

The Effect of Aggregate Sampling Distance on the Durability of Asphalt Concrete-Wearing Course (AC-WC) Mixtures

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Abstract : The utilization of aggregates from the Labuan River, Donggala Regency, Central Sulawesi, as pavement materials must be supported by research regarding the material characteristics and its capability to maintain asphalt mixture performance. The material sampling distance from the river mouth can exhibit differences in material characteristics at each sampling point due to transport, abrasion, and sedimentation processes, which potentially influence the durability of the Asphalt Concrete-Wearing Course (AC-WC) mixture. Testing was conducted using aggregates from 5 sampling points located at distances of 100 m, 200 m, 300 m, 400 m, and 500 m from the Labuan River mouth, combined with 60/70 penetration grade asphalt. Mixture characteristics were determined via Marshall testing, while durability was evaluated through immersion durations of 30 minutes, 24, 48, 72, and 96 hours based on the Retained Strength Index (IKS), First Durability Index (IDP), and Second Durability Index (IDK). The results indicated that the durability of the AC-WC mixture tends to decrease as immersion time increases, displaying varying rates of strength loss at each sampling point. The IKS value after 24 hours of immersion fell below the minimum requirement of 90%. Meanwhile, the cumulative IDP values from Point 1 to Point 5 were 1.78%, 1.41%, 1.04%, 0.94%, and 1.46%, respectively, demonstrating that strength loss occurred during immersion. The IDK values also indicated cumulative strength loss at varying rates for each sampling location. XRF results showed a relatively homogeneous aggregate chemical composition, dominated by SiO₂ at 58.422%–59.421%, which serves as supporting material characteristic data. Overall, variations in the aggregate sampling distance from the river mouth revealed relatively minor differences in the ability of the AC-WC mixture to retain its strength against water damage.

Keywords: AC-WC, Labuan River Aggregate, Durability, XRF

Date Of Submission: 10-10-2026

Date Of Acceptance: 22-10-2026

I. INTRODUCTION

Infrastructure development, particularly within the land transportation sector, continues to expand alongside population growth and economic activities across various regions in Indonesia. A vital component of this infrastructure development is the availability of construction materials, specifically sand and gravel aggregates used to produce concrete, asphalt, and road structures. The aggregate availability from the Labuan River has become a primary pillar supporting the construction industry in the Donggala region and its surroundings, including the Parigi Moutong Regency.

Aggregate characteristics constitute a critical factor governing the performance of asphalt concrete mixtures. Aggregate properties such as durability, gradation, and cleanliness heavily dictate the mixture quality and influence mixture characteristics, including stability and durability (Weimentoro et al., 2021). Durability is an essential characteristic of asphalt mixtures that reflects the mix's ability to retain its quality against environmental influences (Heriyana et al., 2024). Water from flooding or surface puddles can impair pavement performance, especially regarding its durability and longevity (Attamimi et al., 2021). Beyond conventional mechanical properties, understanding the geochemistry of local andesite rocks via X-Ray Fluorescence (XRF) testing is necessary to map dominant hydrophilic compounds like silica (SiO₂). The geochemical characteristics of rocks can be determined based on their chemical composition, including the concentration of oxides and elements present in the rock samples (Oggier et al., 2023). This experimental study aims to determine aggregate characteristics based on several spatial sampling points from the river mouth and evaluate their impact on the durability indices (IKS, IDP, and IDK) of AC-WC mixtures, in compliance with the 2025 General Specifications for Road and Bridge Works.

II. RESEARCH METHODOLOGY

A quantitative approach was adopted to process laboratory testing data to produce an objective and measurable analysis. Materials were sampled directly from the submerged riverbed of the Labuan River at 5 distinct sampling locations spaced at 100-meter intervals from the river mouth: Point 1 (100 m), Point 2 (200 m), Point 3 (300 m), Point 4 (400 m), and Point 5 (500 m). The binder used was 60/70 penetration asphalt. Physical property testing of the aggregates referred to the 2025 General Specifications for Road and Bridge Pavements and BSI standards, encompassing the Flakiness/Elongation Index, Los Angeles abrasion loss, specific gravity, and water absorption.

