Optimizing Nickel Slag in Stone Matrix Asphalt: A Sustainable Alternative to Natural Coarse Aggregate

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Received: 27 March 2025 | Revised: 25 April 2025 and 13 May 2025 | Accepted: 15 May 2025

DOI: https://doi.org/10.48084/etasr.11175

ABSTRACT

This study investigated the potential of utilizing water-cooled Nickel Slag (NS) as a replacement for Crushed Stone (CS) in Stone Matrix Asphalt (SMA) mixtures, where structural strength relied on aggregate interlocking. Key empirical parameters from the Marshall test, including stability, flow, Void in Mix (VIM), Void in Mineral Aggregate (VMA), and asphalt drainage, were assessed across asphalt content levels of 6%, 6.25%, 6.5%, 6.75%, and 7%. The results indicated that the optimum Marshall characteristics for SMA mixtures using 100% NS as coarse aggregate occurred at an asphalt content of 6.25%, corresponding to those of conventional CS mixtures. Additionally, they exhibited high stability and low flow, enhancing resistance to rutting and permanent deformation, while their low asphalt absorption reduced binder demand. These finding suggests that NS is a viable, cost-effective alternative to natural aggregates.

Keywords-nickel slag; crushed stone aggregate; SMA; Marshall characteristics; draindown

I. INTRODUCTION

Road infrastructure development has been prioritized by the government to enhance regional connectivity, economic growth, and the transportation sector [1]. However, the lack of road construction materials contributes to the delay of these infrastructure projects. One solution to this challenge is the utilization of industrial waste from excavated materials, including slag, coal ash, and tailings, as they meet the appropriate specifications, are easy to use, and cost-effective. Nevertheless, if not managed properly, these wastes can pose significant environmental risks. Current waste management practices focus on processes in order to comply with environmental regulations rather than addressing the root of the problem. This approach requires substantial costs and fails to provide a long-term solution [2]. Among various minerals, nickel is of great importance. Indonesia includes a high amount of nickel ore resources (11,887 million tons), with 5,094 million tons inferred, 5,094 million tons indicated, 2,626 million tons measured, and 228 million tons being hypothetical. A significant byproduct of nickel production is slag waste, generated during the smelting of metal ores, such as nickel, iron, and steel. After extracting certain metals, the remaining stuff solidifies into slag, with annual deposits exceeding 1.5 million tons. Physically resembling natural stone, slag waste can be processed into various sizes, making it a promising alternative to natural aggregates. Proper utilization and management of NS waste could not only reduce environmental impact, but also support sustainable construction practices [3].

In South Sulawesi Province, one of the key nickel smelters operating is PT. Huadi Nickel Alloy Indonesia (PT. HNAI), located in the Bantaeng Regency Industrial Estate [4]. With nickel playing a crucial role in renewable energy and the electric vehicle industry, PT. HNAI has successfully processed NS into construction materials, such as concrete, bricks, and paving blocks similar to the Harita Group in North Maluku, which produces 2 million tons of slag-based products. However, this industry focuses on producing Nickel Pig Iron (NPI), which contains the lowest nickel content (2-15%) compared to ferronickel (15-40%) and Ni-matte (30-80%). The lack of a clear strategy for utilizing NS, which has accumulated to 2 million tons, has resulted in land overuse and rising operational costs. Addressing this issue could unlock new opportunities for sustainable waste management and cost efficiency [5].

