Mechanical and Microstructural Evaluation of Utilizing Nickel Slag as Sustainable Aggregate in Asphalt Mixtures

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ABSTRACT

The use of industrial waste materials in asphalt mixes boosts sustainability in road building. This research examines the mechanical properties and microstructure of Nickel Slag (NS) in Stone Matrix Asphalt (SMA) mixes. NS replaces the coarse aggregates in asphalt. SMA test samples were prepared with different NS levels (0%, 50%, and 100%) at asphalt contents of 6%, 6.25%, 6.5%, 6.75%, and 7%. Mechanical testing employed the Marshall method to assess volumetric properties, stability, and flow. The highest stability scores for each mix occurred at an asphalt content of 6.5%, with values of 1031 kg, 919 kg, and 809 kg for SMA NS 100, SMA NS 50, and SMA Crush Stone (CS), respectively, surpassing the minimum requirement of 600 kg. The Voids in the Mix (VIM) values ranged from 3.078% to 4.95%, aligning with the standard of 3%–5%. The Voids in Mineral Aggregate (VMA) values ranged from 17.73% to 21.68%, all above the minimum of 17%. The flow values increased as the NS content grew, all meeting the 2 mm–4.5 mm requirement; however, SMA NS 100 at 6.75% and 7% asphalt exceeded this limit (4.66 mm and 5.00 mm). The Scanning Electron Microscope (SEM) analysis of the microstructure revealed a rough NS surface, which helped improve the asphalt-aggregate bonding. The XRD testing of the NS elements showed dominant components like O (20.96%), Si (19.97%), Ni (16.65%), Al (8.74%), and Fe (5.83%), present as silica (SiO_2), nickel oxide (NiO), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), potentially increasing mixture stability. This study demonstrates that NS can be a viable alternative material for road pavement asphalt.

Keywords-nickel slag; stone matrix asphalt; Marshall test; SEM; EDX; sustainable pavement

I. INTRODUCTION

Road infrastructure construction is increasing to support the mobility of people and goods, in line with the growth of various daily life aspects. Quality road infrastructure is an important requirement in supporting economic, social, and cultural activities. However, in this development effort, environmental sustainability needs to be considered, especially in the provision of infrastructure materials. The excessive use of natural materials, such as aggregates from local rivers and hills, can further damage the natural balance and ecosystems. Therefore, the utilization of waste materials, such as industrial waste for road construction, is an attractive alternative that not only reduces the environmental impact, but also adds value to materials previously considered waste. The service life of roads is declining more rapidly due to the increasing number and weight of vehicles. One of the most common forms of pavement damage is rutting, a permanent deformation caused by repeated heavy loads. Adverse weather conditions, such as heavy rainfall, can further reduce the effectiveness of pavement structures. For this reason, selecting appropriate construction materials is essential to address road deterioration. SMA has gained attention as a solution because of its proven resistance to permanent deformation, particularly rutting, on heavily trafficked roads. SMA is an open-graded asphalt mixture with a high asphalt content and strong stone-on-stone contact, which provides greater resistance to repeated loading [1]. Laboratory tests and field applications confirm that SMA mixtures perform better against rutting under high temperatures than dense-graded mixtures, especially when designed with proper gradation and modifiers [2, 3]. Indonesia, the world's largest nickel producer with over 40% of the global output [4], generates substantial NS as a byproduct of smelting. This waste material presents significant potential for use in construction, particularly as a coarse aggregate in asphalt mixtures. Utilizing NS can help reduce the reliance on natural aggregates, improve the waste management efficiency, and lower the costs [5]. Slag-based aggregates have been widely studied as sustainable substitutes, with Life Cycle Analysis (LCA) showing that incorporating steel slag can reduce the carbon emissions by up to 14% compared to conventional aggregates [6], while also lowering the energy consumption during production [7]. In addition, slag enhances asphalt pavement durability, extends service life, and reduces maintenance-related emissions.

