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ASPHALT CONCRETE–WEARING COURSE (AC-WC) PERFORMANCE USING GOLD-MINING SAND WASTE AS FINE AGGREGATE IN SUSTAINABLE PAVEMENTS

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ABSTRACT: This study evaluates the mechanical and volumetric performance of Asphalt Concrete–Wearing Course (AC-WC) mixtures incorporating Gold-Mining Residual Sand Waste (GMRSW) as a sustainable substitute for natural fine aggregate. Four mix designs were prepared with GMRSW substitution levels of 0%, 25%, 50%, and 75% by weight of fine aggregate. The Marshall mix design method was used to determine the optimal performance in terms of Marshall stability, flow, Marshall Quotient (MQ), and volumetric properties. The results showed that the 75% GMRSW mixture achieved the highest Marshall stability (1202.87 kg) and Marshall Quotient (498.33 kg/mm), significantly outperforming the control mixture (989.83 kg and 369.69 kg/mm, respectively). These improvements are attributed to the angular texture and rough surface of GMRSW particles, which enhanced particle interlocking and load-bearing capacity. However, the 25% GMRSW mixture exceeded the allowable limit for Voids in Mix (VIM) at 5.57%, slightly above the Indonesian highway specification threshold of 5%. All other mixtures met the required specifications for AC-WC, indicating that GMRSW is a viable and effective fine aggregate replacement up to 75% substitution. Despite the improvements in stability, the increased angularity also made compaction more difficult, highlighting a trade-off that should be optimized in future applications. This research supports the beneficial reuse of GMRSW in tropical pavement engineering, contributing to environmental sustainability by reducing the reliance on natural aggregates. Further investigations are recommended to evaluate fatigue resistance, moisture susceptibility, and long-term field performance of GMRSW-modified asphalt mixtures.

Keywords: Gold mine waste; Fine aggregate substitution; Marshall stability; AC-WC asphalt mixture; Sustainable pavement materials

1. INTRODUCTION

Environmental degradation is a manifestation of human civilization, in which humans alter the natural environment to meet their survival needs. This phenomenon occurs in multiple forms and exerts diverse environmental, ecological, and social impacts. A particularly significant form is mining-induced environmental degradation, where residues from mining activities are seldom reburied, and mining areas are rarely revegetated. This neglect often results in landslides and soil instability. Furthermore, the processing waste generated during mining operations is frequently discharged without purification, polluting water bodies, soil, and the surrounding flora and fauna. Prolonged exposure to such contamination can jeopardize public health, yet these impacts are often overlooked by affected communities[1-2].

Indonesia, as a developing country endowed with rich natural resources ranging from biodiversity to mineral wealth has long relied on its mining sector for economic development. According to Article 33, paragraph (3) of the 1945 Constitution, land, water, and all natural resources are controlled by the state and are to be used for the greatest benefit of the people [3]. Among Indonesia's many mineral resources, gold plays a particularly important role due to its rarity and valuable physical characteristics. Gold is extracted through both legal and illegal mining activities [4]. While formal mining operations are overseen by government-licensed corporations, unregulated artisanal and small-scale mining (ASM) remains prevalent, especially in remote regions such as Sumbawa Island, West Nusa Tenggara [5-6]. This has resulted in serious environmental concerns, as mercury-laden tailings and sand sludge from unregulated gold processing are often discharged directly into the environment, contaminating rivers, lakes, and agricultural lands [7].

Sumbawa Island is not only known for its scenic landscapes but also for its extensive mineral reserves, particularly copper and gold. However, the mining industry in this region faces mounting challenges regarding waste management. Solid waste generated during the life cycle of mines poses critical risks, including limited storage capacities and the threat of environmental pollution [8]. In many cases, mining operations conducted by local communities bypass proper waste treatment practices, leading to mercury and other contaminants being released untreated. These unsustainable practices highlight the urgent need for solutions that can simultaneously mitigate environmental harm and promote resource efficiency.

One such opportunity lies in the reproduction of mining by-products in the construction sector, particularly in transportation infrastructure. The transportation sector plays a pivotal role in regional development, with road infrastructure acting as a backbone for mobility and economic integration. Within the domain of traffic engineering and safety, durable pavement design is essential to ensure long-term serviceability under varying environmental conditions [9]. Asphalt pavements in tropical climates are especially prone to degradation due to extreme heat and high rainfall. The upper layers of pavement, namely the Asphalt Concrete-Wearing Course (AC-WC) and Asphalt Concrete-Binder Course (AC-BC), are most susceptible to such damage [10]. Poor-quality materials particularly aggregates with high mud content can accelerate deterioration, highlighting the importance of stringent material selection and processing [11].

Aggregates, which consist of crushed stone, gravel, and sand sourced from natural or artificial origins, are a fundamental component of asphalt mixtures. They are generally categorized into coarse aggregates (retained on a No. 4 sieve) and fine aggregates (passing through a No. 4 sieve) [12-13]. In line with sustainable construction practices, recent research has explored the use of alternative aggregates to reduce dependency on natural sources. One promising approach involves substituting fine aggregates with sand waste from gold mining activities [8]. This not only minimizes environmental impact but also supports circular economy principles by repurposing industrial by-products. The potential of recycled fine aggregates in sustainable pavement has also been explored in recent studies, such as Islam [14], who evaluated its usability in cool pavement systems—further reinforcing the importance of aggregate morphology and source.