SMA is widely used in asphalt pavement technologies for achieving high stability [6, 7]. It is classified as an open-graded pavement, which means it contains a high percentage of coarse aggregates. While it effectively resists in cracking and deformation, surface damage can occur. Additionally, SMA is typically 20% - 25% more expensive than Hot Mix Asphalt (HMA), which highlights the need for alternative materials. Authors in [8] indicated that nickel waste met Bina Marga (2018) standards and is suitable for road pavement mixes. Authors in [9] investigated the resistance effect of adding Palm Leaf Fibers (PLF) to HMA on cracking. Their results suggested that the Indirect Tensile Strength (ITS) test by itself was not enough to figure out how a mixture will behave, since it depends heavily on peak load. Authors in [10] revealed that HMA with 40% of Reduced Ferronickel Slag (RFNS) exhibited an average elastic modulus of 6.323 MPa, using the Marshall method and a visual inspection after four years, demonstrating that the pavement remained in excellent condition. Additionally, authors in [11] observed a deformation of 5.3 mm in anti-dust-treated mixtures under a 33 kg load, compared to 7.76 mm in stabilized reject-emulsion mixtures. In [12], the reuse of iron ore waste was evaluated in road construction. A mixture of 50% waste in Phyllite Residual Soil (PRS) improved strength by 130% and met Brazilian sub-base standards. Lateritic Clayey Soil (LCS) indicated moderate gains at 20% waste, but performance declined with higher amounts.

II. EXPERIMENTAL PROCEDURE

A. *Material Characteristics*

This study utilized several materials in the SMA mixture, including coarse and fine aggregate, filler, and a stabilizer. NS obtained from water-cooled NS, produced by PT Huadi Nickel-Alloy in Bantaeng Regency, South Sulawesi, Indonesia, was used as a full replacement (100%) of coarse aggregate. The fine aggregate consisted of CS derived from Bili-Bili dam in Gowa Regency, Indonesia. Portland Composite Cement (PCC) from Semen Tonasa served as the filler, and as for the binder, PT Pertamina Indonesia provided 60/70 penetration asphalt. Additionally, 0.3% of the total mixture weight incorporated a natural stabilizer in the form of 6 mm palm fiber. Palm fiber was added as it is a natural cellulose-based fiber with high lignin content, which enhances its resistance to decay and dimensional stability. It also complies with Bina Marga regulations, which limit natural fiber content to a maximum of 0.3%. Figure 1 illustrates the utilized materials in the SMA mixture.

Fig. 1. Asphalt mix materials: (a) NS, (b) CS, (c) cement filler, and (d) palm fiber.

Physical property testing was essential to evaluate the performance of the SMA mixture. Coarse aggregate forms a structural framework that supports the load, while fine aggregate fills the voids, binding with asphalt to create a stable mix. Table I presents the results of the laboratory tests.

TABLE I. TEST RESULT AGGREGATE CHARACTERISTICS

Testing	Spesification	Aggregate test results	
		Local	NS
Abrasion	Max 30%	12.89%	24.48%
Bulk density of coarse aggregate			
Bulk	≥ 2.5	2.62	2.64
SSD	≥ 2.5	2.65	2.67
Apparent	≥ 2.5	2.70	2.71
Absorption	< 3	1.11	0.81
Flakiness & Elongated (1:5)	<5%	1.11% & 1.53%	2.78% & 2.81%
Angularity	100/90	100/98	100/95
Sand equivalent value	Min 12%	96.20%	-
Material passing sieve no. 200	Max 1%	0.40%	-

NS primarily consisted of 59.03% silica (SiO_2), 19.1% iron compounds (FeO/Fe_2O_3), 15.46% alumina (Al_2O_3), 2.53% chromium oxide (Cr_2O_3), 2.09% calcium oxide (CaO), 1.53% manganous oxide (MnO), and trace amounts of other elements. This composition contributed to the chemical stability and structural strength required for road construction applications [1, 2, 13]. The aggregate gradation followed the [14] standards in [14], specifically, aligning with the coarse SMA gradation curve as specified in [15] standard. The specifications established upper and lower limits for each aggregate fraction, and a middle value gradation was utilized. For the coarse aggregate fraction, 100% NS and 100% CS were employed with mixed asphalt contents of 6%, 6.25%, 6.5%, 6.75%, and 7%, as presented in Table II and Figure 2. The detailed composition is depicted in Table III.