Studies on the heavy metal concentration of NS demonstrate its safety as a construction material [8, 9]. The Indonesian government has reclassified NS, eliminating its designation as hazardous or toxic waste, thereby facilitating new opportunities [10]. The feasibility of incorporating slag elements into asphalt mixtures has been demonstrated. The mechanical properties of the composites exhibit adherence to the established standards. Incorporating NS into hot-mix asphalt with a dense gradient could enhance Marshall stability and decrease deformation [11]. The incorporation of NS as a substitute for coarse aggregate in asphalt concrete formulations significantly enhances the mechanical integrity and abrasion resistance of the pavement structure. [12]. Adding steel slag aggregates to warm asphalt mixes makes the Marshall stability, stiffness, and resilience modulus of the asphalt mixtures more appealing, which means that the structure is stronger when traffic is on it [13]. Research on varying amounts of steel slag has shown that its unique physical properties, such as a coarse surface texture and high density, improve the moisture resistance and efficacy of asphalt concrete. Microstructural analyses of slag have been conducted to enhance the comprehension of its characteristics as an aggregate in road construction. These tests may yield more comprehensive insights into the structure, material content, texture, and morphology of slag, hence enhancing its effective utilization in asphalt mixtures. Steel slag with high angularity and surface texture has been shown to lower skid risk, based on microstructural analysis. This is crucial not only for safety, but also for how well the road surface works in different weather conditions [14, 15]. The objective of this study is to test how well SMA mixtures perform mechanically when NS is used as the coarse material. Marshall testing was performed for mechanical assessment, while microstructural analysis was undertaken utilizing a SEM with Energy Dispersive X-ray Spectroscopy (EDX). This study aims to enhance the awareness and application of NS as a more sustainable alternative material for road construction.

II. MATERIALS AND METHODS

A. Materials

SMA mixtures are made up of coarse and fine aggregate, filler, and bitumen binder. In this study, all materials met the 2018 Revision 2 standards from the Directorate of Highways [16]. The aggregates were sourced from crushed stone in the Bili-Bili area, South Sulawesi, selected for their strong physical properties. To utilize industrial waste, part of the coarse aggregate was replaced with air-cooled NS from PT Vale Indonesia Tbk's smelting operations in Sorowako. Portland Pozzolan Cement (PPC) from PT Semen Tonasa was employed as the filler, while 60/70 penetration asphalt produced by PT Pertamina served as the binder. To mitigate the asphalt drain down during the mixing and compaction process, coconut fibers of 6 mm length were incorporated at 0.3% of the mixture's weight. The role of natural fibers as stabilizing agents in SMA has been highlighted, with coconut fiber identified as one of the most effective due to its ability to reduce the drain down and enhance the structural integrity [17]. All materials satisfied the required technical specifications, with coarse and fine aggregate characteristics reported in Table I and the CS–NS aggregates illustrated in Figure 1.

TABLE I. CHARACTERISTICS OF AGGREGATE MATERIALS

Testing	**Result**		**Specification requirements**
	CS	**NS**	
Coarse aggregate			
Los Angeles Abrasion	16.34%	11.42%	Max 30%
Specific gravity:			
Bulk	2.59	2.89	≥ 2.5
Saturated surface dry	2.64	2.92	≥ 2.5
Apparent	2.73	2.99	≥ 2.5
Water absorption	2.03%	0.86%	< 3%
Flakiness /longiness index (1:5)	2.63% /2.35%	1.13% /1.06%	<5%
Angularity	100/90	100/97	100/90
Fine aggregate			
Sand equivalent	95.5%		Min 12%
Material passing sieve No. 200	0.38%		Max 1%

Fig. 1. CS and NS Coarse aggregates used in this study.

B. Preparation of Test Specimens

Asphalt mixture production was conducted in accordance with the standards prescribed in [18], which serves as the guideline for SMA mixtures in Indonesia. In accordance with the relevant standard, the blend utilized was SMA Fine, defined by a nominal maximum aggregate size of 12.5 mm. The gradation of the mix used is displayed in Figure 2.