However, most previous studies have focused on full replacement or applications outside the AC-WC layer, which are less applicable to real-world implementation. For example, Susanto et al. (2021) [15] found that while 60% tailings replacement met Marshall test requirements for asphalt base layers, the tailings alone had low cohesion and required cement stabilization, indicating that full replacement may not provide sufficient mechanical performance for high-strength wearing courses. These findings support the conclusion that 100% substitution of natural fine aggregates often yields mixtures with increased voids, lower stability, and inadequate moisture resistance—especially in tropical conditions where durability demands are higher. In contrast, partial substitution offers a more feasible balance, maintaining performance and workability while enhancing sustainability. Nevertheless, systematic investigations of partial GMRSW substitution under tropical climates remain scarce.

GMRSW is particularly relevant for tropical climates like Indonesia, where high temperatures and heavy rainfall challenge pavement durability. Its angular, non-plastic texture may reduce moisture retention and enhance mechanical interlock, making it suitable for minimizing rutting and moisture damage. This study evaluates the mechanical and volumetric performance of AC-WC mixtures with 25%, 50%, and 75% GMRSW substitution using Marshall parameters.

2. RESEARCH SIGNIFICANCE

This research introduces a novel application of Gold-Mining Residual Sand Waste (GMRSW) as a fine aggregate substitute in Asphalt Concrete–Wearing Course (AC-WC) mixtures, addressing both pavement performance and industrial waste management. While previous studies have focused on conventional aggregates or common waste materials, this study is among the first to systematically evaluate the mechanical and volumetric effects of GMRSW in tropical pavement conditions. The finding that up to 75% substitution improves Marshall stability and stiffness highlights its potential for sustainable infrastructure. The originality lies in demonstrating GMRSW’s dual function: enhancing asphalt mix performance while promoting resource recovery in mining regions.

3. MATERIALS AND METHODS

3.1 Materials

The materials used in this study consisted of coarse aggregates, fine aggregates, filler, gold-mining residual sand waste, and 60/70 penetration-grade asphalt. The coarse aggregates employed comprised two size fractions, namely 10–10 mm and 5–10 mm, with a specific gravity of 2.7, water absorption of 1.1%, and Los Angeles abrasion value of 24.04%. The fine aggregate utilized was a local material sourced from Lumajang, East Java, with a particle size of 0–5 mm, a specific gravity of 2.6, and water absorption of 1.9%. The filler material used in the mixture was defined as aggregate passing through a No. 200 sieve.

The gold-mining residual sand waste used in this study originated from West Sumbawa, West Nusa Tenggara, Indonesia, and had a maximum particle size retained on the No. 30 sieve. The results of the plasticity index test indicated that this waste material was classified as Non-Plastic (NP), as the plastic limit (PL) value of 28.59% was higher than the liquid limit

(LL) value of 23.62%, signifying non-plastic behavior. Meanwhile, the asphalt used was a 60/70 penetration-grade asphalt [16]. The physical properties of the asphalt, obtained from standard laboratory testing, are presented in Table 1.

Table 1. The physical properties of the asphalt

Parameters	Value
Density (kg/m^3)	1.018
Losing weight (%)	0.042
Penetration (%)	68.1
Flash point (°C)	330
Fire point (°C)	338
Softening point (°C)	48.25

3.2 Mixture Formulation and Research Methods

The formulation of the mixture composition in this study began with the design of the combined aggregate proportion, derived from the various aggregate fractions, referring to the Specifications of the Directorate General of Highways 2018 Revision 2 [13]. **Error! Reference source not found.** presents t he combined aggregate proportion. The resulting combined fraction values were used as a reference for determining the percentage of aggregate passing through each sieve size in the asphalt mixture composition.

The planning of the combined aggregate proportion was conducted using the Rothfuchs graphical method alongside a trial-and-error approach to determine the optimal aggregate percentages for the AC-WC asphalt mixture. The aggregate composition used in the asphalt mixture is summarized in

The determined OAC was used as the fixed asphalt content for preparing modified AC-WC specimens. Fine aggregate was partially replaced with gold-mining residual sand waste (GMRSW) at 25%, 50%, and 75% of the weight retained on and above the No. 30 sieve, alongside a control specimen (0% GMRSW). Marshall parameters for the modified specimens were evaluated using the same criteria as in the OAC determination.

The specimen preparation began with sieving, classifying, and weighing aggregates to a total of 1200 g, followed by heating them to 170 ± 1 °C. Separately, 60/70 penetration-grade asphalt was heated to 120 ± 1 °C. The preheated asphalt and aggregates were then blended (adjusted for the target asphalt content), producing a 1200 g mixture. Finally, the mixture was reheated to 155 ± 1 °C to ensure homogeneity.. Meanwhile, the planned asphalt content (Pb) for this study was determined based on Eq. (1).

$$Pb = 0.035\ (\%CA) + 0.045\ (\%FA) + 0.18\ (\%FF) + K \quad (1)$$

where Pb represents the asphalt content; CA denotes the percentage of coarse aggregate retained on the No. 8 sieve; FA refers to the percentage of fine aggregate passing the No. 8 sieve and retained on the No. 200 sieve; FF is the percentage of filler material passing the No. 200 sieve; and K is a constant value ranging from approximately 0.5 to 1.

