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Utilization of Waste Glass Material in Asphalt Concrete-Wearing Course (Acwc) as a Substitute for Fine Aggregate

Muhammad Taufik Habibillah Ibnu Ahmad* , Helyanto, Sarpawi, Robert
Politeknik Negeri Pontianak, Indonesia
Email: taufikdeware@gmail.com*

ABSTRACT

Sustainable development encourages the use of waste as an alternative material in infrastructure, including on road pavement. This study evaluated the performance of Laston Coated Wear (AC-WC) asphalt mixture with the substitution of glass waste as fine aggregates in variations in 0%, 10%, 20%, and 30% levels. Material characteristics testing as well as Marshall tests and residual stability were carried out referring to the General Specification of Highways Division 6 of 2018 Revision 2. The results show that the glass waste meets the technical specifications as a fine aggregate. Blends with 10% glass content produce the highest Marshall stability value of 93.4% and the best overall performance. The Optimum Asphalt (KAO) content has increased as the glass content has increased, but it remains below the normal mix KAO. Mixing with glass also shows good water resistance. Therefore, a 10% glass waste substitution is recommended as an alternative to fine aggregates in AC-WC mixtures to support environmentally friendly road infrastructure.

Keywords: *waste glass, laston, wear coating, fine aggregate, Marshall, AC-WC.*

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INTRODUCTION

Awareness of the importance of sustainable development encourages the use of waste as an alternative material in the construction industry, including for road pavement. One of the important layers in the road structure is the asphalt concrete wear layer (Laston), which is designed to withstand traffic loads and ensure driving comfort. In its composition, fine aggregates play an important role in determining the strength and stability of the mixture. Therefore, replacing fine aggregates with waste materials such as glass is a potential innovative solution. Glass waste contains high silica and has hard, sharp physical properties, which have the potential to strengthen the bonds between particles in asphalt mixtures (Ali et al., 2020; Cheng et al., 2021; Hussain et al., 2019; Mohajerani et al., 2017; Qiao et al., 2022; Yildirim et al., 2023).

The use of glass waste as a fine aggregate in Laston mixtures still results in Marshall stability values and indirect tensile strength that are acceptable, though slightly lower than conventional mixtures. In addition, the resistance to moisture still meets technical specifications. The use of glass waste fillers up to 75% of the total weight of the filler can improve the stiffness and durability of the mixture. The mixture also has smaller cavities and stronger bonds between particles, resulting in a thicker, more durable asphalt layer (Arulrajah et al., 2020; Choudhary et al., 2018; Hassan et al., 2022; Nguyen et al., 2023; Singh & Jain, 2021; Tang et al., 2019). Other research by Anochie-Boateng and George showed that the use of crushed glass in place of fine aggregates in asphalt mixtures can produce performance comparable to conventional mixtures. This mixture meets volumetric design standards and exhibits good tensile strength and moisture resistance, provided that the size of the glass particles is kept fine (Akinyemi et al., 2021; Gao et al., 2022; Karmakar et al., 2023; Osei-Asibey et al., 2019; Zhang et al., 2020; Zhao et al., 2018).

The use of glass waste as an additive in asphalt mixtures has become a focus in the field of sustainable construction. Glass waste, with its high silica content and sharp particle shape, is considered capable of replacing part of the fine aggregates or fillers in the *Laston* mixture. A study by Abu Salem et al. showed that the addition of up to 10% glass to the asphalt mixture provides good stability results, as well as water resistance that still meets specifications (Chen F., 2012; Ogundipe E. S., 2020; Putra Salmi; Mayalita Fikka, 2015). Ogundipe and Nnochiri also reported that the addition of glass waste as a filler of up to 18% was able to improve Marshall stability, although flow values tended to increase. Meanwhile, Ramadani explained that the chemical characteristics of glass waste, especially silica content (SiO_2) above 70%, allow its use as a technical material, including in the modification of asphalt mixtures .

Furthermore, research by Setiawan et al. revealed that the use of glass fillers in *HRS* and *SMA* mixtures can increase stability values and Marshall Quotient, although workability decreases as glass content increases. Chen et al. added that crushed glass used in asphalt mixtures can also increase the light reflection of road surfaces and has the potential for thermal efficiency, although particle size must be controlled so as not to interfere with adhesion. Zhu et al. emphasized the interlocking effect between particles of fine glass waste, which contributes to the increase in the mechanical strength of the mixture. In addition, Putra et al. note that the strong and non-degradable physical properties of glass make it a promising alternative for engineering materials in pavement mixtures. Considering these various positive results, this study aims to evaluate the performance of the wear-layer *Laston* by using glass waste as a substitute for fine aggregates, as a real contribution toward realizing environmentally friendly and resource-efficient road construction.

METHOD

This study was conducted to analyze the extent of the effect of using glass waste as a substitution for fine aggregates in the *Laston* wear layer mixture, viewed from both its characteristics and performance aspects. The samples used in this study were varied based on the percentage of glass waste: 0%, 10%, 20%, and 30%. The glass waste used came from discarded glass bottles (garbage), while other materials, in the form of natural aggregates and 60/70 pen-type asphalt from Pertamina, were obtained from PT. TMPI in the Cagak area, Subang, West Java. Testing the properties of glass as a material for asphalt mixtures refers to the standard guidelines of the Highway Specification Division 6 of 2018 Revision 2 . Broadly speaking, research on *Laston* wear layer mixtures that use glass waste in place of fine aggregates includes Marshall characteristic testing and residual stability testing.

Material testing was carried out to understand the properties of the constituent materials in the asphalt mixture, including the combination of aggregate and asphalt, by referring to the guidelines of the Highway Specification Division 6 of 2018 Revision 2 . Testing of properties and characteristics in this study was performed using the Marshall method. The evaluation of the characteristics of the asphalt mixture includes parameters such as density, stability (kg), flow, VMA (%), VIM (%), VFB (%), Marshall residual stability (%), and Optimum Asphalt Content (*KAO*). Data from each test specimen were analyzed and compared to determine the effect of variations in the percentage of glass waste, at predetermined levels, as a substitution for fine aggregates in the *Laston* wear layer mixture. Through the analysis results, the glass waste percentage with the most optimal performance—resulting in the highest parameter values—will be determined and recommended as the optimal glass waste content for use in wear-layer asphalt mixtures.