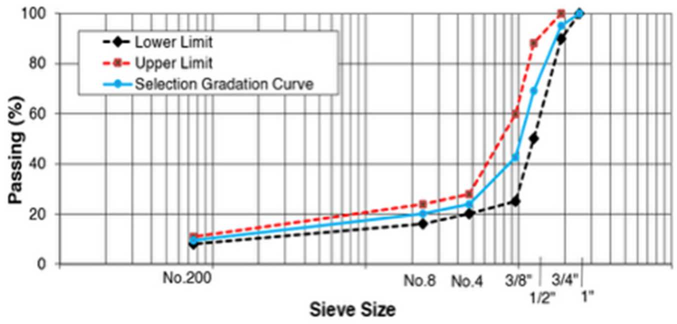


Fig. 2. Gradation of SMA Fine.

TABLE II. PROPORTION OF SMA CS GRADATION MIX

Sieve	Asphalt content									
	6%		6.25%		6.5%		6.75%		7%	
	CS	NS	CS	NS	CS	NS	CS	NS	CS	NS
	(gr)		(gr)		(gr)		(gr)		(gr)	
3/4”	48	-	47.5	-	47	-	46.5	-	46	-
½”	300	-	299.5	-	299	-	298.5	-	298	-
3/8”	486	-	485.5	-	485	-	484.5	-	484	-
No. 4	78	-	77.5	-	77	-	76.5	-	76	-
No. 8	-	-	-	-	-	-	-	-	-	-
No. 16	-	-	-	-	-	-	-	-	-	-
No. 30	-	-	-	-	-	-	-	-	-	-
No. 50	-	-	-	-	-	-	-	-	-	-
No. 100	-	-	-	-	-	-	-	-	-	-
No.200	114	-	113.5	-	113	-	112.5	-	112	-
Filler	102		101.5		101		100.5		100	
Asphalt	72		75		78		81		84	

TABLE III. PROPORTION OF SMA NS 50 GRADATION MIX

Sieve	Asphalt content									
	6%		6.25%		6.5%		6.75%		7%	
	CS	NS	CS	NS	CS	NS	CS	NS	CS	NS
	(gr)		(gr)		(gr)		(gr)		(gr)	
3/4”	24	24	23.75	23.75	23.5	23.5	23.25	23.25	23	23
½”	150	150	149.75	149.75	149.5	149.5	149.25	149.25	149	149
3/8”	243	243	242.75	242.75	242.5	242.5	242.25	242.25	242	242
No. 4	78	-	77.5	-	77	-	76.5	-	76	-
No. 8	-	-	-	-	-	-	-	-	-	-
No. 16	-	-	-	-	-	-	-	-	-	-
No. 30	-	-	-	-	-	-	-	-	-	-
No. 50	-	-	-	-	-	-	-	-	-	-
No. 100	-	-	-	-	-	-	-	-	-	-
No.200	114	-	113.5	-	113	-	112.5	-	112	-
Filler	102		101.5		101		100.5		100	
Asphalt	72		75		78		81		84	

To evaluate the performance of NS aggregate in SMA mixtures, this study developed three different types of mixtures. The first type is the SMA CS mix, which serves as the comparative mix, utilizing 100% CS aggregate as the coarse aggregate. The second variant is NS 50 SMA mix, incorporating 50% NS aggregate instead of coarse aggregate, while the third is NS 100 SMA mix, utilizing 100% NS aggregate for the coarse aggregate. According to [18], the ideal asphalt content for SMA blends varies between 6% and 7% of total weight, leading to the exploration of five specific levels: 6%, 6.25%, 6.5%, 6.75%, and 7%. These were applied to three mixture types: SMA CS, SMA NS 50, and SMA NS 100. All specimens were prepared using the Marshall method, with 50 blows applied to each side during compaction. The aggregate gradation designs for each mixture are detailed in Tables I-III. To ensure reliable results and consistent testing, three specimens were produced for each variation.