The AC-WC design mix was prepared using a range of trial asphalt contents: 4.5%, 5%, 5.5%, 6%, and 6.5%, applying mechanical compaction of 75 blows per side to simulate heavy traffic conditions. The Optimum Asphalt Content (KAO) for rocks from each location was determined using Marshall volumetric charts. Once the KAO values were established, specimens were remolded to be evaluated in a modified Marshall Immersion test at a constant water temperature of 60°C for planned immersion durations of 30 minutes, 24 hours, 48 hours, 72 hours, and 96 hours. The mechanical strength degradation of the mixture was converted into quantitative durability indicators based on the criteria by Craus, Ishai, and Sides (1981): Retained Strength Index (IKS), First Durability Index (IDP / rate of stability degradation), and Second Durability Index (IDK / average daily strength loss).

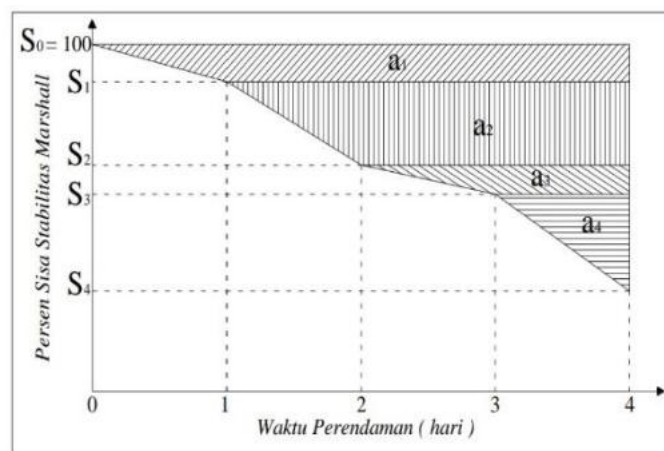


Figure 2.1 Durability Curve

According to Craus et al. (1981), the durability curve illustrates the relationship between the percentage of retained strength and immersion duration.

III. RESULTS AND DISCUSSION

3.1 Test Results of AC-WC Mixture Components

Aggregate testing was performed to verify the material's conformity with the 2025 General Specifications for Road and Bridge Construction Works as a component for AC-WC mixtures. Testing included the flakiness and elongation index, specific gravity, absorption, Los Angeles abrasion, and sieve analysis.

Table 3.1 Flakiness Index and Elongation Index Test Results

Test Type	Point 1	Point 2	Point 3	Point 4	Point 5	Standard Specification
Flakiness Ag. 3/4	7.26	8.15	7.22	8.48	9.68	Maks. 25 %
Elongation Ag. 3/8	6.93	7.06	7.08	7.50	8.18	Maks. 25 %
Flakiness Ag. 3/4	12.28	11.66	12.46	9.64	10.26	Maks. 25 %
Elongation Ag. 3/8	18.86	19.97	19.71	22.52	22.18	Maks. 25 %

Based on the test data in Table 3.1, all flakiness and elongation values for the 3/4" and 3/8" aggregates met the BSI specification standards as they remained below the 25% maximum limit. Aggregates with lower flakiness and elongation values tend to generate higher stability due to proportional particle shapes that establish interlocking strength

Tabel 3.2 Specific Gravity and Absorption Test Results of Coarse Aggregate

Test Type	Point 1	Point 2	Point 3	Point 4	Point 5	Standard Specification
Bulk Sp. Gr.	2,634	2,646	2,651	2,661	2,652	Maks. 3 %
SSD Sp. Gr.	2,670	2,679	2,688	2,682	2,677	Maks. 3 %
Apparent Sp. Gr.	2,733	2,736	2,753	2,718	2,719	Maks. 3 %
Absorption (%)	1,378	1,251	1,399	0,777	0,931	Maks. 3 %