RESULT AND DISCUSSION

The test results on the characteristics parameters of glass waste materials, normal material characteristics, 60/70 pen asphalt characteristics and the results of the marshall characteristics of normal wear layer paved mixture and wear layer laston asphalt mixture with glass waste as a substitute for fine aggregates with variations of 10%, 20%, and 30%.

Results of the Gross Aggregate properties test

Rough aggregate testing aims to be able to determine the properties and properties (characteristics) of aggregates in asphalted mixtures. The results of the coarse aggregate test in this study refer to the requirements and standards stated in the General Specification of Bina Marga Division 6 2018 Revision 2 [10]. The testing of the characteristics of the coarse aggregate that has been carried out includes:

1. Specific Gravity and Absorption of Crude Aggregates;
2. Angularity of coarse aggregate;
3. Flat Particles Oval Rough Aggregate;
4. Abrasion with Los Angeles Tools (500 rounds);
5. Testing of Rough Aggregate Passes Sieve No. 200;
6. Adhesion to asphalt;
7. Aggregate Permanence (Soundness) (Magnesium Sulfate).
8. Clay Clumps

The recapitulation of the results of the gross aggregate properties test that has been carried out is as stated in Table 1 as follows.

Table 1. Results of coarse aggregate properties test

Yes	Testing	Specifications	Result	Information
1.	Specific Gravity	Min 2,5	2,67	**FULFILLED**
2.	Absorption	Max 3%	1,10%	**FULFILLED**
3.	Angularities	Min :95% (CA) 90% (MA)	100%	**FULFILLED**
4.	Flat Elongated Particles	Max 10%	5,35%	**FULFILLED**
5.	Abrasion (500 rounds)	Max 30%	16,7%	**FULFILLED**
6.	Pass Filter No. 200	Max 1%	0,08%	**FULFILLED**
7.	Adhesion To Asphalt	Min 95%	98%	**FULFILLED**
8.	Aggregate Retention (Sound-ness) (Magnesium Sulfate)	Max 18%	8%	**FULFILLED**
9.	Clay Lumps	Max 1%	0,3	**FULFILLED**

Fine Aggregate Properties Test Results

The fine aggregate material to be used in this study comes from TMPI Company with a location in the Cagak quarry, Subang, West Java. The fine aggregate testing carried out aims to be the same as the purpose of coarse aggregate testing, which is to determine the properties and properties (characteristics) of the fine aggregate to be used in the paved mixture. The results of the fine aggregate test in this study refer to the requirements of the 2018 Revised 2018 General Specification of Highways Division 6 Revision 2 [10]. The testing of the characteristics of fine aggregates that has been carried out includes:

1. Specific gravity and fine aggregate absorption;
2. Fine aggregate testing passed sieve No. 200;
3. Sand Equivalent Testing;

The following is a recapitulation of the results of the fine aggregate properties test that has been carried out as stated in Table 2 as follows.

Table 2. Results of fine aggregate properties testing

Yes	Testing	Specifications	Result	Information
1.	Specific Gravity	Min 2.5	2,71	**FULFILLED**
2.	Absorption	Max 3%	2,1%	**FULFILLED**
3.	Pass Filter No. 200	Max 10%	6,127%	**FULFILLED**
4.	Sand Equivalent	Min 50%	85%	**FULFILLED**

Pertamina's Pen 60/70 Asphalt Material Test Results

Pertamina's Asphalt Pen 60-70 material that will be used in the worn-coated asphalt mixture (AC-WC) in this study is first tested to determine the properties and characteristics of asphalt. The characteristics of Pertamina's Asphalt Pen 60/70 that have been tested are as follows:

- Penetration of Asphalt at 25oC for 1-2 Hours;
- Viscosite Kinematics 135oC (cST);
- Specific Gravity of Asphalt;
- Ductility at 25oC;
- Asphalt Soft Spots;
- Asphalt Flash Point;
- Loss of Asphalt Weight;
- Solubility of Asphalt in Trichloroethylene;
- Up to paraffin candle;
- TFOT Asphalt Penetration at 25oC(%original);
- TFOT ductility at 25oC;

The results of the asphalt test must meet the requirements as stated in the General Specification of Bina Marga Division 6 2018 Revision 2 [10]. The following are the test results of Pertamina's Asphalt Pen 60/70 as stated in Table 3 as follows:

Table 3. Pertamina Asphalt Pen 60/70 Test Results

Yes	Testing	Specifications	Result	Information
1.	Penetration at 25oC for 1-2 Hours	60 – 70	61	**FULFILLED**
2.	Viscosite Kinematics 135oC (cST)	$\geq$ 300	382,5	**FULFILLED**
3.	Specific Gravity	$\geq$1,0	1,037	**FULFILLED**
4.	Ductility at 25oC	$\geq$ 100 cm	140 cm	**FULFILLED**
5.	Soft Spots	$\geq$ 48oC	49,6 ^{oC}	**FULFILLED**

Yes	Testing	Specifications	Result	Information
6.	Flash Point	≥ 232 °C	340 oC	**FULFILLED**
7.	Weight Loss	≤ 0,8 %	0,048 %	**FULFILLED**
8.	Deep Asphalt Solubility *Trichloroethylene*	≥ 99%	99,35 %	**FULFILLED**
9.	Up Paraffin Lilin	≤ 2 %	0,088 %	**FULFILLED**
10.	TFOT penetration at 25oC (%original)	≥ 54%	70,5%	**FULFILLED**
11.	TFOT ductility at 25oC	≥ 50 cm	140 cm	**FULFILLED**

Glass Property Test Results for Paved Mixtures

Glass property testing for paved mixtures using the Highway Division 6 2018 Revised 2 (Marga, 2020). The glass property testing carried out is as follows:
Specific Gravity and Glass Absorption Testing
Glass Material Abrasion Testing
Sieve Analysis Testing
Adhesion Testing To Paved Mixtures
Glass Clay Lump Testing