The Pb value was influenced by the aggregate gradation. Five asphalt content levels were selected based on a ±1% variation from the estimated Pb (6.5%), aligning with standard practice in Marshall mix design. This range allows a sufficient sensitivity evaluation and ensures that the Optimum Asphalt Content (OAC) is determined from a range that realistically captures both under- and over-asphalted mixtures. The OAC was determined using the arithmetic mean method based on the asphalt contents that met the specification criteria for all Marshall parameters. While multi-objective optimization techniques can provide theoretical precision, the arithmetic mean remains a widely accepted and practical approach in many applied studies, particularly in contexts where laboratory and field implementation consistency is prioritized. The asphalt content value was determined based on Eq. (1). The planned asphalt content variations are presented in Table 4.

Table 2. Combined aggregate proportion

Sieve size		Coarse aggregate (%)	Medium aggregate (%)	Fine aggregate (%)	Filler (%)	Combined fraction (%)	Specifications pass (%)
inch	mm						
¾”	19	100.00	100.00	100.00	100	100.00	100 - 100
½”	12.5	96.45	41.07	100.00	100	95.50	90 - 100
3/8”	9.5	38.10	5.14	100.00	100	83.50	77 - 90
No. 4	4.75	0.00	0.00	95.82	100	63.50	53 - 69
No. 8	2.36	0.00	0.00	85.23	100	45.00	33 - 53
No. 16	1.18	0.00	0.00	75.28	100	21.50	21 - 40

No. 30	0.6	0.00	0.00	55.33	100	20.50	14 - 30
No. 50	0.3	0.00	0.00	35.51	100	17.00	9 - 22
No. 100	0.15	0.00	0.00	16.15	100	14.00	6 - 15
No. 200	0.075	0.00	0.00	8.38	100	6.50	4 - 9
PAN fraction		0.00	0.00	0.00	100		0 - 0

Table 3. Aggregate composition

Aggregate	Component (%)
Coarse Aggregate	36.5
Medium Aggregate	42
Fine Aggregate	15
Filler	6.5

Table 4. Asphalt content variations

Pb-1	Pb-0.5	Pb	Pb+0.5	Pb+1
5.5	6	6.5	7	7.5

From these 5 asphalt contents, the OAC was identified based on Marshall testing parameters, which included Void in Mixture (VIM), Void in Mineral Aggregate (VMA), Void Filled with Asphalt (VFA), stability, flow, and Marshall Quotient (MQ). All testing procedures and criteria referred to the Specifications of the Directorate General of Highways 2018 Revision 2. The equations utilized to calculate these Marshall parameters are provided in Eq. (2) - (6).

$$\text{VIM}=\left(100\times\frac{\text{Gmm-Gmb}}{\text{Gmm}}\right) \quad (2)$$

$$\text{VMA}=\left(100-\frac{\text{Gmb}}{\text{Gsb}}\text{x}\frac{100}{(100\text{-Pb})}\text{x}100\right) \quad (3)$$

$$\text{VFA}=\left(100\text{x}\frac{\text{VMA-VIM}}{\text{VMA}}\right) \quad (4)$$

$$\text{Stability} = \text{Marshall test calibration x dial} \quad (5)$$

$$\text{MQ} = \left(\frac{\text{Stability}}{\text{Flow}}\right) \quad (6)$$

where Gmm denotes the maximum theoretical specific gravity of the mixture at zero air voids; Gmb refers to the bulk specific gravity of the compacted asphalt mixture; Gsb is the bulk specific gravity of the aggregate; and Pb represents the asphalt content expressed as a percentage of the total mixture weight (%).

The determined OAC was used as the fixed asphalt content for preparing modified AC-WC specimens. Fine aggregate was partially replaced with gold-mining residual sand waste (GMRSW) at 25%, 50%, and 75% of the weight retained on and above the No. 30 sieve, alongside a control specimen (0% GMRSW). Marshall parameters for the modified specimens were evaluated using the same criteria as in the OAC determination.

The specimen preparation began with sieving, classifying, and weighing aggregates to a total of 1200 g, followed by heating them to 170 ± 1 °C. Separately, 60/70 penetration-grade asphalt was heated to 120 ± 1 °C. The preheated asphalt and aggregates were then blended (adjusted for the target asphalt content), producing a 1200 g mixture. Finally, the mixture was reheated to 155 ± 1 °C to ensure homogeneity. After achieving a uniform mixture, the hot mix was placed into a mold of standard dimensions (see Fig. 1) until the mixture temperature decreased to 140 ± 1 °C. Compaction was performed by applying 75 blows on each side of the specimen using a Marshall compactor, resulting in a total of 150 blows per specimen.

Fig. 1. Asphalt mold

Following compaction, the specimens were left to rest for 2 to 3 hours at room temperature before being extruded from the mold using a mechanical extruder. Each specimen was then labeled with a unique identifier. The dimensions of the specimens were measured using a caliper with an accuracy of 0.01 mm, and the dry weight of each specimen was recorded. Prior to the Marshall stability testing, the specimens were immersed in a water bath maintained at 60°C for approximately 30 minutes (see Fig. 2). Each specimen was then subjected to loading under conditions that adhered to different specified immersion times, according to the standard Marshall testing procedure.