Tabel 3.3 Specific Gravity and Absorption Test Results of Fine Aggregate

Test Type	Point 1	Point 2	Point 3	Point 4	Point 5	Standard Specification
Bulk Sp. Gr.	2,604	2,,627	2,606	2,595	2,607	Max. 3 %
SSD Sp. Gr.	2,645	2,663	2,659	2,652	2,659	Max. 3 %
Apparent Sp. Gr.	2,715	2,724	2,752	2,751	2,751	Max. 3 %
Absorption (%)	1,562	1,355	2,036	2,176	2,014	Max. 3 %

Based on the test data in Table 3.2 (coarse aggregate) and Table 3.3 (fine aggregate), all materials fully complied with the 2025 General Specifications. Water absorption values consistently stayed below the 3% maximum limit, ranging from 0.777% to 1.399% for coarse aggregate and 1.355% to 2.176% for fine aggregate.

Tabel 3.4 Aggregate Abrasion Test Results Using Los Angeles Machine

Test Type	Point 1	Point 2	Point 3	Point 4	Point 5	Standard Specification
Agg. Size 3/4	19,80	19,86	19,78	19,33	19,81	Max. 40 %
Agg. Size 3/8	21,2	21,24	20,89	21,02	21,19	Max. 40 %

According to the data in Table 3.4, the abrasion values for the 3/4" and 3/8" aggregates across all sampling points ranged between 19.33% and 21.24%, well below the 40% specification ceiling. This reveals that the aggregate possesses sound quality and high resistance to friction and traffic loading. The aggregate at all sampling distance variations satisfied the established specification criteria. Nonetheless, fluctuations in absorption and abrasion values at individual locations indicate that the aggregate sampling distance introduces an effect on the quality of the material used in the mix.

3.2 Asphalt Test Results

Tabel 3.5 Asphalt Test Results

Test Type	Result	2025 General Specification Requirements
Penetration (0,1 mm)	66,5	60/70
Softening Point (°C)	48,25	Min. 48
Ductility (cm)	128,25	Min. 100
Specific Gravity	1.078	Min. 1,0

Asphalt testing was executed to determine the properties of the penetration grade asphalt used as a binder in the AC-WC mixture. The parameters tested included penetration, softening point, ductility, and specific gravity. The results show that all asphalt parameters fell within the required specification boundaries. The penetration value matches the stiffness level required for flexible pavements, while the ductility value demonstrates the asphalt's capacity to deform without cracking. High-quality asphalt characteristics enhance the adhesion between aggregate and asphalt, thereby amplifying the stability and durability of the AC-WC mixture.

3.3 XRF (X-Ray Fluorescence) Test Results

Mineral content testing of the aggregates was carried out to identify the elemental or oxide composition making up the aggregate material at each sample collection location.