TABLE II. SPECIFICATIONS AND GRADATION OF SMA MIXED AGGREGATES

Sieve size		Sieve passing			
in	mm	Specifications (%)			Mix gradation (%)
1½	37.500				-
1	25.000		100		100
¾	19.000	90	-	100	95.00
½	12.500	50	-	88	69.00
3/8	9.500	25	-	60	42.50
No.4	4.750	20	-	28	24.00
No.8	2.360	16	-	24	20.00
No.16	1.180		-		-
No.30	0.600		-		-
No.50	0.300		-		-
No.100	0.150		-		-
No.200	0.075	8	-	11	9.50
Pan (filler)					9.5
Asphalt					6.00

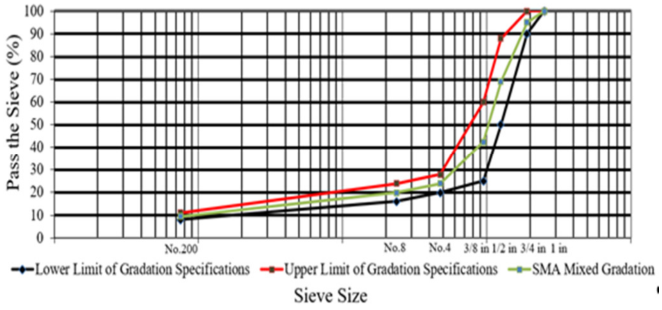

Fig. 2. Graph of aggregate mix combinations for SMA.

TABLE III. SMA MIXTURE COMPOSITION

Sieve size		Asphalt content (%)				
in	mm	6.00	6.25	6.50	6.75	7.00
1½ in	37.500	-				
1 in	25.000					
¾ in	19.000	49.71	49.29	48.86	48.43	48.00
½ in	12.500	301.71	301.29	300.86	300.43	300.00
3/8 in	9.500	307.71	307.29	306.86	306.43	306.00
No.4	4.750	211.71	211.29	210.86	210.43	210.00
No.8	2.360	37.71	37.29	36.86	36.43	36.00
No.16	1.180	-				
No.30	0.600					
No.50	0.300					
No.100	0.150					
No.200	0.075	115.71	115.29	114.86	114.43	114.00
Pan (filler)		103.71	103.71	103.29	102.86	102.43
Asphalt		72.00	72.00	75.00	78.00	81.00
Total (g)		1200	1200	1200	1200	1200

B. Stone Matrix Asphalt Mixture Testing Method

The primary objectives of asphalt mixture testing was to verify compliance with technical specifications, ensure quality and consistency, assess stability and durability, optimize density and air voids, enhance economic and environmental efficiency, and evaluate the performance under varying traffic and weather conditions. The specifications for the SMA mixture, as stated in [14], are presented in Table IV.

TABLE IV. SMA MIX SPECIFICATIONS

Properties of mixtures		Requirements
Asphalt content (%)		6.0 - 7.0
Number of collisions per field		50
VIM (%)	Min	4.0
	Max	5.0
VMA (%)	Min	17
Draindown at production temperature (%) by weight in mixture (1-Hour Duration)	Max	0.3
Marshall stability (kg)	Min	600
Flow (mm)	Min	2.0
	Max	4.5
Cellulose fiber:		
% by weight in mixture	Max	0.3
Fiber length (mm)		6.35

Based on these specifications, the mixture tests conducted in this study included:

1) Marshall Test

To assess the impact of using NS as a substitute for CS coarse aggregate, a Marshall test was conducted following SNI 2489 [16]. This test evaluated the SMA mixture's stability, flow, and volumetric properties, including VIM and VMA, serving as indicators of the asphalt mixture's resistance to applied loads. As displayed in Figure 3, the Marshall apparatus is a modified version of the Universal Testing Machine (UTM) [16].

Fig. 3. Marshall test apparatus.

2) Asphalt Drain-down Test

Asphalt flow testing was performed according to the AASHTO T 305 [17] drain-down test to assess the asphalt flow within the mixture, particularly when using NS as a substitute for coarse aggregates and natural palm fiber as a stabilizing agent. This procedure confirmed that the SMA mixture remains stable, homogeneous, and within specifications, enhancing pavement durability and performance. Figure 4 portrays the drain-down test apparatus.

