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Material Characterization and Mechanical Performance of Stone Matrix Asphalt Incorporating Murung Raya Local Aggregates

Khairil Yanuar[1], Surat[2*], Yogi Adriyanto[3], Rinova Firman Cahyani[4]

Politeknik Negeri Banjarmasin

Corresponding Author: Surat surat@poliban.ac.id

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A B S T R A C T

Stone Matrix Asphalt (SMA) has been increasingly adopted in pavement engineering due to its stable stone-on-stone skeleton, high binder richness, and exceptional rutting resistance under heavy traffic. This study investigates the engineering performance of SMA coarse mixtures incorporating local aggregates sourced from Murung Raya District, Central Kalimantan, Indonesia—a remote region where locally available materials remain underexplored for high-performance asphalt mixtures. The experimental program included aggregate characterization, asphalt binder testing, sieve analysis, mixture gradation design, and Marshall stability evaluations across multiple binder contents (4.0–6.0%). Aggregate results satisfied national specifications, while Marshall testing indicated that the 5.0% asphalt content yielded the most favorable volumetric properties and stability, although VIM and VMA remained higher than typical SMA thresholds due to the fine aggregate scarcity inherent in local aggregate morphology. These findings highlight both the potential and constraints of implementing SMA using Murung Raya aggregates. The study provides foundational data to support sustainable, locally sourced pavement construction in tropical, high-precipitation regions

Introduction

Asphalt pavements represent a vital component of national road infrastructure, particularly in tropical developing countries where high rainfall, elevated temperatures, and increasing freight traffic accelerate pavement deterioration. The interaction between excessive axle loads and environmental moisture typically induces premature failures such as rutting, stripping, and fatigue cracking, thereby compromising safety and increasing maintenance expenditure (Zhou et al., 2022; Du et al., 2023). In Indonesia, such failures are prevalent on strategic logistics corridors, underscoring the need for more durable surface mixtures suitable for challenging climates.

Stone Matrix Asphalt (SMA) has emerged as a high-performance mixture noted for its stone-on-stone contact structure and elevated binder content. These characteristics enhance rutting resistance, durability, and macrotexture, offering superior performance under heavy loading conditions relative to conventional dense-graded asphalt mixtures (Ding et al., 2022; Zhang et al., 2025). The coarse aggregate skeleton, comprising approximately 70–80% of the mixture, is complemented by mineral filler and modified mastics that improve stability and moisture resistance (Ma et al., 2021; Li et al., 2022). These properties make SMA particularly attractive for road networks in tropical, high-rainfall environments where hydrothermal-induced distress is prevalent.

Recent global studies demonstrate that SMA mixtures incorporating alternative filler, polymer additives, recycled wastes, or natural fibers can enhance mechanical and environmental performance (Sadeghpour et al., 2024; Athanasiou et al., 2021; Xiao et al., 2021). Research in ASEAN climates similarly confirms that SMA is suitable for humid regions with variable aggregate quality, provided the gradation and binder dosage are optimized (Nguyen et al., 2023; Gao et al., 2024). However, tropical applications frequently encounter challenges in achieving desirable volumetric properties due to the angularity and scarcity of fine aggregates, which directly affect VIM, VMA, and overall mixture integrity (Yu et al., 2023).

Despite extensive SMA research internationally, studies utilizing local materials from remote Indonesian regions—particularly Murung Raya, Central Kalimantan—remain scarce or nonexistent. Prior Indonesian studies have examined SMA using local waste fillers or volcanic aggregates, yet these investigations were not conducted in Kalimantan and did not address coarse SMA gradations using unmodified Pen 60/70 binder (Haryanto et al., 2022). Given that Murung Raya has abundant riverine and mountainous aggregate sources, evaluating their suitability for SMA is essential for reducing supply-chain dependence and supporting sustainable regional infrastructure development.

The Murung Raya–Barito Utara corridor, serving as the primary inter-district connection, experiences rapid structural degradation attributed to heavy mining traffic, varied subgrade conditions, and extreme precipitation typical of equatorial climates. Prior research suggests that SMA may mitigate rutting and moisture sensitivity in such conditions (Du et al., 2023; Zhou et al., 2022), but no published studies have confirmed this for local Kalimantan aggregates. Thus, a critical research gap exists in the scientific understanding of SMA performance using locally sourced materials from the Murung Raya region.