TABLE IV. PROPORTION OF SMA NS 100 GRADATION MIX

Sieve	Asphalt content									
	6%		6.25%		6.5%		6.75%		7%	
	CS	NS	CS	NS	CS	NS	CS	NS	CS	NS
	(gr)		(gr)		(gr)		(gr)		(gr)	
3/4”	-	48	-	47.5	-	47	-	46.5	-	46
½”	-	300	-	299.5	-	299	-	298.5	-	298
3/8”	-	486	-	485.5	-	485	-	484.5	-	484
No. 4	78	-	77.5	-	77	-	76.5	-	76	-
No. 8	-	-	-	-	-	-	-	-	-	-
No. 16	-	-	-	-	-	-	-	-	-	-
No. 30	-	-	-	-	-	-	-	-	-	-
No. 50	-	-	-	-	-	-	-	-	-	-
No. 100	-	-	-	-	-	-	-	-	-	-
No.200	114	-	113.5	-	113	-	112.5	-	112	-
Filler	102		101.5		101		100.5		100	
Asphalt	72		75		78		81		84	

C. Testing Methods

The mechanical properties of the SMA mixtures were evaluated using Marshall stability and flow tests in accordance with [27]. As depicted in Figure 3, the tests were conducted with a Universal Testing Machine (UTM) equipped with a Marshall pressure head, LVDT, load cell, and data recorder to ensure accurate measurements.

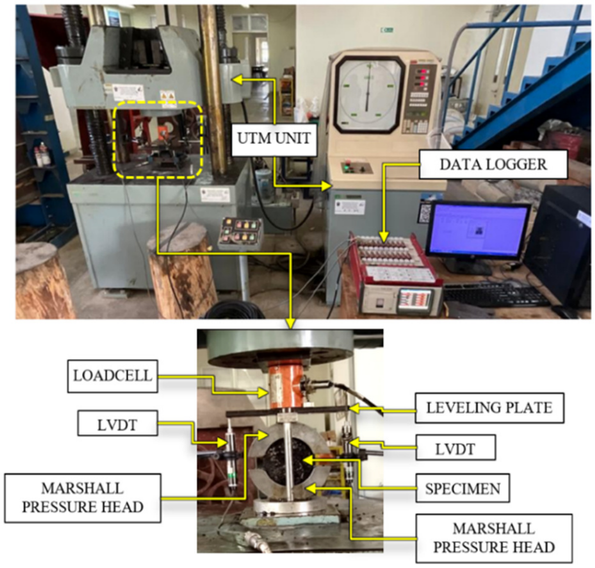


Fig. 3. UTM instrument unit.

The loading rate was maintained at 50 ± 5 mm/min to assess both stability and deformation (flow) under controlled conditions. These measurements provide critical insights into the mixture's ability to withstand applied loads and its susceptibility to deformation, thereby reflecting its structural reliability in service. The UTM ensured reliable and consistent data collection while adhering to standard testing procedures.

III. RESULTS AND DISCUSSION

A. *Mechanical Evaluation with Marshall Test*

The results of the Marshall test were assessed according to the standards set in the 2018 Revision 2 of the General Specifications for Roads and Bridges

1) *Volumetric Value*

This segment unveils the findings from volumetric evaluations, focusing on the VIM and VMA values. These measurements are crucial for assessing the density and void distribution within the asphalt mixture, both of which directly influence pavement performance. The VIM and VMA values for each mixture variation are illustrated in Figures 4 and 5.

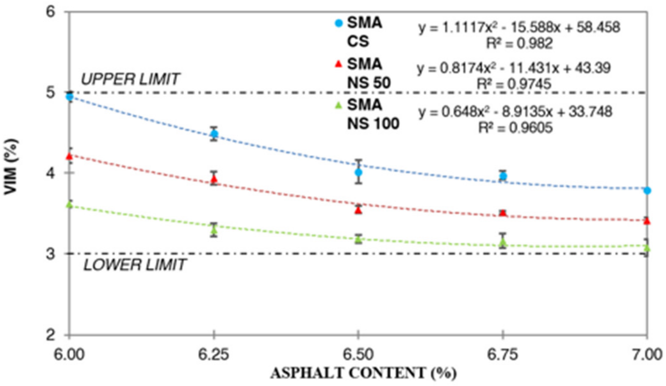


Fig. 4. VIM value of SMA.

