA DEPAN,” *Bearing: Jurnal Penelitian dan Kajian Teknik Sipil*, vol. 9, no. 1, pp. 1–9, 2024.

[11] Y. Li, S. Wu, and S. Amirkhanian, “Effects of graphene oxide on asphalt binders,” in *Nanotechnology in Eco-Efficient Construction*, Elsevier, 2019, pp. 203–226. Accessed: Mar. 26, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780081026410000104

[12] X. Zhang, J.-X. He, G. Huang, C. Zhou, M.-M. Feng, and Y. Li, “Preparation and characteristics of ethylene bis (stearamide)-based graphene-modified asphalt,” *Materials*, vol. 12, no. 5, p. 757, 2019.

[13] W. S. B. Dwandaru, R. I. W. Wijaya, and L. D. Parwati, “Nanomaterial Graphene Oxide Sintesis dan Karakterisasinya.” UNY Press, 2019.

[14] Y. Maulana, S. Sukirman, and R. Zurni, “Studi Kadar Aspal Optimum Menggunakan Alat Marshall dan Alat Percentage Refusal Density,” *RekaRacana: Jurnal Teknil Sipil*, vol. 2, no. 1, p. 26, 2016.

[15] A. Susilowati and E. Wiyono, “VARIASI SUHU PEMADATAN PADA CAMPURAN BETON ASPAL MENGGUNAKAN BAHAN TAMBAH ANTI STRIPPING,” *cmj*, vol. 1, no. 1, pp. 12–20, Mar. 2019, doi: 10.32722/cmj.v1i1.1324.
[16] “SNI ASTM C136-2012 Metode Uji untuk Analisis Saringan Agregat Halus dan Agregat Kasar.”
[17] “SNI 03-4804-1998 Metode Pengujian Berat Isi dan Rongga Udara Dalam Agregat.”
[18] “SNI 1969-2016 Metode Uji Berat Jenis dan Penyerapan Air Agregat Kasar.”
[19] “SNI 1970-2016 Metode Uji Berat Jenis dan Penyerapan Air Agregat Halus.”