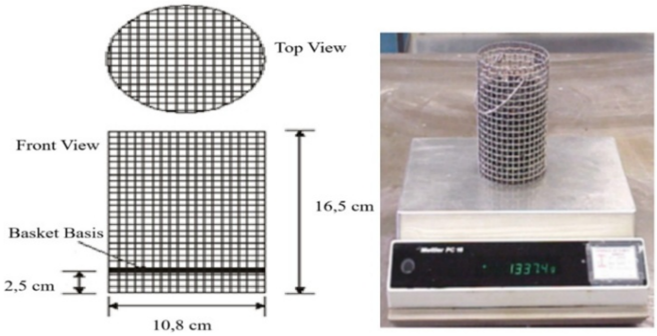

Fig. 4. Drain-down test apparatus.

III. RESULTS AND DISCUSSION

A. Marshall and Volumetric Characteristics

SMA is a pavement mixture with a coarse aggregate gradation, higher asphalt content, and fillers, such as cellulose fibers, to prevent bleeding. The Marshall test for SMA assessed stability, flow, density, and air voids to ensure high resistance to deformation and cracking. The key parameters obtained from the Marshall test are:

1) Stability

Stability is the ability of a paved mixture to withstand loads before plastic (permanent) deformation occurs. Figure 5 illustrates the stability of SMA mixtures using NS as a substitute for coarse aggregate. The stability of both mixtures increased as the asphalt content rose to 6.25% and then declined when it reached 7%. This occurred due to the addition of asphalt, which strengthened the interlocking bond between aggregates. However, excessive asphalt created a thicker coating between aggregates, weakening the bond and reducing structural stability. SMA mixtures incorporating NS as a coarse aggregate replacement exhibited lower stability than those using traditional aggregates. This reduction can be attributed to the smoother, less water-absorbent surface and the more rounded shape of NS, which weakens aggregate interlock. Nevertheless, the stability values remained within the minimum requirement of 600 kg, as specified in [14] standard.

2) Flow

Flow measures the asphalt mixture's ability to undergo plastic deformation before cracking or failure. Figure 6 shows the flow characteristics of the mixture. The flow value decreased as the asphalt content increased, reaching 6.25% for non-NS mixtures and 6.5% for NS mixtures, and then increased to 7%. When compressed, the asphalt separated more easily, reducing flow. The flow values met the requirements of [14], ranging from 2 mm to 4.5 mm [14].

3) Void in Mix

VIM represents the amount of empty space between the aggregate particles in the compacted asphalt mixture, given as a percentage. This value is crucial as it impacts the mixture's resistance to deformation, bleeding, and water infiltration, leading to premature damage. The VIM values for the mixture are depicted in Figure 7. A decrease was observed when the asphalt content increased, since asphalt acted as a binder and filled the voids between aggregate particles. According to the general specifications of [14], the required VIM value ranges from 4% to 5%, and all test results were within this variation [14].

4) Void in Mineral Aggregate

VMA represents the total volume of voids within the aggregate that can be filled by asphalt and air in HMA. An optimal VMA helps prevent rutting (permanent deformation) and cracking under traffic loads. The test results for VMA are exhibited in Figure 8.

B. Stability-Flow Relationship in Stone Matrix Asphalt Mixtures

The stability of a paved mixture is generally inversely proportional to its flexibility (flow). A mixture with high stability but low flow due to insufficient asphalt becomes brittle and prone to cracking. Conversely, excessive asphalt increases flow but reduces stability, making the mixture too soft and susceptible to deformation.