This study aims to fill that gap by evaluating aggregate characteristics, designing SMA gradation, and assessing Marshall properties—including Stability, Flow, VIM, VMA, VFB, and Marshall Quotient—using locally sourced aggregates and Pen 60/70 asphalt. The results contribute essential empirical data for future asphalt mixture design and support locally driven, cost-effective pavement construction in remote Indonesian regions.

Methods

The methodological framework of this study was designed to systematically evaluate the feasibility of using locally sourced Murung Raya aggregates for Stone Matrix Asphalt (SMA) coarse mixtures following international and Indonesian standards. Laboratory procedures adhered to established asphalt testing protocols, including SNI methods, AASHTO standards, and globally recognized SMA design principles (Ma et al., 2021; Li et al., 2022; Ding et al., 2022).

The research workflow consisted of five main stages: (1) aggregate sampling and preparation, (2) material characterization, (3) gradation design and mixture proportioning, (4) Marshall specimen fabrication and conditioning, and (5) performance testing and data analysis. This structure aligns with standard SMA mix design methodologies employed internationally (Nguyen et al., 2023; Athanasiou et al., 2021).

Aggregates were sourced from quarry sites in Murung Raya and prepared through drying, sieving, and splitting to ensure homogeneity. The binder used was penetration-grade 60/70 asphalt, commonly applied in tropical regions due to its viscosity and resistance to temperature fluctuations (Zhou et al., 2022). Aggregate characterization included specific gravity (bulk, SSD, apparent), water absorption, and abrasion resistance using the Los Angeles (LA) abrasion test, which evaluates aggregate toughness and degradation under mechanical stress (Gao et al., 2024).

Sieve analysis was conducted on coarse aggregates, medium aggregates, and stone dust to determine individual gradations prior to blend formulation. Combined aggregate gradations were developed through targeted trial-and-error mixing to approximate the mid-range values specified in SMA gradation limits. This iterative approach follows international best practices due to SMA's sensitivity to aggregate structure and the need to maintain stone-on-stone contact (Yu et al., 2023).

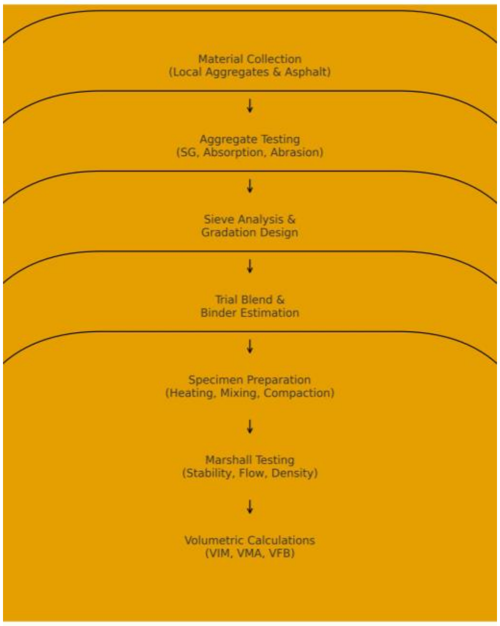
The asphalt content was estimated using a widely accepted empirical formula incorporating percentages of coarse aggregate, fine aggregate, and filler, along with a constant calibrated for SMA mixtures. Four asphalt binder contents—4.0%, 4.5%, 5.0%, and 5.5%—were selected for Marshall specimen fabrication after initial trials revealed bleeding issues at 6.5%. This binder range is consistent with global SMA literature, in which binder contents typically fall between 5–7% (Zhang et al., 2025).

Marshall specimens were mixed at 140°C, compacted with 50 blows per side, and conditioned at 60°C for 30 minutes prior to testing. Testing included measurements of stability, flow, bulk specific gravity, and maximum theoretical specific gravity. From these values, volumetric parameters—VIM, VMA, and VFB—were computed based on standard equations (Li et al., 2022; Du et al., 2023). Each parameter was evaluated against SMA specifications to identify the optimal binder content.

Data were analyzed through comparative volumetric and mechanical evaluation to identify trends in density, flow, Marshall stability, and void ratios across the asphalt content range. Interpretation aligned with international SMA performance criteria, considering rutting potential, moisture susceptibility, and skeletal integrity (Sadeghpour et al., 2024; Xiao et al., 2021).