Table 4. Glass properties test results

Yes	Testing	Specifications	Result	Information
1.	Specific Gravity	Min 2.5	2,52	**FULFILLED**
2.	Absorption	Max 3%	1,184%	**FULFILLED**
3.	Abrasion (500 rounds)	Max 40%	24,2%	**FULFILLED**
4.	Adhesion To Asphalt	Min 95%	96%	**FULFILLED**
5.	Clay Lumps	Max 1%	0,3%	**FULFILLED**

Asphalt Grade Test Results

The planned asphalt content to be used in this study is determined by analyzing the gradation of the combined aggregate in the asphalted mixture. Gradation on the asphalt mixture aggregate was obtained by conducting Sieve Analysis testing, namely by conducting sifting referring to the requirements of the 2018 Revised 2018 Highway Specification Division 6 Revision 2 [10]. The percentage of aggregate pass weight produced is then adjusted to the lower limit and the upper limit of the mixed aggregate gradation provision based on the specifications used. Requirements and results of sieve analysis for the determination of combined aggregate gradation used in AC-WC paved mixtures as shown in Table 5 below.

Table 5. Gradation of paved mixed aggregates

Combined Gradation AC-WC paved mixture				
Strainer Size		**%Weight Escape**		
Inch	**mm**	**Lower Limit**	**Upper Limit**	**Result Sieve Analysis**
3/4"	19	100	100	100
1/2"	12,5	90	100	92
3/8"	9,5	77	90	84
N0. 4	4,75	53	69	56
N0. 8	2,36	33	53	40
No. 16	1,18	21	40	27
No. 30	0,6	14	30	17
No. 50	0,3	9	22	11
No. 100	0,15	6	15	7
No.200	0,075	4	9	5

Based on the results of the Filter Analysis above, the aggregate gradation that will be used in the asphalt mixture in this study has met the Highway Specification Division 6 2018 Revision 2 (Marga, 2020). The combined gradation is illustrated in the graph in **Figure 1** below:

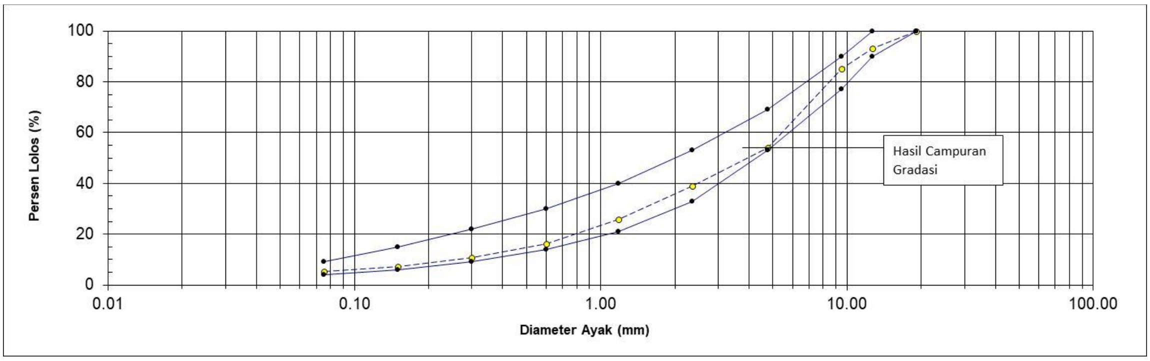

Figure 1. Aggregate combined gradation

The results of the aggregate combined gradation are then calculated to determine the asphalt content of the asphalt mix plan. The calculation of the planned asphalt content is carried out based on **Equation 1**. The following are the steps and results of calculating the asphalt level of the plan:

Pb = 0,035 (%CA) + 0,045 (%FA)+0,18(%FF) + K

Dimana:

- % Aggregate retained sieve number 2.36 mm (CA) = 46%
- % Aggregates that pass the sieve number 2.36 mm (FA) = 50%
- % Aggregates that pass the sieve number no.200 (FF) = 4%
- K = 0,5

Pb = 0,035 (46%) + 0.045 (50%) + 0.18(4%) + 0,5

= 5,5458 % rounding into 5,5%

Based on the results of the calculation above, the planned asphalt content for the normal asphalted mixture of AC-WC is taken at 5.5%. The results of the asphalt level testing are planned to produce the composition of the asphalted mixture to be used. The paved mixture is mostly composed of CA (Coarse Aggregate), FA (Fine Aggregate), and Filler (Filler). The composition of the asphalted mixture is CA: 46%, FA: 50%, and Filler: 4% respectively to the weight of the asphalted mixture. Based on the composition, the following is the aggregate level that will be used in each test that will be carried out in this study.

Normal AC-WC Paved Mix

The first mixture to be tested in this study is a Normal AC-WC paved mixture with aggregate composition as in general (conventional) or referring to the Bina Marga standard, 2018 Revision 2 [10] which consists of Coarse Aggregate, Fine Aggregate, and Filler where the content in each material uses the results of the planned asphalt content test that has been calculated and analyzed previously. The following is the composition of the Normal AC-WC paved mixture as stated in Table 6 below.

Table 6. Composition of Normal AC-WC Paved Mixture

Planned Asphalt Content	**4.50%**	**5.00%**	**5.50%**	**6.00%**	**6.50%**
	marshall	marshall	marshall	marshall	marshall
Total Mix	1150	1150	1150	1150	1150
Asphalt Weight	51.75	57.50	63.25	69.00	74.75
Aggregate Weight	**1098.25**	**1092.5**	**1086.75**	**1081**	**1075.25**
Inch					
1	0.0	0.0	0.0	0.0	0.0
3/4	0.0	0.0	0.0	0.0	0.0
1/2	76.7	76.3	75.9	75.5	75.1
3/8	86.1	85.6	85.2	84.7	84.3
No. 4	341.7	339.9	338.2	336.4	334.6
No. 8	170.5	169.6	168.7	167.8	166.9
No. 16	150,3	149,5	148,7	148,0	147,2
No. 30	170.1	106.6	106.0	105.5	104.9
No. 50	61,6	61,3	61,0	60,6	60,3
No. 100	35,8	35,6	35,4	35,3	35,1
No. 200	21,6	21,5	21,4	21,3	21,2
Pan	46.7	46.5	46.2	46.0	45.8
Total	**1098.25**	**1092.5**	**1086.75**	**1081.0**	**1075.25**

AC-WC Paved Mixture with Glass Substitution as Fine Aggregate

The second mixture, namely AC-WC paved mixture with glass substitution as Fine Aggregate, is carried out by substituting AC-WC paved mixture with broken glass material as Fine Aggregate. The glass material used as a substitution for fine aggregate is retained in filter no.16 to filter no.200 (Bina Marga, 2018) (Marga, 2020). with the glass content used at 10%, 20%, and 30%. The following is the composition of AC-WC paved mixture with Glass substitution as Fine Aggregate as stated in Table 7 below.