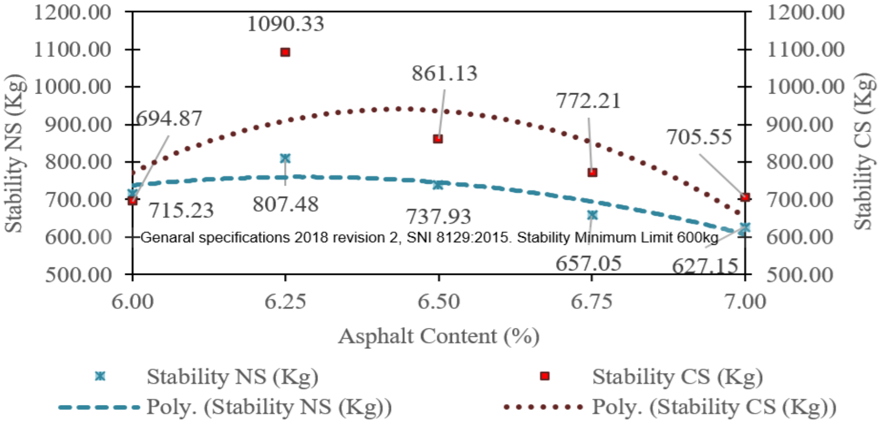

Fig. 5. Stability of SMA mixtures.

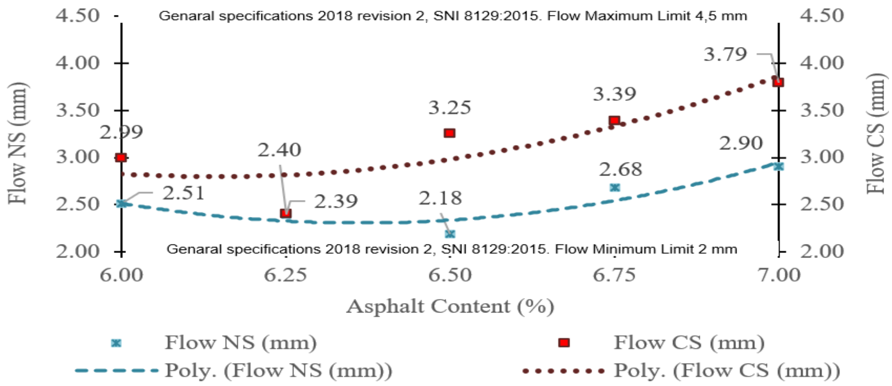

Fig. 6. Flow of SMA mixtures.

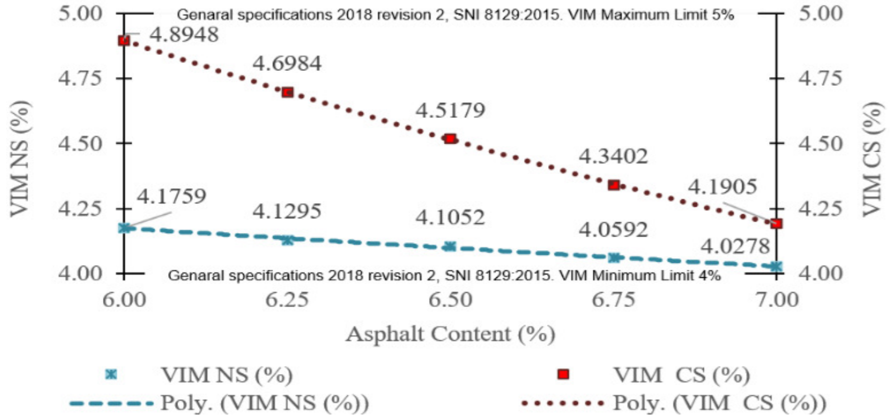

Fig. 7. VIM of SMA mixtures.

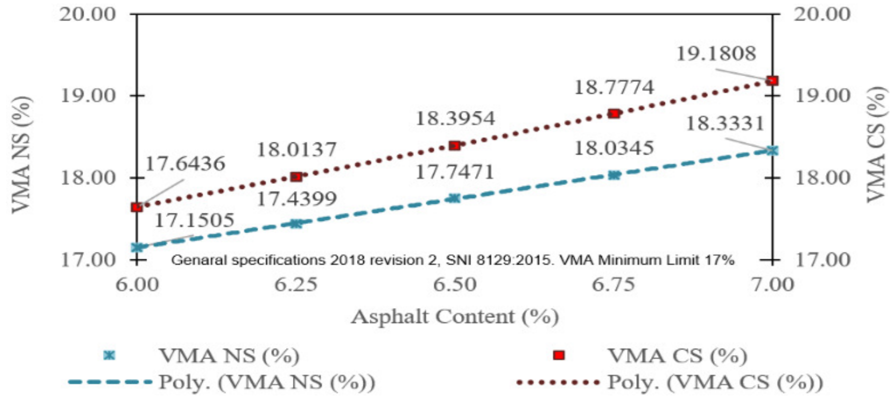

Fig. 8. VIM of SMA mixtures.