Table 1. Summary of Experimental Methodology for SMA Coarse Mix Evaluation

Stage	**Procedure**	**Standard / Reference**	**Purpose**
Aggregate Testing	Specific gravity (bulk, SSD, apparent), absorption	SNI 1969–2016	Material suitability
LA Abrasion	Mechanical degradation	SNI 2417–2008	Assess toughness & durability
Binder Testing	Penetration, softening point, ductility, density	SNI 2456–2011, 2432–2011	Binder performance
Sieve Analysis	CA, MA, FA, filler	ASTM C136	Gradation structure
Mix Design	Trial-and-error gradation, Pb estimation	Ma et al. (2021), Li et al. (2022)	SMA stone-on-stone structure
Specimen Prep	140°C mixing, 50 blows/side compaction	ASTM D1559	Density & mechanical uniformity
Marshall Test	Stability, flow, Gmm	ASTM D6927	Mechanical characterization
Volumetric Analysis	VIM, VMA, VFB	Li et al. (2022)	Performance evaluation



Picture 1. Research Methodological Flow

RESULTS AND DISCUSSION

The evaluation of the physical properties of the Murung Raya aggregates yielded results that meet the fundamental quality criteria prescribed in the Indonesian SNI standards. Table 1 summarises the specific gravity and water absorption values for the coarse aggregate (CA) and medium aggregate (MA) fractions, which display bulk specific gravities of 2.661 and 2.629, SSD specific gravities of 2.689 and 2.661, and apparent specific gravities of 2.737 and 2.716, respectively. Water absorption values were relatively low at 1.052% and 1.210%. These metrics indicate a dense aggregate structure with low porosity, which is desirable for producing Stone Matrix Asphalt (SMA) mixtures with strong stone-on-stone contact.

Table 2. Specific Gravity and Water Absorption of Coarse Aggregates

Characteristic	Standard	Unit	CA	MA
Bulk SG	SNI 1969:2016	g/cm³	2.661	2.629
SSD SG	SNI 1969:2016	g/cm³	2.689	2.661
Apparent SG	SNI 1969:2016	g/cm³	2.737	2.716
Water Absorption	SNI 1969:2016	%	1.052	1.210

The fine aggregate (stone dust) exhibited similarly favourable characteristics, as shown in Table 2. With a bulk specific gravity of 2.667, SSD specific gravity of 2.685, and apparent specific gravity of 2.714, coupled with a low water absorption of 0.563%, the fine aggregate is of suitable quality to produce a stable mastic phase in SMA.

Table 3. Specific Gravity and Water Absorption of Fine Aggregates

Characteristic	Standard	Unit	Value
Bulk SG	SNI 1970:2016	g/cm³	2.667
SSD SG	SNI 1970:2016	g/cm³	2.685
Apparent SG	SNI 1970:2016	g/cm³	2.714
Water Absorption	SNI 1970:2016	%	0.563

The mechanical strength of the coarse aggregates was assessed using the Los Angeles abrasion test. Table 3 presents the abrasion loss of 28.11%, which is below the maximum allowable limit of 30%, demonstrating that these aggregates possess adequate resistance to fragmentation during mixing and service.

Table 4. Los Angeles Abrasion Test Result

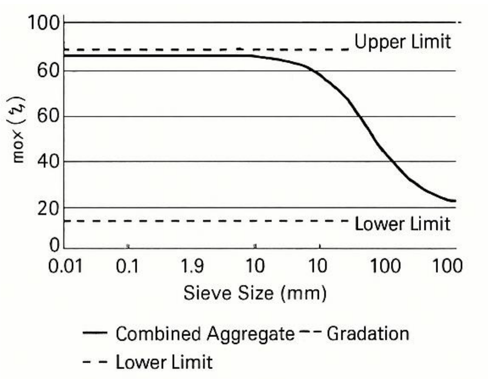
Characteristic	Standard	Unit	Result	Requirement
LA Abrasion	SNI 03-2417:2008	%	28.11	≤ 30

The sieve analysis results for CA, MA, and fine aggregate (FA) reveal the expected gap-graded structure necessary for SMA production. Table 4 summarises the percentage passing for each aggregate fraction, showing that the CA fraction progressively decreases in passing percentage with smaller sieve sizes, while MA and FA demonstrate a finer gradation profile.