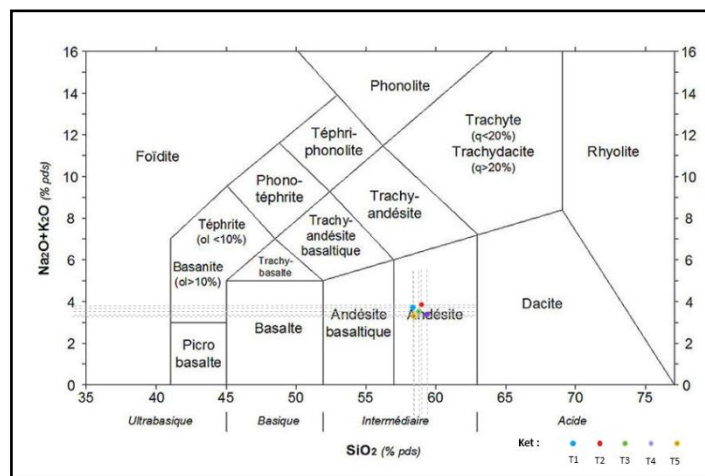
Tabel 3.6 XRF Test Results

Mineral Content	Point 1 (%)	Point 2 (%)	Point 3 (%)	Point 4 (%)	Point 5 (%)
SiO ₂	58,422	59,002	58,794	59,421	58,406
CaO	3,583	3,445	3,445	3,609	3,454
Al ₂ O ₃	18,262	17,488	18,343	18,220	18,427
Fe ₂ O ₃	7,570	7,599	7,652	7,428	7,704
MgO	7,209	7,025	6,880	6,671	7,306
Na ₂ O	1,808	1,970	1,693	1,574	1,522
K ₂ O	1,860	1,835	1,870	1,790	1,795

X-Ray Fluorescence (XRF) testing identified the chemical composition of the aggregate at five sampling locations along the Labuan River. In this study, the SiO₂ content was combined with Na₂O and K₂O concentrations utilizing the Total Alkali Silica (TAS) approach. The TAS diagram developed by Le Bas et al. (1986) is a chemical classification system for volcanic rocks that places SiO₂ on the horizontal axis and the sum of Na₂O + K₂O on the vertical axis. The calculated values for each sampling point are displayed below.

Table. 3.7 TAS Diagram Calculation Results

Sample	SiO ₂ (%)	Na ₂ O (%)	K ₂ O (%)	Na ₂ O + K ₂ O (%)
Point 1	58,422	1,808	1,860	3,668
Point 2	59,002	1,970	1,835	3,805
Point 3	58,794	1,693	1,870	3,563
Point 4	59,421	1,574	1,790	3,364
Point 5	58,406	1,522	1,795	3,317



(Figure 3.1 Total Alkali Silica (TAS) Diagram)

Plotting results on the TAS diagram showed that points T1, T2, T3, T4, and T5 all fall within the andesite field. This uniform classification shows that no significant variations in chemical properties occurred across the 100–500 m sampling corridor from the Labuan River mouth.

3.4 Marshall Mixture Characteristics and KAO Selection

The trial asphalt content was determined based on aggregate characteristics and aggregate blending percentages. In this study, asphalt content varied at 4.5%, 5.0%, 5.5%, 6.0%, and 6.5%. Marshall testing results on the AC-WC mix evaluated mixture parameters across variations in aggregate sampling points. The analyzed parameters included stability, flow, VIM, VMA, VFB, and Marshall Quotient (MQ).

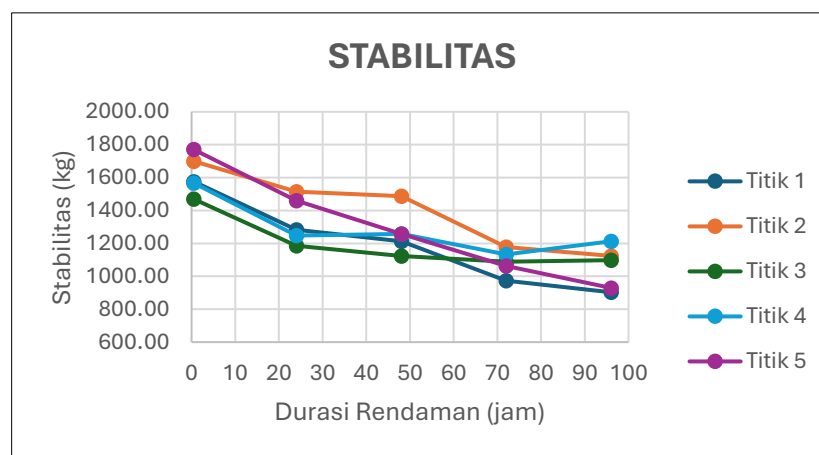
Selecting the optimum asphalt content was based on the Marshall parameters that fulfilled the specification. The established KAO balances stability, flexibility, durability, and density to secure optimal pavement service life performance. Analysis revealed that the Optimum Asphalt Content (KAO) differed at each collection site: Point 1 reached a KAO of 6.1%, Point 2 attained 6.05%, Point 3 yielded 6.0%, Point 4 obtained 6.03%, and Point 5 recorded 6.02%.