The required VIM value ranges from 3% - 5%. In Figure 4, an inverse relationship is observed between the VIM values and the asphalt content across all SMA variations, with the incorporation of NS in coarse aggregates further diminishing the VIM values. All variations of SMA mixtures appear to meet the VIM requirements. The largest VIM value in SMA CS mixtures at 6% asphalt content was 4.95% and the smallest VIM value in SMA NS 100 mixtures at 7% asphalt content was 3.08%.

The asphalt content had a direct effect on the VIM values across all SMA variations. Increasing the asphalt content reduced VIM, as additional binder filled the available voids during compaction. The substitution of natural aggregates with NS further lowered VIM due to the higher density of NS, which more effectively occupied voids and reduced the air content. Lower air voids generally improve the durability and lifespan of asphalt mixtures by minimizing the susceptibility to water damage and oxidation [19]. However, if VIM decreases too much, the mixture can become overly compact, restricting the aggregate movement under traffic loads and creating a rigid, crack-prone structure [20]. In contrast, VMA values increased with higher asphalt content. Both SMA NS 50 and SMA NS 100 mixtures showed higher VMA values compared to SMA CS, with SMA NS 50 consistently producing the highest values across all asphalt levels. The lowest VMA was recorded for SMA CS at 6% asphalt content (17.73%), while the highest was observed in SMA NS 50 at 7% asphalt content (21.68%). Since the specification requires a minimum VMA of 17%, all mixtures met the standard. The higher VMA in NS mixtures can be attributed to the lower absorption of NS aggregates relative to CS, which allows a thicker asphalt film to coat the aggregates. This phenomenon is consistent with findings from steel slag studies in porous asphalt mixtures [21]. The slight reduction in VMA for SMA NS 50 and SMA NS 100 at certain asphalt levels may be linked to the cubical shape of NS aggregates, which enhances the packing efficiency and reduces the void space.

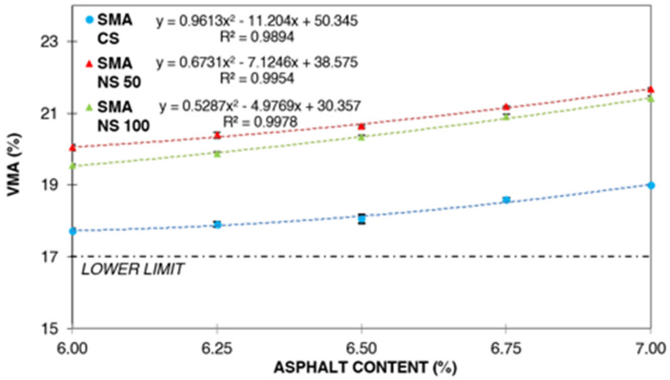


Fig. 5. VMA value of SMA.

2) *Stability and Flow*

The subsequent presentation of the Marshall stability and flow test outcomes for SMA mixes is intended to assess the mechanical integrity and deformability of asphalt mixtures subjected to specified loads, thus elucidating the mix's performance under load conditions. The correlation curve between stability and deformation for each mixture variation is portrayed in Figure 6, while the results are presented in Figures 7 and 8.

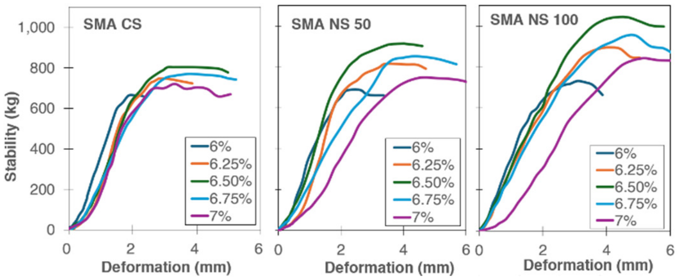


Fig. 6. Stability and deformation relationship.