Table 5. Sieve Analysis Results

Sieve Size (mm)	CA (%)	MA (%)	FA (%)
25.0	100	100	100
19.1	93.61	100	100
12.7	64.42	100	100
9.52	26.29	100	100
4.76	2.39	44.00	98.5
2.38	1.08	16.90	94.83
0.075	0.22	0.98	4.15

A combined aggregate gradation was then produced using a 70% CA, 8% MA, 20% FA, and 2% filler blend. When plotted against the SMA specification bands, the gradation lies predominantly within the required range. A text-formatted representation of the gradation is provided in Picture 2.



Picture 2. Combined Aggregate Gradation

(*Narrative integration: The combined gradation generally aligns with the SMA envelope, though the finer fraction appears insufficient to fill the voids within the coarse aggregate skeleton.*)

The binder content was estimated using empirical formulas, leading to an initial Pb ≈ 5.5%. However, laboratory trials confirmed bleeding at 6.5%, resulting in the selected binder content range of 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% for the Marshall evaluation.

Marshall specimens prepared using these binder contents yielded performance trends that highlight the influence of binder percentage on mixture volumetrics and strength. Density values increased from 2.215 g/cm³ at 4.0%, peaked at 2.240 g/cm³ at 5.0%, then decreased with higher binder contents. The behaviour is summarised in Table 5 and visualised textually in Figure 2.