3.5 Durability Test Results of AC-WC Mixtures

Durability testing examined the capacity of AC-WC mixtures to retain strength and stability under water and temperature actions. Testing was executed through several parameters, including the Retained Strength Index (IKS), First Durability Index (IDP), and Second Durability Index (IDK).

Table 3.8 AC-WC Mixture Durability Test Results (Stability)

Immersion Variation	Point 1	Point 2	Point 3	Point 4	Point 5
30 Minutes	1575.83	1699.78	1469.60	1566.98	1770.60
24 Hours	1283.69	1513.86	1186.30	1248.27	1460.75
48 Hours	1212.86	1487.30	1124.33	1257.13	1275.13
72 Hours	973.83	1177.45	1088.92	1133.18	1062.36
96 Hours	903.01	1124.33	1097.77	1212.86	929.57



(Figure 3.2 AC-WC Mixture Durability Test Results Curve)

Based on the curve, the relationship between immersion duration and Marshall stability shows a degradation in stability as immersion time lengthens, despite some data fluctuations at specific intervals. This indicates that prolonged water exposure prompts a loss in the mixture's ability to maintain its mechanical strength.

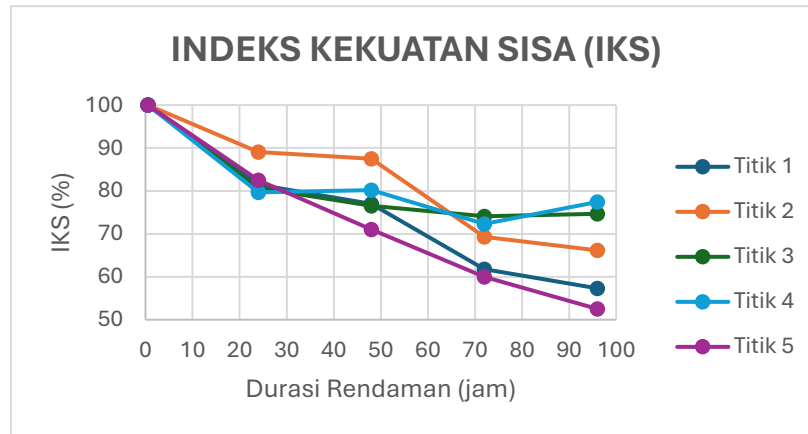
Retained Strength Index (IKS)

The ratio of Marshall stability after 24 hours of immersion to the stability after 30 minutes of immersion, expressed as a percentage, defines the Retained Strength Index (IKS).

Table 3.9 Retained Strength Index Results

Immersion Variation	Retained Strength Index (IKS) %				
	Point 1	Point 2	Point 3	Point 4	Point 5
30 Minutes	100	100	100	100	100
24 Hours	81.46	89.06	80.72	79.66	82.50
48 Hours	76.97	87.50	76.51	80.23	71.00
72 Hours	61.80	69.27	74.10	72.32	60.00
96 Hours	57.30	66.15	74.70	77.40	52.50

Calculations for the Retained Strength Index (IKS) in Table 3.10 demonstrate that IKS scores dropped progressively with prolonged immersion time, displaying concurrent fluctuations at specific stages. Following a 24-hour immersion, the IKS dipped below the minimum standardized specification limit of 90%. Over extension of water contact diminishes the mixture's strength preservation capability, though this loss does not follow a completely linear path at every point.