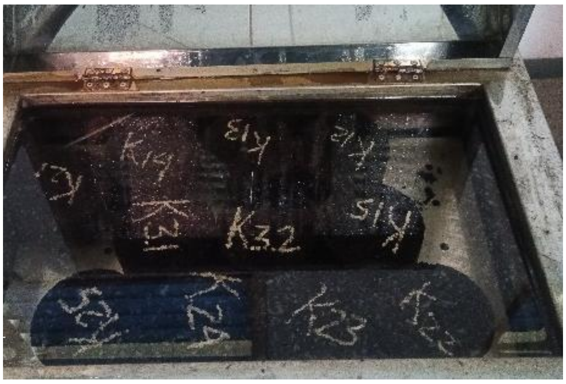

Fig. 2. Immersion of specimens in water at 60°C

Each level of asphalt content and substitution was tested using five replicates (n = 5) to ensure data reliability and minimize variability due to sample handling or testing inconsistencies. During the mixing process, several technical challenges were encountered, primarily related to the fine physical characteristics of the GMRSW material. Due to its soft texture and predominantly small particle size, it was difficult to obtain slightly coarser grains needed to maintain a balanced aggregate gradation. Therefore, sieving was performed with a maximum particle size retained on the No. 30 sieve to ensure that only particles within the desired size range were used in the mixture.

In terms of material characterization, the GMRSW was classified as non-plastic based on standard Atterberg limits testing. However, no Scanning Electron Microscopy (SEM) or Toxicity Characteristic Leaching Procedure (TCLP) tests were conducted within the scope of this study. These tests are recommended for future investigations to evaluate surface morphology and potential heavy metal content to ensure environmental safety and performance durability in real-world applications.

Quantitative image-based morphological analyses, including Scanning Electron Microscopy (SEM), angularity index, sphericity, and surface roughness measurements, were not conducted in this study. Furthermore, heavy metal leaching was not assessed, as no Toxicity Characteristic Leaching Procedure (TCLP) tests were performed. To ensure environmental safety and enhance understanding of performance durability, future studies are recommended to incorporate SEM and TCLP analyses. Such detailed morphological and chemical characterizations will help establish the influence of GMRSW particle geometry and composition on binder interaction, interparticle friction, and overall mechanical behavior in asphalt mixtures.

4. RESULT AND DISCUSSION

4.1 Optimum Asphalt Content Calculation

The primary parameter that must be identified in this study is the Optimum Asphalt Content (OAC), which is determined through Marshall testing. In this study, the OAC was calculated as the arithmetic mean of the asphalt contents corresponding to the target values for VIM, VFA, VMA, flow, stability, and (MQ) [17]. The procedure for calculating the Marshall parameters to determine the OAC follows the method described by Machsus (2020) & (2021) [18-19]. A summary of the OAC determination is presented in Table 5.

Table 5 shows that the asphalt contents that conform to the specification criteria for each Marshall parameter were 6.0% and 6.5%. Therefore, the final OAC was determined by averaging these two values, resulting in an optimum asphalt content of 6.25%.

4.2 Marshall Test Parameters for AC-WC Mixtures with Fine Aggregate Substitution

The percentage of GMRSW used as a partial substitution for fine aggregate was set at 25%, 50%, and 75% by total aggregate weight. Each of these mixtures was combined with asphalt at the OAC of 6.25%. The following presents the results of the Marshall characteristics testing of AC-WC asphalt mixtures incorporating varying levels of fine aggregate substitution**.**

4.2.1. Density

The density of asphalt mixtures is a critical parameter that reflects the level of compactness achieved during production and compaction processes. It is influenced by aggregate gradation, particle shape, and physical characteristics of the constituent materials. In this study, the partial substitution of fine aggregate with GMRSW resulted in a generally decreasing trend in density. A 25% substitution reduced the density by 0.03%, a 50% substitution showed a 0.02% decrease, while a 75% substitution led to a slight recovery with a 0.01% increase compared to the 50% level (see Fig. 3). This non-linear behavior can be attributed to the dual influence of GMRSW's angularity and porous texture.

At lower substitution levels, the introduction of GMRSW disrupts the optimized packing structure of the mix, reducing density due to inefficient interlocking and higher air voids. However, at 75% substitution, the higher concentration of angular particles appears to enhance interparticle friction and mechanical interlocking, slightly improving compaction and bulk density. These observations align with findings by [20] and [21], which demonstrate that density and volumetric stability in asphalt mixtures are strongly governed by aggregate gradation, shape, and compaction behavior.