Table 6. Bulk Density vs. Binder Content

Binder Content (%)	**Density (g/cm³)**
4.0	2.215
4.5	1.931
5.0	2.240
5.5	1.985
6.0	1.988

```
2.30 |          ● (5.0%)
2.25 |     ● (4.0%)
2.20 |
2.15 |
2.10 |
2.05 |               ● (5.5%)
2.00 |           ● (6.0%)
1.95 | ● (4.5%)
1.90 |_____________________________________________
      4.0    4.5    5.0    5.5    6.0   (% Asphalt)
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Picture 3. Density Variation

The optimum density at 5.0% asphalt corresponds to enhanced aggregate packing and reduced inter-particle voids.

Flow values displayed a sinusoidal behaviour with the lowest deformation occurring at 5.0%. Excessive flow was observed at 4.5%, 5.5%, and 6.0%, indicating plastic mixture behaviour and inadequate internal stability. The flow response is summarised in Table 7.

Table 7. Marshall Flow Values

Binder Content (%)	**Flow (mm)**
4.0	2.8
4.5	7.8
5.0	2.2
5.5	5.9
6.0	6.0

Air voids (VIM) and voids in mineral aggregate (VMA) were significantly higher than specification requirements. Target VIM for SMA is typically 3–5%, yet measured values ranged from 11.45% to above 24%, demonstrating a porous structure. Table 8 summarises these findings.

Table 8. Air Void (VIM) Values

Binder Content (%)	**VIM (%)**
4.0	13.76
4.5	24.24
5.0	11.45
5.5	20.90
6.0	23.76

This excessive void presence is attributable to insufficient fine aggregate and filler within the matrix, confirming that the aggregate skeleton lacks adequate packing density.

The Marshall stability values shown in Table 8 indicate that only the 5.0% asphalt content achieved compliance with the SMA stability requirement of ≥ 600 kg.

Table 9. Marshall Stability

Binder Content (%)	**Stability (kg)**
4.0	520
4.5	551
5.0	650
5.5	523
6.0	499

The peak value of 650 kg at 5.0% aligns with the optimal density and minimal flow at this binder content, reinforcing the conclusion that the mixture performs best at 5.0%, despite still not meeting VIM specifications.

Across all results, the key observation is that the **aggregate quality is adequate**, and the **binder performance is acceptable**, but the **combined gradation and insufficient filler content result in elevated voids and instability outside the 5% binder level**. Thus, the primary limitation is not material quality but **volumetric design**, specifically the fine fraction content.

CONCLUSION

This study evaluated the feasibility of using local Murung Raya aggregates for Stone Matrix Asphalt (SMA) coarse mixtures through detailed aggregate characterization, gradation analysis, and Marshall performance testing. The findings demonstrate that the aggregates fulfill fundamental physical and mechanical requirements, including specific gravity, absorption, and abrasion resistance, indicating their intrinsic suitability for SMA skeletal structures. However, volumetric analyses revealed significant deviations from standard SMA criteria, particularly in VIM and VMA values, attributable to inadequate fine aggregate fractions and the inherently porous aggregate nature typical of regional river and mountain deposits.

Marshall testing confirmed that a binder content of 5.0% produced the most balanced performance, exhibiting maximum density, acceptable flow values, and the highest stability exceeding specification thresholds. Nevertheless, elevated void content persisted even at the optimum binder level, highlighting the necessity for gradation refinement or incorporation of supplementary fines or mineral fillers to achieve compliance with SMA standards.

These results underscore both the potential and limitations of deploying Murung Raya materials for SMA applications. While the aggregates possess adequate mechanical strength, achieving suitable volumetric balance requires improved aggregate processing, optimized fine aggregate production, or innovative filler augmentation strategies. This research provides essential baseline data supporting the advancement of region-specific SMA pavement designs in Central Kalimantan and contributes to broader efforts toward sustainable, locally sourced road construction in tropical environments.

Future work should investigate modified mastic compositions, polymer-enhanced binders, or fiber reinforcement to enhance durability, moisture resistance, and structural performance in alignment with modern SMA advancements reported globally.

REFERENCES

Athanasiou, E., Gkekas, C., Kalagasidis, A., & Nikolaides, A. (2021). Evaluation of Stone Mastic Asphalt mixtures containing various types of fibers. Construction and Building Materials, 268, 121177. https://doi.org/10.1016/j.conbuildmat.2020.121177

Ding, X., Ma, T., Zhang, D., & Hu, J. (2022). Influence of aggregate morphological characteristics on SMA rutting resistance. International Journal of Pavement Engineering, 23(8), 3010–3021. https://doi.org/10.1080/10298436.2020.1838011

Du, Y., Ma, B., & Ma, J. (2023). Laboratory evaluation of high-content asphalt SMA mixtures under tropical environmental conditions. Journal of Traffic and Transportation Engineering, 10(2), 245–254. https://doi.org/10.1016/j.jtte.2021.11.004

Gao, J., Zhang, Y., & Cao, X. (2024). Mechanical and volumetric properties of Stone Mastic Asphalt using basalt and limestone aggregates. Construction and Building Materials, 389, 131715. https://doi.org/10.1016/j.conbuildmat.2023.131715

Li, J., Chen, S., Wang, L., & Li, X. (2022). Optimizing fines and filler content in SMA mixtures for improved durability. Journal of Materials in Civil Engineering, 34(7), 04022143. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004289

Ma, T., Yu, H., Zhang, D., & Huang, X. (2021). Effects of mineral filler type on the viscoelastic behavior of asphalt mastic in SMA.

Construction and Building Materials, 292, 123482. https://doi.org/10.1016/j.conbuildmat.2021.123482

Nguyen, T., Bui, T., & Do, H. (2023). Characterization of SMA mixtures using local aggregates under Southeast Asian climate conditions. Sustainability, 15(1), 512. https://doi.org/10.3390/su15010512

Sadeghpour, G., Ziari, H., & Khabiri, M. (2024). Evaluation of SMA mixtures reinforced with natural fibers. Journal of Cleaner Production, 436, 140655. https://doi.org/10.1016/j.jclepro.2023.140655

Xiao, F., Amirkhanian, S., & Hou, X. (2021). Performance evaluation of SMA mixtures incorporating warm-mix and recycled additives. Journal of Materials in Civil Engineering, 33(5), 04021070. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003678

Yu, H., Ma, T., & Li, N. (2023). Relationship between aggregate gradation and mastic distribution in SMA mixtures. Materials, 16(4), 1508. https://doi.org/10.3390/ma16041508

Zhang, D., Ma, T., Han, S., & Sun, L. (2025). Multi-scale analysis of SMA skeleton structure and its influence on rutting performance. Construction and Building Materials. https://doi.org/10.1016/j.conbuildmat.2024.133984

Zhou, X., Chen, Z., & Huang, B. (2022). Influence of tropical rainfall and temperature on moisture damage in SMA mixtures. Journal of Transportation Engineering Part B: Pavements, 148(3), 04022039. https://doi.org/10.1061/JPEODX.0000370