(Figure 3.3 Durability Curve)

According to the IKS chart, all test specimens start at a baseline value of 100% at 0 hours, given that this value acts as the control condition against which subsequent post-immersion stabilities are compared. As immersion duration increased, the IKS values generally decreased across all points, despite experiencing temporary fluctuations at certain durations. To validate the laboratory testing data across sampling points, statistical testing via the ANOVA (Analysis of Variance) method was implemented to evaluate variations in aggregate properties across the 5 sampling locations.

Table 3.10 ANOVA Analysis

Anova: Two-Factor Without Replication

SUMMARY	Count	Sum	Average	Variance
0,5	5	500	100	0
24	5	413,407083	82,68142	13,79999595
48	5	392,198305	78,43966	36,63475818
72	5	337,481356	67,49627	39,65281575
96	5	328,049129	65,60983	115,6990623
Titik 1	5	377,52809	75,50562	289,199596
Titik 2	5	411,979167	82,39583	204,1829427
Titik 3	5	406,024096	81,20482	117,1069821
Titik 4	5	409,60452	81,9209	111,8771745
Titik 5	5	366	73,2	353,075

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	3831,8995	4	957,9749	32,62112078	1,65E-07	3,006917
Columns	353,27923	4	88,31981	3,007480876	0,049972	3,006917
Error	469,8673	16	29,36671			
Total	4655,046	24				

The Two-Factor Without Replication ANOVA evaluated two operating factors simultaneously—immersion duration and the spatial sampling location at 100-meter increments from the river mouth—against the mix's Retained Strength Index (IKS), revealing key findings:

- **Effect of Immersion Duration:** The immersion duration factor produced an F-value of 32.621, heavily exceeding the F-critical threshold of 3.007, bolstered by an extremely small p-value of 1.65×10^{-7} (far below 0.05). This statistical proof confirms that immersion length exercises an extremely significant effect on the IKS value.
- **Effect of Sampling Location:** The sampling location factor yielded an F-value of 3.0074, just passing the F-critical boundary of 3.0069, with a p-value of 0.049972 (below the critical 0.05 index). This statistical measure validates that the data fluctuations and non-uniform results recorded across individual sampling locations are statistically real and significant.

First Durability Index (IDP)

The First Durability Index (IDP) represents the rate of Marshall stability loss relative to immersion time, computed using stability data at each testing sequence.

Table 3.11 First Durability Index (IDP) Results

Immersion Variation	First Durability Index (IDP) %				
	Point 1	Point 2	Point 3	Point 4	Point 5
30 Minutes	-	-	-	-	-
24 Hours	0.77	0.46	0.80	0.85	0.73
48 Hours	0.19	0.07	0.18	-0.02	0.48
72 Hours	0.63	0.76	0.10	0.33	0.46
96 Hours	0.19	0.13	-0.03	-0.21	0.31
Total Result	1.78	1.41	1.05	0.94	1.98

Based on the calculations, the IDP values mostly reflected a positive trend ($r > 0$). According to Craus et al. (1987), a positive r value implies a net loss of strength during immersion, whereas a negative r value points to a temporary strength gain. Consequently, these results show that all AC-WC mixtures underwent stability reduction from immersion, yielding distinct strength degradation rates based on aggregate source distances.

Second Durability Index (IDK)

The IDK tracks the cumulative strength loss within the mixture over the entire course of the immersion cycle.

Table 3.12 Second Durability Index (IDK) - 1-Day Strength Loss, "a" (%)

Immersion Variation	Second Durability Index (IDK) Strength Loss over 1 Day, a (%)				
	Point 1	Point 2	Point 3	Point 4	Point 5
30 Minutes	-	-	-	-	-
24 Hours	16.22	9.57	16.87	17.80	15.31
48 Hours	2.81	0.98	2.64	-0.35	7.19
72 Hours	5.69	6.84	0.90	2.97	4.13
96 Hours	0.56	0.39	-0.08	-0.64	0.94
Total Result	25.28	17.77	20.33	19.77	27.56

In the IDK calculation for Point 1, the cumulative 1-day strength loss value (a) scored the highest. This reveals that water rapidly penetrated the air voids of the mixture, breaking down the adhesion bond between asphalt and aggregate, which forced down mixture stability. Most of the IDK values returned positive numbers ($a > 0$). Craus et al. (1987) note that a positive "a" signifies structural strength loss during water immersion, whereas a negative value points to strength gains. Hence, the overall outcome underscores that water exposure continuously compromised the stability of all AC-WC mixtures.