4.2.2. Void In Mixture (VIM)

The Void in Mixture (VIM) reflects the percentage of air voids within asphalt mixtures, which critically influences their durability, permeability, and resistance to moisture-induced damage. In this study, VIM values showed a non-linear trend, peaking at 5.57% for the 25% GMRSW substitution before declining to 4.90% and 4.91% at 50% and 75% substitution levels, respectively (see Fig. 4). This anomaly at 25% substitution exceeds the Indonesian Highway Specification range of 3–5% and may suggest a less compacted mixture with increased void connectivity. The elevated VIM at 25% can be attributed to the transitional disruption of optimal aggregate packing caused by the introduction of finer GMRSW particles, which do not provide sufficient angular interlock to maintain structural cohesion. At this level, the GMRSW volume is insufficient to reinforce the aggregate skeleton effectively, resulting in excessive voids. However, at higher substitution levels (50% and 75%), the increased proportion of GMRSW—with its angular and rough-textured particles—enhances interparticle friction and packing efficiency, restoring mixture stability and reducing air voids. These findings align with Amrani (2020) [22] and Garcia (2010) [23], who noted that irregular particle shapes tend to increase VIM unless adequately incorporated. The observed behavior also underscores that only beyond a certain threshold does GMRSW effectively integrate into the aggregate matrix to improve volumetric performance, highlighting the need for optimized gradation and substitution levels in mix design.

Table 5. Optimum asphalt content determination

Parameters	Unit	Asphalt contents (%)					Specification	
		5.5	6	6.5	7	7.5	Min	Max
Stability	kg	1066.85	1042.84	973.50	1029.51	1061.51	800	-
Flow	mm	2.41	2.58	3.06	2.69	2.74	2	4
VIM	%	**6.99**	3.54	3.39	**1.87**	**2.26**	3	5
VMA	%	21.36	19.68	20.49	20.21	17.77	15	-
VFA	%	67.39	82.10	83.47	90.74	87.25	65	-
MQ	kg/mm	457.93	410.51	330.11	383.90	391.16	250	-

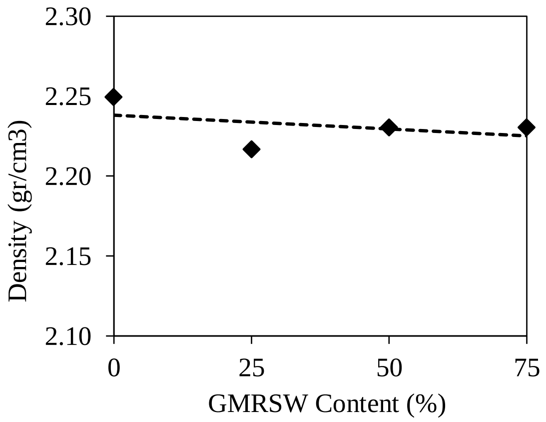

Fig. 3. Relationship between GMRSW Content and Density

The contrast with Taherkhani & Arshadi (2019) [24], who observed a linear decrease in VIM and a consistent increase in stability with higher waste substitution, may be attributed to fundamental differences in material characteristics, mixture design, and compaction methods. In their study, the waste material used was ceramic powder with high angularity and consistent gradation, which facilitated uniform particle packing and enhanced mechanical strength. In contrast, the GMRSW used in this study exhibits finer, more irregular textures with variable particle sizes, leading to more complex interactions with the asphalt binder, particularly at lower substitution levels. These physical variations, combined with differences in mineral composition, porosity, and binder absorption behavior, likely contributed to the contrasting VIM trends. Furthermore, their research employed a gyratory compactor with a different temperature profile, while this study followed the Marshall method, potentially resulting in differing air void distributions and compaction efficiencies. Notably, the 25% substitution level in this study exceeded the maximum VIM limit (5%) set by the Directorate General of Highways [13], rendering it non-compliant with AC-WC specifications. These findings highlight the importance of understanding how material properties and laboratory procedures influence the volumetric performance of asphalt mixtures.

Environmental exposure such as wet–dry cycles could further influence the volumetric behavior of

GMRSW mixtures. Frianeza and Adajar [25] emphasized this effect in compacted polyurethane–clay, suggesting future studies should examine AC-WC response under similar cyclic conditions.

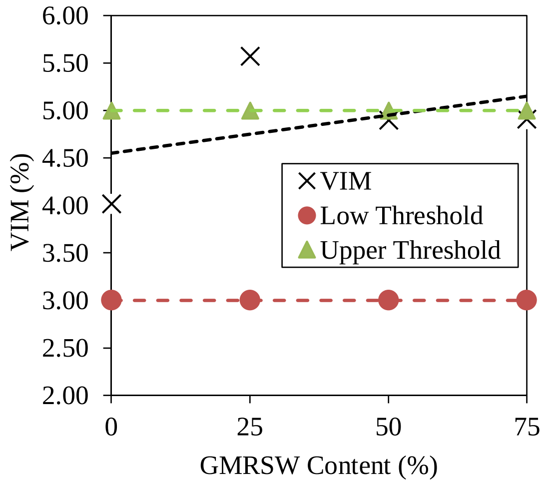

Fig. 4. Relationship between GMRSW Content and VIM

Although the GMRSW-modified mixtures generally met the VIM specifications (except at the 25% level), the potential for moisture-induced damage remains a concern due to the mining origin of the material. Atterberg limits testing classified GMRSW as non-plastic, indicating minimal clay content and low moisture sensitivity. However, since moisture resistance tests such as the Indirect Tensile Strength Ratio (TSR) or Moisture-Induced Stress Tester (MIST) were not conducted, further evaluation is needed to confirm the long-term performance of GMRSW mixtures under high rainfall conditions.