Gradation also plays a key role as coarser gradation enhances stability but reduces flow, resulting in a stiffer mixture. In contrast, finer gradation lowers stability while increasing flow, making the mixture softer. Additionally, aggregate shape and texture significantly affect the overall performance. Rough, angular aggregates improve interlocking, enhancing stability, while smoother, more rounded aggregates increase flow due to weaker bonding. Achieving a balance between stability and flow is essential for a durable, damage-resistant pavement. The relationship between stability and flow is depicted in Figure 9. Regarding the relationship between stability and flow in SMA mixtures using NS, high stability and low flow were demonstrated, whereas mixtures using CS exhibited high values for both. This confirms that the smoother surface and rounder shape of NS influenced both parameters.

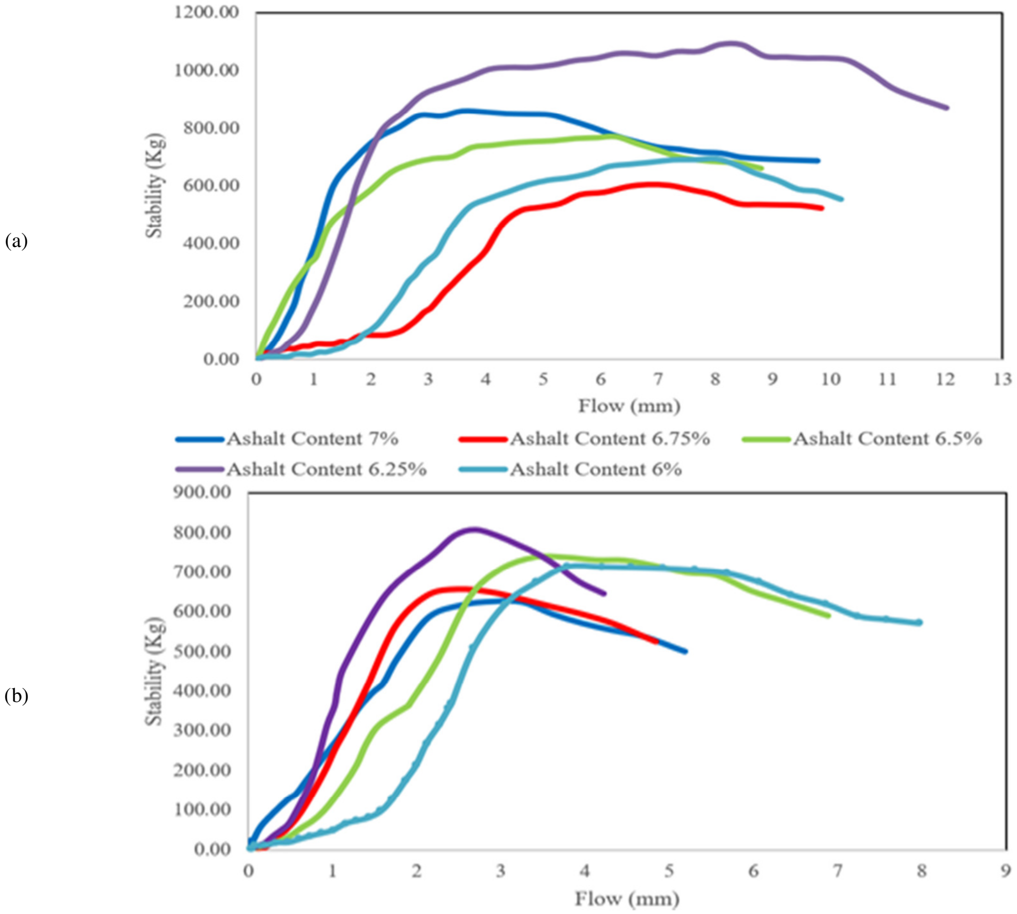

Fig. 9. The relationship between stability and flow. (a) SMA with 100% CS, (b) SMA with 100% NS.