This durability index defines a single day's strength loss, where a positive value "a" signifies loss, and a negative value "a" portrays a strength gain. Based on this parameter, $a < 100$. This allows the formulation of the equivalent percentage of 1-day retained strength ($(S_{\{a\}})$), as detailed in the following table.

Table 3.13 One-Day Retained Strength, Sa (%)

Immersion Variation	Second Durability Index (IDK) Retained Strength over 1 Day, Sa (%)				
	Point 1	Point 2	Point 3	Point 4	Point 5
30 Minutes	100	100	100	100	100
24 Hours	83.78	90.43	83.13	82.20	84.69
48 Hours	80.97	89.45	80.50	82.56	77.50

72 Hours	75.28	82.62	79.59	79.59	73.38
96 Hours	74.72	82.23	79.67	80.23	72.44

Based on the retained strength values ((S_a)), all mixtures showed declining strength as immersion expanded, indicated by a contracting (S_a) coefficient from the initial 30-minute standard down to the 96-hour stage. This confirms that aggregate properties from individual collection coordinates impact the durability of asphalt mixes in resisting water damage.

The Second Durability Index can also be framed as absolute values of equivalent strength loss, as seen below.

Table 3.14 One-Day Strength Loss, A (kg)

Immersion Variation	Second Durability Index (IDK) Strength Loss over 1 Day, A (kg)				
	Titik 1	Titik 2	Titik 3	Titik 4	Titik 5
30 Minutes	0	0	0	0	0
24 Hours	255.63	162.67	247.88	278.87	271.12
48 Hours	44.27	16.60	38.73	-5.53	127.26
72 Hours	89.64	116.20	13.28	46.48	73.04
96 Hours	8.85	6.64	-1.11	-9.96	16.60

Regarding the absolute 1-day strength loss value (A), all aggregate variations showed a general contracting trend in strength loss values as immersion went on. Negative numbers at Point 4 (48-hour immersion) and Points 3 and 4 (96-hour immersion) capture temporary stability rises. Despite encountering minor fluctuations at select points, it does not alter the core conclusion that water gradually undermines the durability of the asphalt mixture over time. This vulnerability is clearly exposed by the heavy strength loss values documented during the initial 24-hour immersion cycle across all sampling coordinates.

IV. CONCLUSION

Based on the experimental investigation and analysis, the following conclusions are drawn:

1. Variations in the aggregate sampling distance introduce changes in the aggregate's physical properties, notably influencing absorption, abrasion resistance, and surface texture. These shifting properties alter the Marshall volumetric parameters of the AC-WC mixture, causing variations in Stability, Flow, VIM, VMA, VFB, Marshall Quotient (MQ), and the Optimum Asphalt Content (KAO) across different sampling coordinates.
2. The durability of AC-WC mixtures drops sharply as water immersion extends, reflected by a consistent decline in the Retained Strength Index (IKS) at all aggregate testing sites. This decline proves that longer water contact accelerates strength loss inside the pavement structure. Computations for the First Durability Index (IDP) and Second Durability Index (IDK) returned positive total values which, according to the Craus et al. (1981) framework, confirms a net loss of mechanical strength during immersion.
3. XRF testing revealed a highly uniform mineral layout across all sampling coordinates, heavily dominated by SiO_2 concentrations (58.406%–59.421%). This composition places the Labuan River aggregate within the intermediate hydrophilic andesite rock category, supporting its application in AC-WC asphalt pavement mixes, specifically regarding surface texture interactions and aggregate-binder adhesion.
4. ANOVA statistical analysis confirmed that the mix's Retained Strength Index (IKS) is simultaneously driven by immersion duration ($p\text{-value} = 1.65 \times 10^{-7} < 0.05$) and spatial sampling location ($p\text{-value} = 0.049972 < 0.05$). The 100-meter sampling increments from the river mouth introduce spatial variations affecting particle morphology (flakiness and elongation indices) and rock porosity in the field, showing a highly significant statistical effect on the mix's IKS.