4.2.3. Voids in Mineral Aggregates (VMA)

The Voids in Mineral Aggregate (VMA) represent the volume of voids within the mineral aggregate framework of a compacted asphalt mixture, which directly influences its durability, binder retention, and rutting resistance [26-27]. In this study, the VMA values demonstrated a fluctuating trend with increasing GMRSW substitution levels. The control mixture (0% substitution) recorded a VMA of 20.51%, which increased to 21.67% at 25% substitution, then slightly decreased to 21.18% at 50%, and marginally increased again to 21.19% at 75% substitution (see Fig. 5). Although the variations are modest, all values remain well above the minimum threshold of 15% as mandated by the Indonesian Highway Directorate General [13], indicating acceptable binder accommodation across all mixtures.

The observed increase in VMA at all substitution levels compared to the control can be attributed to the inclusion of GMRSW, which alters the aggregate packing structure. The fine particle size distribution, irregular shape, and rough texture of GMRSW reduce the efficiency of particle interlock, increasing interparticle voids that must be filled by binder. At 25% substitution, the disruption of optimal gradation and packing is most pronounced, leading to the highest VMA. However, at higher substitutions, despite a consistent presence of angular particles, improved mechanical interlock and a more cohesive skeleton may reduce the extent of void expansion, slightly stabilizing VMA values.

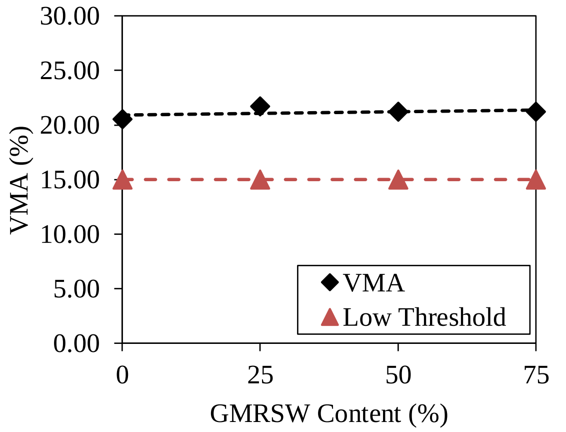

Fig. 5. Relationship between GMRSW Content and VMA

These results are consistent with findings from Woszuk (2019) [28] and Amrani (2020) [22], who reported similar effects when incorporating alternative fine aggregates in asphalt mixtures, especially in LATASIR applications. Overall, the influence of GMRSW on VMA highlights the critical role of aggregate morphology and gradation in determining volumetric properties, and reinforces the need for tailored mix designs when introducing industrial waste materials as partial replacements.

4.2.4. Voids Filled with Asphalt (VFA)

VFA represents the percentage of voids in the mineral aggregate that are filled with asphalt binder [27]. The results of this study indicate a fluctuating trend in VFA values following the partial substitution of fine aggregate with GMRSW. At a 25% substitution level, the VFA reached 74.78%, then increased to 76.92% at 50%, and slightly decreased to 76.88% at 75%. Meanwhile, the control mixture without tailings sand exhibited a VFA value of 74.12% (see Fig. 6).

These findings are in line with those reported by Woszuk (2019) [28], who also observed fluctuations in VFA when fine aggregates were replaced with recycled materials. In that study, the use of construction waste as a partial fine aggregate substitution led to a decrease in VFA at certain substitution levels, followed by an increase at higher levels, a pattern that mirrors the results of the present research. This trend suggests that the characteristics of the substitute material, such as the physical properties of gold mine tailings, can significantly influence the number of binder-filled voids in the aggregate structure, thereby potentially affecting the mixture's durability and overall performance.

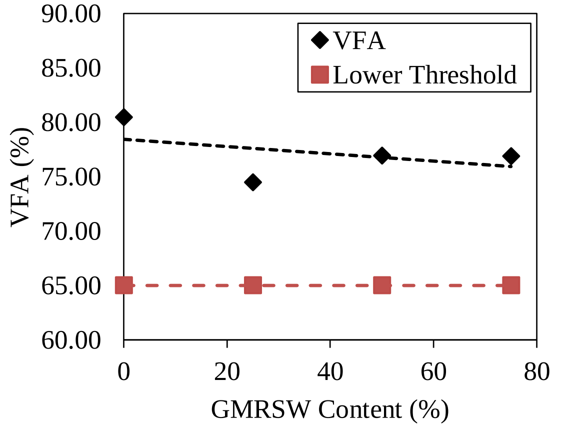

Fig. 6. Relationship between GMRSW Content and VFA

Although the VFA values of the substituted mixtures were slightly lower than those of the control specimen, all values remained above the minimum threshold of 65% as specified in the Indonesian Highway Directorate General Specification [13]. The relatively high VFA values observed indicate that the asphalt binder effectively penetrated the void spaces between aggregate particles, promoting strong interfacial adhesion between the binder and the aggregate, which is crucial for mixture stability and long-term performance [29].

4.2.5. Stability

Marshall Stability reflects the asphalt mixture's ability to resist compressive loads under traffic-induced deformation. As shown in Fig. 7, the stability value for the control mixture (without GMRSW) was 989.83 kg. At 25% GMRSW substitution, the stability slightly decreased to 941.49 kg, likely due to suboptimal adhesion and limited contact area between the angular tailings particles and other aggregates [26-28], which may have weakened the internal matrix structure. However, a substantial increase in stability was observed at 50% (1069.52 kg) and peaked at 75% substitution (1202.87 kg), indicating enhanced resistance to rutting, shear, and permanent deformation.