Table 7. Composition of AC-WC Paved Mixture with 10% Glass Substitution as Fine Aggregate

Glass test case scales 10%					
Planned Asphalt Content	**4.50%**	**5.00%**	**5.50%**	**6.00%**	**6.50%**
	marshall	marshall	marshall	marshall	marshall
Total Mix	1150	1150	1150	1150	1150
Asphalt Weight	51.75	57.50	63.25	69.00	74.75
Aggregate Weight	**1098.25**	**1092.5**	**1086.75**	**1081**	**1075.25**
Inch	0	0	0	0	0
1	0.0	0.0	0.0	0.0	0.0
3/4	0.0	0.0	0.0	0.0	0.0
1/2	76.7	76.3	75.9	75.5	75.1
3/8	86.1	85.6	85.2	84.7	84.3
No. 4	341.7	339.9	338.2	336.4	334.6
No. 8	170.5	169.6	168.7	167.8	166.9

Glass test case scales 10%					
Planned Asphalt Content	**4.50%**	**5.00%**	**5.50%**	**6.00%**	**6.50%**
	marshall	marshall	marshall	marshall	marshall
No. 16	135.3	134.6	133.9	133.2	132.5
No. 30	96.4	95.9	95.4	94.9	94.4
No. 50	55.4	55.1	54.9	54.6	54.3
No. 100	32.2	32.1	31.9	31.7	31.6
No. 200	19.5	19.4	19.3	19.2	19.1
Pan	46.7	46.5	46.2	46.0	45.8
Total	**1060.60**	**1055.05**	**1049.49**	**1043.94**	**1038.39**
Kaca 10%					
Inch	0	0	0	0	0
1	0.0	0.0	0.0	0.0	0.0
3/4	0.0	0.0	0.0	0.0	0.0
1/2	0.0	0.0	0.0	0.0	0.0
3/8	0.0	0.0	0.0	0.0	0.0
No. 4	0.0	0.0	0.0	0.0	0.0
No. 8	0.0	0.0	0.0	0.0	0.0
No. 16	15.0	15.0	14.9	14.8	14.7
No. 30	10.7	10.7	10.6	10.5	10.6
No. 50	6.2	6.1	6.1	6.1	6.0
No. 100	3.6	3.6	3.5	3.5	3.5
No. 200	2.2	2.2	2.1	2.1	2.1
Pan	0.0	0.0	0.0	0.0	0.0
Total	**37.65**	**37.45**	**37.26**	**37.06**	**36.86**

GMM Test Results

The GMM test used in this study uses one test strip from the variation of each type of asphalt mixture. The results of the test will then be used as a reference for the maximum specific gravity value of the paved mixture for marshall testing. The following are the results of the maximum specific gravity test of GMM of asphalted mixtures for each variation of AC-WC asphalted mixture as shown in **Table 8-Table 9** below:

Table 8. GMM test results on Normal Asphalt Mixtures

Kadar Aspal (%)	Campuran Normal
5,5	2,471

Table 9. GMM test results on Glass Fine Aggregate Asphalt Mixtures

Kadar Aspal (%)	FA Kaca 10%	FA Kaca 20%	FA Kaca 30%
5,5	2,462	2,449	2,431

Marshall Test Results

The Marshall test aims to find out the characteristics of the AC-WC paved mixture. In this study, the marshall test was carried out by pounding or beating 2 x 75 times on each side (upper or lower side) of the asphalted mixed test piece with a compaction temperature of 149º C. The number of test pieces used was based on the variation in the level that had been determined. The compacted test piece is then left for a certain time until the temperature of the test piece reaches room temperature (25º C) which aims to stabilize the temperature of the test piece on the inside so that the mixture is also more stable when it is to be tested. The test was then continued by immersing the test specimen in a *waterbath* with a temperature of 60º C before being tested on the marshall test device.

The results of the Marshall test on the AC-WC mixture for each variation are presented in **Table 10** to **Table 11** below.

Table 10 Marshall test results of Normal AC-WC paved mix Marshall

Asphalt rate (%)	Density, (gr/cc)	VMA, (%)	VFB, (%)	VIM 2x75, (%)	Stability, (kg)	Fatigue, (mm)
4,5	2,273	18,61	49,86	8,05	875,9	1,97
5,0	2,300	18,07	58,09	6,44	924,1	2,10
5,5	2,314	18,02	64,81	5,45	995,8	2,23
6,0	2,310	18,61	68,66	4,13	982,6	2,50
6,5	2,311	18,98	73,26	2,59	872,3	2,50

Table 11. Marshall test results of AC-WC paved mixture with Glass Substitute on 10% Fine Aggregate

Up to asphalt (%)	Density, (gr/cc)	VMA, (%)	VFB, (%)	2x75 VIM, (%)	Stability, (kg)	Thickness, (mm)
4,5	2,352	15,510	62,184	5,865	739,003	2,133
5,0	2,350	15,998	67,355	5,223	773,291	2,333
5,5	2,343	16,683	71,197	4,805	816,710	2,400
6,0	2,335	17,423	74,405	4,459	846,548	2,567
6,5	2,334	17,885	78,780	3,797	891,427	2,767

Table 12. Marshall test results of AC-WC paved mixture with Glass Substitute Material on 20% Fine Aggregate