REFERENCES

- [1]. Haris. (2019). Analisis pengujian stabilitas dan durabilitas campuran aspal dengan tes perendaman. *Jurnal LINEARS*, 2(1), 33–47. <https://doi.org/10.26618/j-linears.v2i1.3026>
- [2]. Heriyana, U., Prayitno, A., & Widagdo, D. (2024). Karakteristik asphalt concrete-wearing course (AC-WC) dengan menggunakan aspal peneetraasi 60/70 ditinjau dari durabilitas campuran. *Jurnal rekayas, Teknik sipil STTC*. Vol.02-02
- [3]. Prayogi, A., Syahputra, M. A., Badaron, S. F., Arifin, W., & Salim. (2019). Analisa durabilitas campuran beton aspal dengan penggunaan derbo dan wetfix terhadap kepadatan mutlak. *JILMATEKS (Jurnal Ilmiah Teknik Sipil)*, 1(3), 380–389. <https://jurnal.ft.umi.ac.id/index.php/JILMATEKS>

- [4]. Ji, T., Hao, P., She, H., Yang, K., Li, H., Wang, D., Kang, R., & Liu, J. (2023). Durability behavior of asphalt mixtures in regard to material properties and gradation type. *Frontiers in Materials*, 10, 1151479. <https://doi.org/10.3389/fmats.2023.1151479> (doi.org in Bing)
- [5]. Efendy, A., Muttaqin, A., & Santika, Y. (2025). Analisis durasi perendaman campuran aspal beton untuk perkerasan runway. *INNOVATIVE: Journal of Social Science Research*, 5(1), 6948–6964. <https://j-innovative.org/index.php/Innovative>
- [6]. Craus, J., Ishai, I., and Sides, A., 1981. Durability of Bituminous Paving Mixtures as Related to Filler Type and Properties Proceedings Association of Asphalt Paving Technologists, Technical sessions, February 16,17 and 18, Volume. 50, San Diego, California.
- [7]. Oggier, F., Widiwijayanti, C., & Costa, F. (2023). Global volcanic rock classification of Holocene volcanoes. *Scientific Data*, 10, 422. <https://doi.org/10.1038/s41597-023-02324-7>
- [8]. Setiadji, B. H., Wardani, S. P. R., & Perdana, S. (2015). Durability of road pavement against tidal inundation. *Journal of Society for Transportation and Traffic Studies*, 6(3), 1–11. https://eprints.undip.ac.id/54170/2/Fullpaper_Durability_of_Road_Pavement_Against_Tidal.pdf
- [9]. Abu Dhabi Government. (2020). *Standard construction specifications (Part 1 - Roads)* (2nd ed.). Department of Municipalities and Transport. sinref.ru
- [10]. Direktorat Jenderal Bina Marga. (2025). *Spesifikasi umum 2025 untuk pekerjaan jalan dan jembatan (Divisi 6: Perkerasan aspal)*. Kementerian Pekerjaan Umum dan Perumahan Rakyat.
- [11]. Kementerian Pekerjaan Umum dan Perumahan Rakyat. (2024). *Manual Desain Perkerasan (MDP 2024)*. Direktorat Jenderal Bina Marga, Jakarta.
- [12]. Badan Standardisasi Nasional. (1989). *SNI 03-1737-1989 – Spesifikasi Agregat untuk Campuran Beraspal Panas*. Jakarta: BSN.