This trend can be attributed to several reinforcing mechanisms. The angularity and rough surface texture of GMRSW improved internal friction and mechanical interlocking, resulting in stronger aggregate skeletons and increased structural integrity under load. The finer gradation at higher substitution levels may also enhance particle packing density and frictional resistance, limiting internal slippage. Additionally, the increased surface area of GMRSW particles improves asphalt film distribution, potentially reducing binder drain-off and enhancing overall cohesion. These findings align with prior studies such as Jabbar (2024) [30] and Ismael (2023) [31], who reported similar stability gains with angular waste fillers and industrial by-products due to improved interlock and binder retention mechanisms.

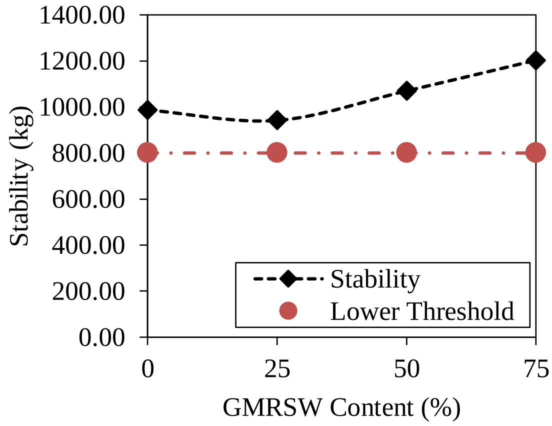

Fig. 7. Relationship between GMRSW Content and Stability

Similar findings were reported by Hamkah [32], who incorporated recycled tire rubber into AC-WC mixtures and observed enhanced Marshall stability and fatigue resistance, supporting the premise that industrial waste with angular particles can improve mixture performance.

Although 75% substitution yielded the highest stability, levels beyond this were not pursued. Preliminary trials indicated that mixtures with ≥80% GMRSW experienced workability issues, including segregation and compaction difficulty. Such difficulties are consistent with findings by Rasoola (2024) [33], who emphasized that filler type and morphology strongly influence compaction characteristics and workability during laboratory preparation. Excessively high fine content disrupted the gradation balance and compromised volumetric parameters such as VMA and VFA. Therefore, 75% was selected as the practical upper limit in this experimental framework. Future research could explore the use of stabilizing agents, gradation optimization, or additive technologies to enable higher substitution levels while preserving mix workability and performance.

In summary, the variation in Marshall stability across substitution levels reflects the complex interplay between particle morphology, gradation, binder interaction, and compaction behavior. Understanding and optimizing these factors are key to maximizing the structural benefits of GMRSW in sustainable asphalt mixtures.

4.2.6. Flow

Flow was measured simultaneously with the stability test. The flow value refers to the vertical deformation that occurs when the specimen reaches its maximum load during the loading process. As shown in Fig. 8, a general decreasing trend in flow was observed with increasing substitution of fine aggregate by GMRSW. The flow value decreased from 2.75 mm (control mixture) to 2.47 mm at 25% substitution, further dropped to 2.27 mm at 50%, and slightly increased to 2.46 mm at 75% substitution.

This trend suggests that increasing the proportion of GMRSW as fine aggregate may enhance the mixture's stiffness, thereby reducing vertical deformation under maximum loading. However, the relationship between stability and flow observed in this study deviates from findings reported in previous research [34–36], where an increase in stability is typically associated with a decrease in flow, and vice versa. In contrast, the current results indicate that both stability and flow can decrease or increase together, depending on the level of substitution and material characteristics. Despite the variations, all mixtures incorporating GMRSW satisfied the flow requirements specified by the Indonesian Highway Specification [13], which mandates a minimum flow of 2 mm and a maximum of 4 mm for AC-WC mixtures.

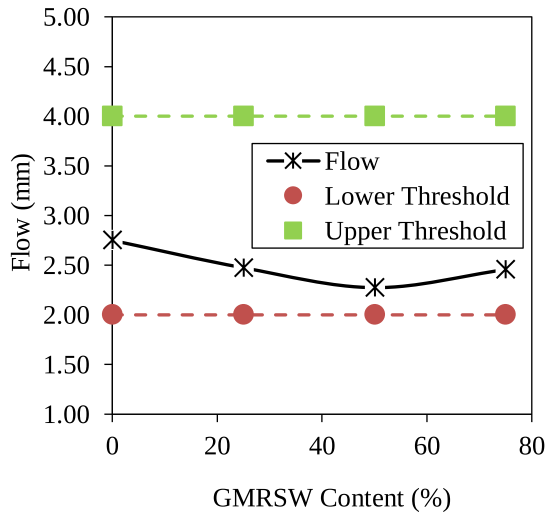

Fig. 8. Relationship between GMRSW Content and Flow

The changes in flow values can be influenced by several factors, including aggregate gradation, particle shape, and surface texture of the GMRSW. Coarser and more angular aggregates tend to improve interlocking between particles, thus enhancing the stiffness of the mixture and reducing flow values. In contrast, smoother or more rounded aggregates can diminish interparticle interlocking, resulting in greater deformation and increased flow values. Material modification has proven effective in enhancing mechanical performance in asphalt layers, as demonstrated by Erlangga [37] using polymer-modified cement asphalt. Similar effects are seen with GMRSW in this study, particularly in terms of increased stiffness and flow reduction.