Up to asphalt (%)	Density, (gr/cc)	VMA, (%)	VFB, (%)	2x75 VIM, (%)	Stability, (kg)	Thickness, (mm)
4,5	2,292	17,368	64,375	6,191	743,393	2,800
5,0	2,285	18,056	67,792	5,818	741,851	2,867
5,5	2,306	17,739	75,862	4,284	815,284	3,033
6,0	2,292	18,647	77,634	4,171	843,641	3,300
6,5	2,299	18,830	82,979	3,208	871,283	3,400

Table 13. Marshall test results of AC-WC paved mixture with Glass Substitute on 30% Fine Aggregate

Asphalt rate (%)	Density, (gr/cc)	VMA, (%)	VFB, (%)	VIM 2x75, (%)	Stability, (kg)	Fatigue, (mm)
4,5	2,306	16,564	60,743	6,503	730,361	2,900
5,0	2,306	16,999	65,725	5,827	768,356	3,067
5,5	2,314	17,155	72,253	4,828	787,266	3,267
6,0	2,304	17,952	74,700	4,569	835,682	3,467
6,5	2,311	18,138	80,189	3,599	843,324	3,633

PRD (Percentage Refusal Density) Test Results

Absolute Density testing is performed after Marshall testing is completed. The determination of asphalt content for absolute density test objects is based on the asphalt content derived from the results of the analysis of the value of each characteristic parameter of the asphalt mixture from the Marshall test and based on the Highway Specification Division 6 2018 Revision 2 (Marga, 2020). The absolute density test was carried out on each mixture variation contained in this study. The following test results are shown in **Table 14**.

Table 14. Absolute density test results of AC-WC paved mixtures for each material and variation

Variations of Paved Mixes AC-WC	Until Aspal (%)	VIMPRD (%)
Normal Mixed AC-WC	5,38	5,36
	5,88	4,11
	6,38	2,68
S.E. 10%; 90%	5,15	5,38
	5,65	4,69
	6,15	3,69
AC-WCC Glass 20%; 80%	5,20	5,68
	5,70	3,58
	6,20	2,57
AC-WC Glass 30%; 70%	5,25	5,83
	5,75	3,46
	6,25	2,01

The results of the analysis determine the Optimum Asphalt Level (KAO) above, the KAO results of each variation in each AC-WC asphalted mixture material are obtained as shown in **Table 15** below.

Table 15. KAO asphalted mix AC-WC

Variations of AC-WC Asphalt Mix	KAO (%)
Normal Mixed AC-WC	5,875
AC-WC FA Glass 10%	5,675
AC-WC FA Glass 20%	5,700
AC-WC FA Glass 30%	5,750

Based on the percentage of KAO in **Table 4.28** above, it is known that there is an increase in the value of KAO in the asphalted mixture of AC-WC with FA Glass which also increases as the level of glass used increases. However, the KAO value is lower than that of a normal AC-WC paved mixture.

Residual Stability Test Results (Immersion Test)

The *Immersion Test* conducted in the study aims to determine the percentage of stability of the AC-WC paved mixture after being immersed in a certain time (for 30 minutes and 24 hours). The test piece for the Residual Stability test uses a paved mixture with the Optimum Asphalt Content (KAO) result of previous tests. Testing is carried out on every variation of percentages and materials. The following are the results of the Residual Stability test on AC-WC paved mixtures as shown in **Table 16**.

Table 16. Residual Stability Test Results (*Immersion Test*)

Variations of AC-WC Asphalt Mix	Residual Stability Value (%)
Normal Mixed AC-WC	91,3
AC-WC FA Glass 10%	93,4
AC-WC FA Glass 20%	91.8
AC-WC FA Glass 30%	89,5

Comparative Analysis of Characteristics of Laston Asphalted Mixes Lapis Au

The comparative analysis of the characteristics was carried out to find out the effect of glass material substitutes on the characteristics of the AC-WC Normal paved mixture. The characteristic parameters of the asphalted mixture include; *Density*, Stability, Fatigue, VIMmarshall, VMA, and VFB. The following are the results of the analysis and comparison of the characteristics of each parameter and variable

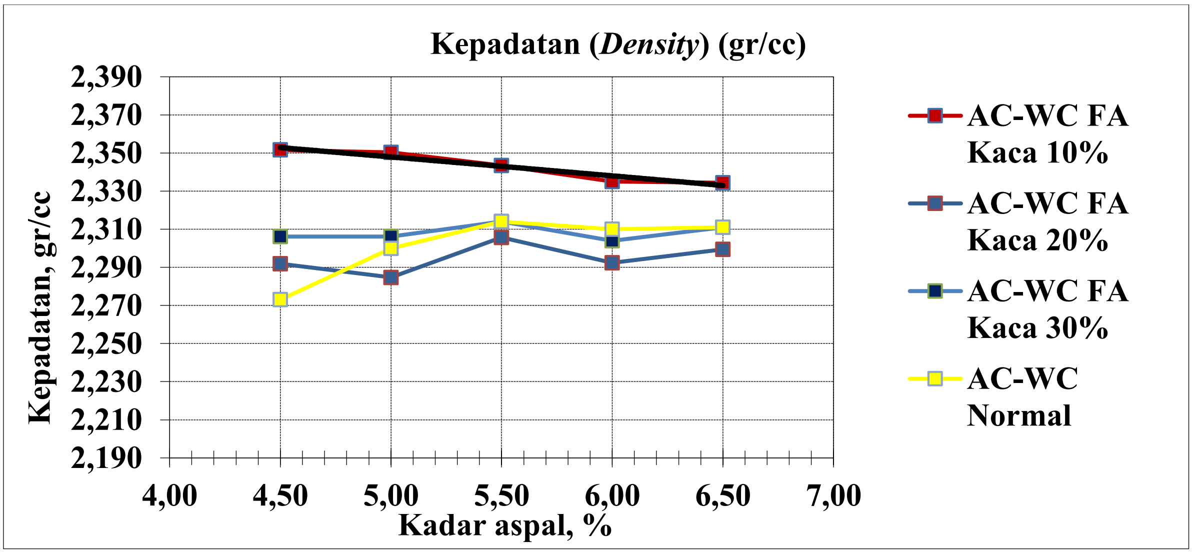

Figure 2. AC-WC Paved Mix Density Graph

The graph in **Figure 2** above shows that in the asphalted mixture of AC-WC with Glass Fine Aggregate Substitute Material 10% the density value decreases as the existing asphalt content increases, while in the variation of 20% and 30% of the content, the variable of the density value increases to 5.5% after which the density rate decreases again. Based on the explanation above, it is concluded that the increasing the content of glass used as a substitute material in fine aggregates, the stability value decreases, but it rises again at the level of 30% but not higher at the level of 10%. This shows that the influence of glass substitutes on the asphalted mixture makes the asphalted mixture denser, but as the glass content increases (10% and 20%) the density tends to decrease and rise again at 30% even though it is not higher than the 10% rate.