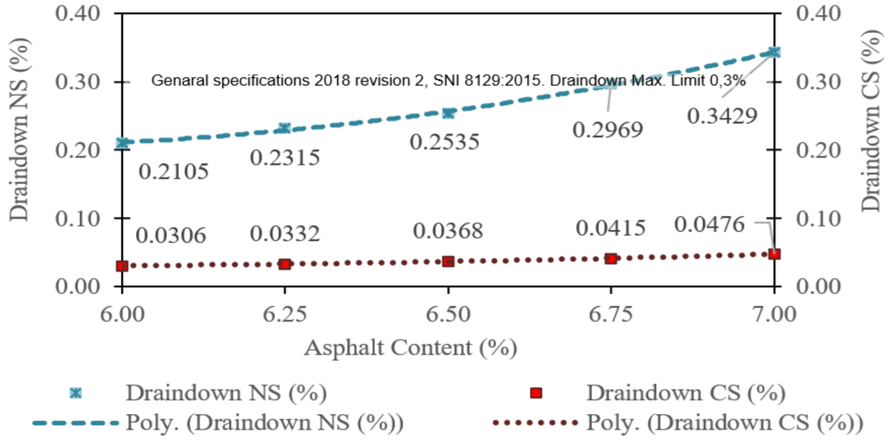

Fig. 10. Draindown testing results.

C. Drain-Down

Drain-down is the separation and downward flow of asphalt or filler in HMA during storage, transportation, or compaction before the mix hardens. This issue is common in asphalt mixes with high asphalt content, particularly those with open aggregate gradations, like SMA. To mitigate this issue, fiber was added to reduce asphalt and filler movement. The drain-down test results are presented in Figure 10. In SMA mixtures with NS, drain-down increased with asphalt content, exceeding specification limits at 7%. Meanwhile, in mixtures using CS, drain-down remained minimal, ranging only from 0% to 0.1%.

D. Discussion

The stability values observed in this study were lower than those reported in [8], probably because the NS from PT Vale Soroako Indonesia had different shape and texture. In [11], a deformation of 5.3 mm was detected in anti-dust-treated mixtures under a 33 kg load, compared to 7.76 mm in stabilized reject-emulsion mixtures. Similarly, anti-dust-treated mixtures of reject soil and emulsion deformed by 4.16 mm, versus the 6.99 mm of deformation recorded for the stabilized ones. This study revealed lower deformations: 2.18-2.90 mm for NS and 2.40-3.79 mm for CS.

IV. CONCLUSION

This study investigated the utilization of Nickel Slag (NS) as an eco-friendly alternative to coarse aggregate in Stone Matrix Asphalt (SMA) mixtures, particularly in terms of stability, resistance to deformation, and durability under varying environmental conditions. Despite some research on other industrial slags, such as steel and copper, no systematic studies have been conducted on the use of NS from Bantaeng in SMA mixtures for road construction.

The main conclusions of this study are:

- SMA mixtures can incorporate NS from Bantaeng Regency, Indonesia, as a road pavement material.
- Due to its smoother surface texture, rounded shape, and low absorption rate, NS influenced the Marshall characteristics, volumetric properties, and asphalt flow in SMA mixtures. These properties led to lower stability, increased flow, reduced Void in Mix (VIM), higher Void in Mineral Aggregate (VMA), and greater drain-down compared to previous studies that used steel slag or NS from other industrial sources.
- The maximum asphalt content to prevent drain-down was found at 6.75%, as exceeding this, such as by using 7% asphalt, resulted in a flow rate above the standard limit [14].
- The optimal asphalt content was 6.25%, providing the highest stability at 807.48 kg (well above the minimum requirement of 600 kg) and an ideal flow rate of 2.39 mm. Both values fell within the specified performance criteria.

Thus, this study not only addressed the industrial waste management and the depletion of natural aggregates, but also provided a solid scientific foundation for the broader NS adoption in sustainable road construction. Other types of asphalt pavement require further research.

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