4.2.7. Marshall Quotient (MQ)

The Marshall Quotient (MQ) is a critical parameter that indicates the stability and resistance of asphalt mixtures to permanent deformation. In various countries, MQ is widely employed as a performance verification metric during mixture design. It is calculated as the ratio of Marshall Stability to Flow (MQ = Stability / Flow). In the present study, MQ values increased progressively with higher substitution levels of GMRSW as a substitution for fine aggregates. As shown in Fig. 9, the highest MQ value was recorded at 75% substitution, reaching 498.33 kg/mm, followed by 50% substitution at 478.35 kg/mm, and 25% at 385.09 kg/mm. The control mixture, with no substitution, exhibited the lowest MQ value of 369.69 kg/mm.

These findings align with previous studies by Awad (2017) [36] and Deskianto (2023) [38], who reported similar increases in MQ values when replacing fine aggregates with waste materials, such as palm oil clinker and mine tailings. The improvement in MQ is largely attributed to the physical characteristics of the alternative materials—particularly their angularity and rough surface texture—which enhance interlocking among particles and increase the mixture's stiffness and resistance to shear deformation.

In line with Israil [39], who observed increased Marshall Quotient in cold-mix asphalt with local binders, the higher MQ in GMRSW-modified mixtures here can be attributed to better interparticle friction and binder distribution.

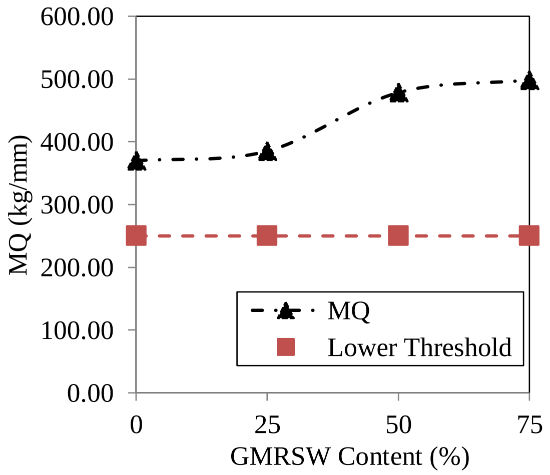

Fig. 9. Relationship between GMRSW Content and MQ

According to several studies [24-36], MQ is an essential indicator of a mixture's ability to resist shear stress and permanent deformation under traffic loading. Therefore, the increasing MQ values observed with up to 75% substitution of GMRSW suggest that the resulting asphalt concrete–wearing course (AC-WC) mixtures possess higher stiffness and better rutting resistance. Moreover, all mixtures in this study exceeded the minimum MQ requirement of 250 kg/mm as specified in the Indonesian Bina Marga 2018 guidelines, [13] indicating compliance with national performance standards across all substitution levels

5. CONCLUSION

Based on the findings of this study, the following conclusions can be drawn: (1) The results of the Marshall test parameters indicate that most asphalt mixtures met the Indonesian Highway Specification criteria; however, the 25% substitution level exceeded the VIM limit (5.57% > 5%), indicating marginal non-compliance. In contrast, 50% and 75% substitution levels satisfied all key Marshall parameters, suggesting their greater compatibility with the AC-WC specification. (2) The incorporation of gold-mining residual sand waste as a fine aggregate substitute affects the volumetric and mechanical properties of the AC-WC mixture. Specifically, the addition of waste sand increases VIM and VMA values by up to 1.55% and 1.16% respectively, while reducing the mixture's density by 0.03%. (3) The use of GMRSW up to 75% demonstrates technical feasibility and environmental value, making it a viable option for sustainable pavement material in tropical regions. (4) Flow values remain within the standard limits of 2–4 mm, confirming that the modified mixtures maintain sufficient flexibility and deformation capacity. (5) These results support the feasibility of using gold-mining residual sand waste as a sustainable material in asphalt concrete, contributing to waste valorization and environmentally responsible infrastructure development.

Despite promising results, this study has several limitations. All tests were conducted under controlled laboratory conditions, which may not reflect field variability. Key assessments such as Scanning Electron Microscopy (SEM), angularity index analysis, and heavy metal leaching (e.g., TCLP) were not performed, limiting understanding of GMRSW's microstructural and environmental behavior. Additionally, long-term performance indicators—such as rutting, fatigue resistance, and moisture susceptibility—were not evaluated. No statistical analyses (e.g., ANOVA) were conducted to determine the significance of differences between substitution levels, which could provide more robust validation of the observed trends. Therefore, future research should incorporate statistical testing to assess the reliability of comparative results. Further studies should also focus on field trials, advanced durability testing (e.g., TSR, MIST, wheel tracking), and accelerated aging to validate field applicability. Exploring additive incorporation and gradation optimization is recommended to support substitutions beyond 75% without compromising mix quality. Additionally, evaluating a broader range of substitution ratios (e.g., 10%, 100%) is encouraged to better understand threshold effects and performance trends across the full spectrum of GMRSW incorporation. These steps will be critical to developing robust, sustainable mix design guidelines that promote the safe and effective use of GMRSW in tropical road infrastructure.

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