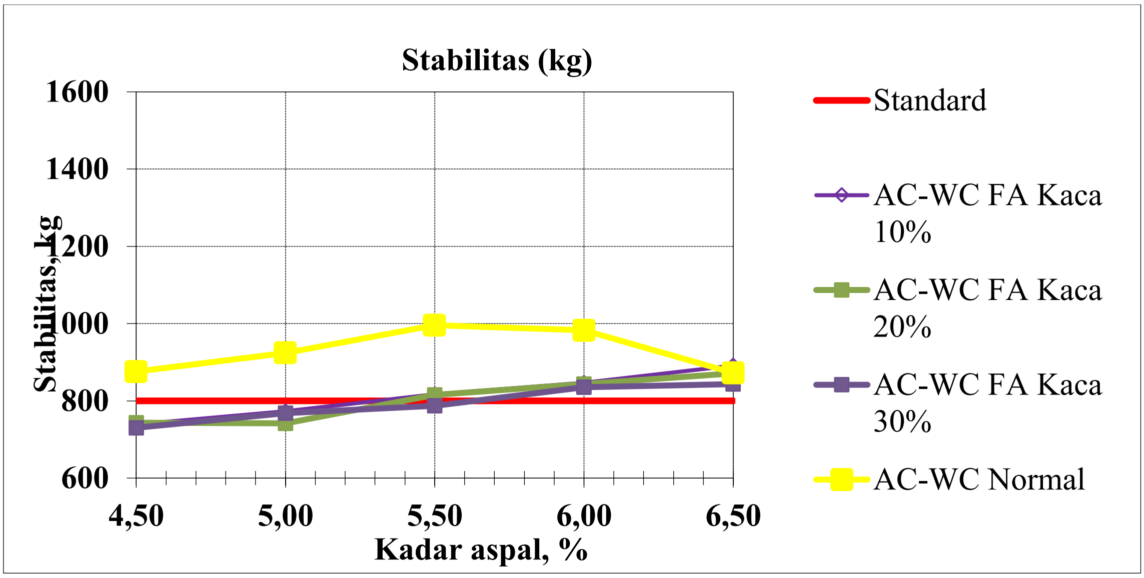

Figure 3. AC-WC4 Paved Mix Stability Graph

The graph shown in **Figure 3** above shows that the AC-WC paved mixture uses Glass Fine Aggregator Substitute Material, the stability value tends to increase along with the amount of glass and asphalt content.

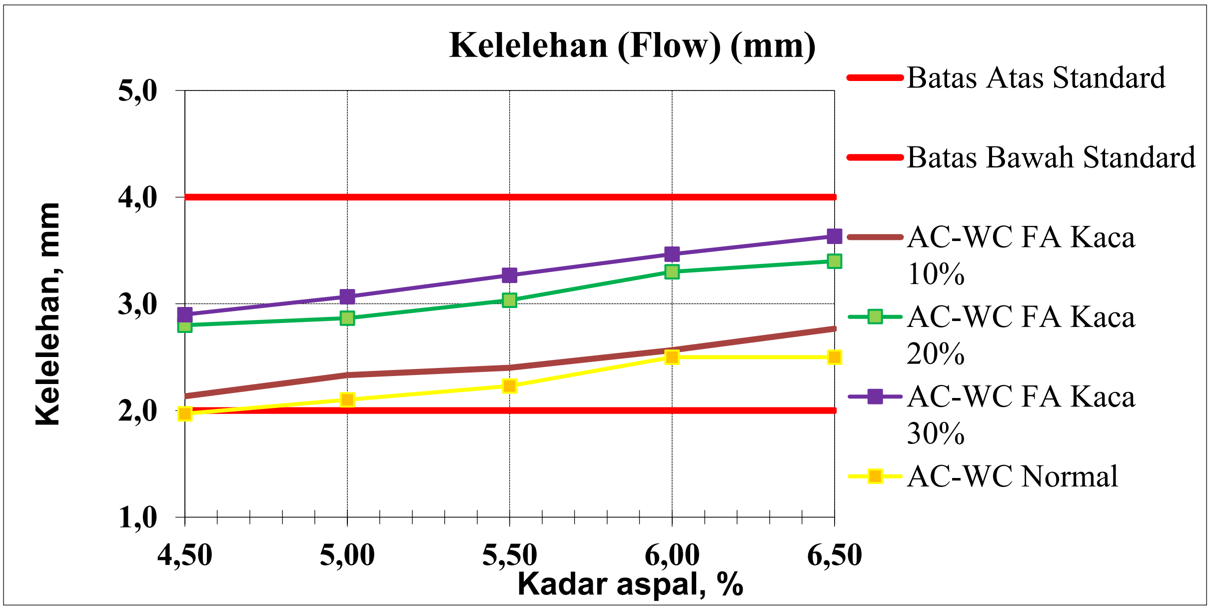

Figure 4. the fatigue rate in the asphalt mixture of AC-WC FA Glass

The graph in **Figure 4** shows that the fatigue rate in the asphalt mixture of AC-WC FA Glass has increased as the value of the glass used increases.

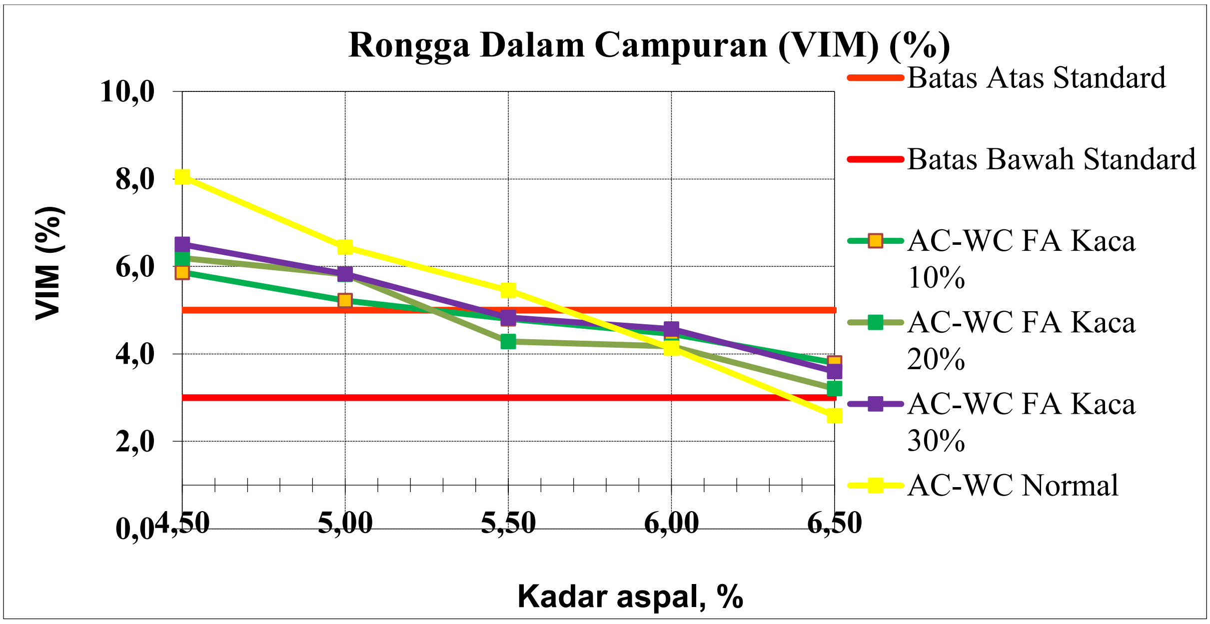

Figure 5. the asphalted mixture of AC-WC FA Glass value VIM

The graph shown in **Figure 5** shows that the asphalted mixture of AC-WC FA Glass value VIM has decreased as the asphalt used increases.

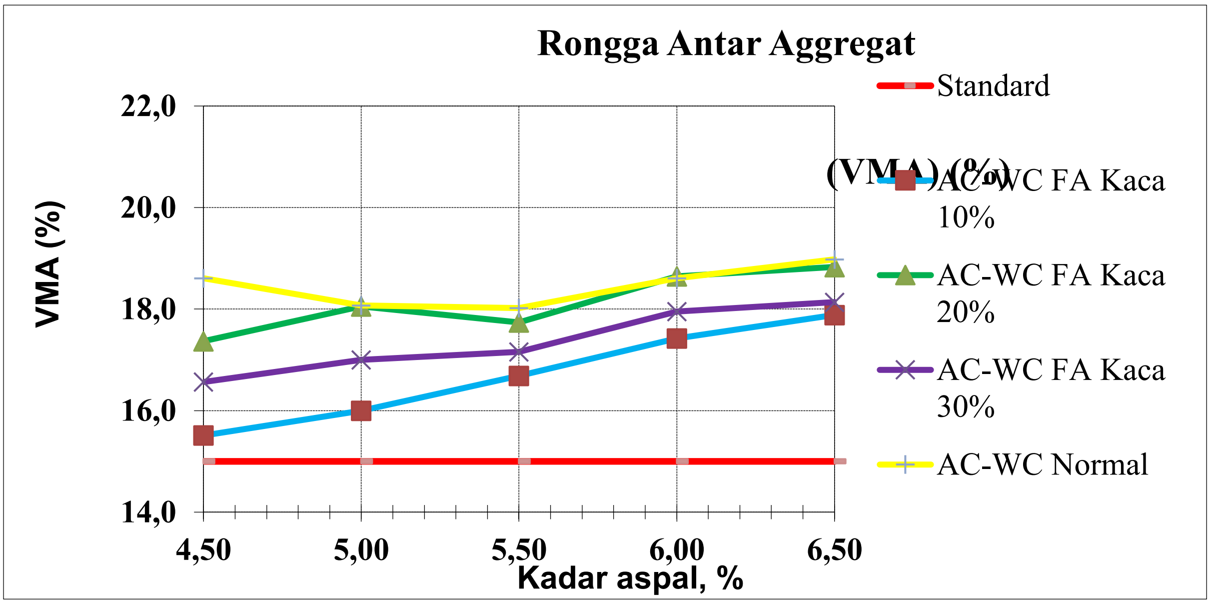

Figure 6. the asphalted mixture of AC-WC FA Glass inter-aggregate cavity value (VMA)

The graph in **Figure 6** shows that the asphalted mixture of AC-WC FA Glass inter-aggregate cavity value (VMA) has increased along with the increase in the glass content used.

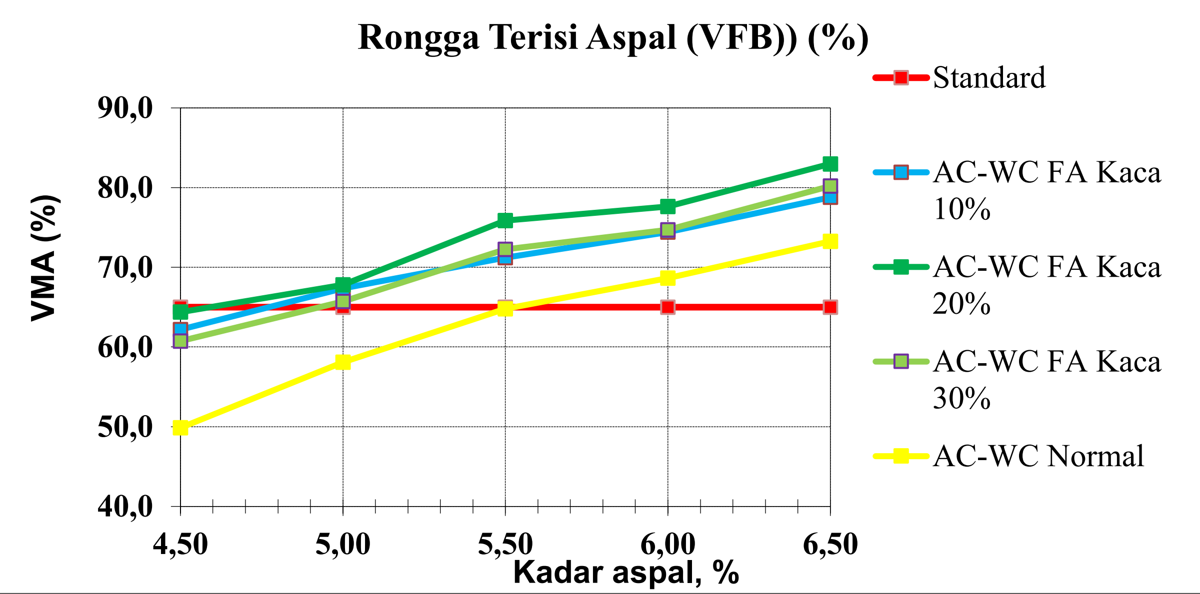

Figure 7. the asphalted mixture of AC-WC FA Glass

The graph in **Figure 7** shows that the asphalted mixture of AC-WC FA Glass has more or less the same condition, namely the value of the cavity filled with asphalt (VFB) increases along with the increase in the amount of glass used.

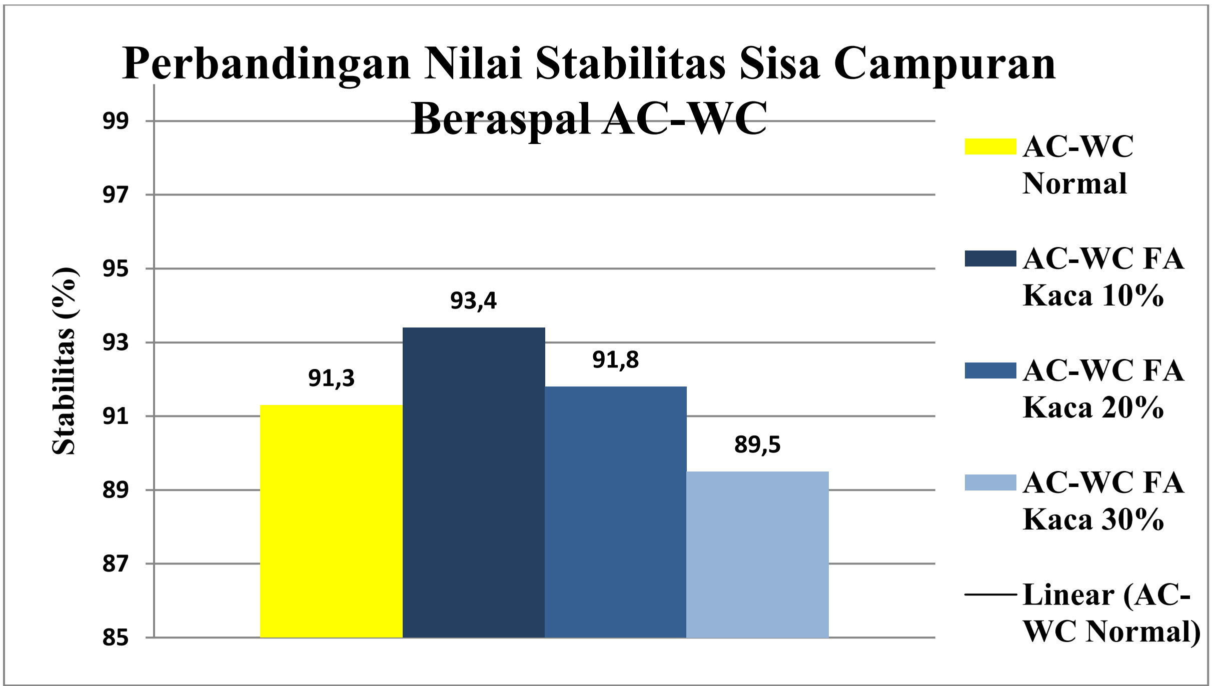

Figure 8. Comparison of Residual Stability Values of AC-WC Paved Mixture

The graph in **Figure 8** above shows that the use of glass substitutes in fine aggregates in AC-WC paved mixtures has decreased in tandem with the amount of glass used. Based on this, the recommended glass content as a substitute for fine aggregate is 10% with a stability value of 93.4%.

CONCLUSION

The study on using glass waste as a fine aggregate substitute in *AC-WC* asphalt mixtures yielded several key findings. First, the glass waste met all required technical specifications, including specific gravity, water absorption, adhesion, and abrasion resistance, complying with *Bina Marga* Division 6 (2018) standards. While substituting up to 30% glass waste maintained acceptable performance, the 10% substitution rate achieved the highest stability (93.4%), despite a general decline in stability and density compared to conventional mixtures. Additionally, the optimum asphalt content (*KAO*) increased with higher glass waste substitution but remained below normal mixture levels, indicating no need for excessive asphalt adjustments. The mixture also demonstrated strong water resistance, as evidenced by high residual stability in immersion tests. Overall, the 10% substitution rate was identified as the most optimal based on Marshall parameters and durability performance.

For future research, it is recommended to investigate the long-term durability and fatigue resistance of glass waste–modified asphalt under varying traffic loads and environmental conditions. Further studies could also explore the economic and environmental benefits of large-scale implementation, including cost analysis and carbon footprint reduction. Additionally, combining glass waste with other recycled materials (e.g., plastic or rubber) could optimize performance while addressing waste management challenges. Field trials would help validate laboratory findings and assess real-world applicability, particularly in regions with high glass waste generation. Lastly, exploring chemical treatments or additives to enhance glass–asphalt adhesion at higher substitution rates (beyond 10%) could expand its sustainable use in pavement construction.

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