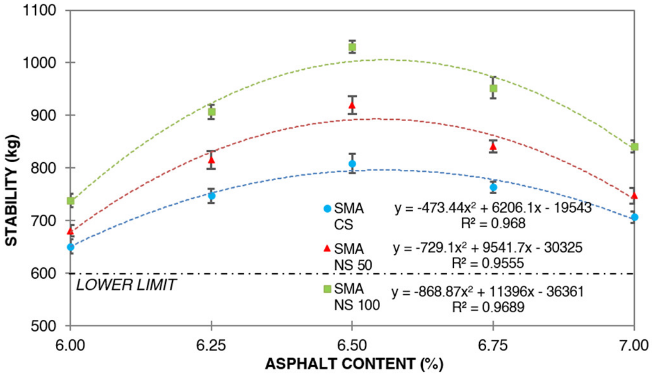


Fig. 7. Stability of SMA.

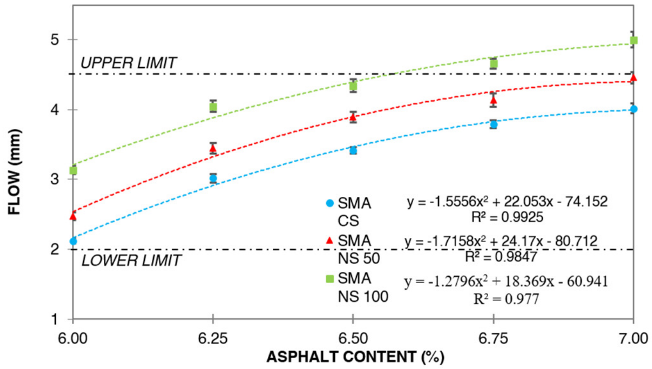


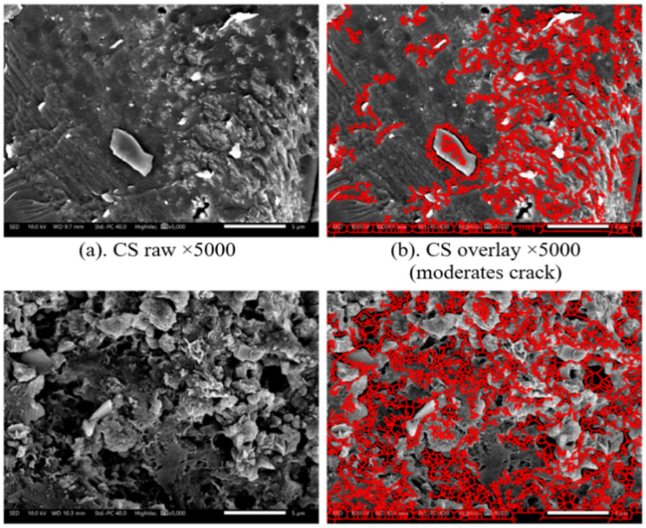
Fig. 8. Flow of SMA.

In the curves of Figure 6, in all types of SMA, the highest stability is obtained at 6.5% asphalt content. It is also observed that the mixtures with higher NS content have higher stability. The stability of SMA NS 100, SMA NS 50, and SMA CS mixtures is 1031 kg, 919 kg, and 809 kg, respectively. The specification requirement for SMA is a minimum of 600 kg; all SMA variations meet this requirement. The augmented stability in NS-inclusive SMA mixtures is associated with superior aggregate interlocking, notably with increased NS proportions. The angular and dense nature of NS significantly boosts rigidity and stability, improving the deformation resistance under load. This indicates that NS not only replaces traditional aggregates, but also enhances the structural integrity of SMA mixes, thus elevating the rutting resistance and overall pavement performance. Steel slag aggregates enhance the asphalt mixtures due to their abrasive surface and geometric configuration [22]. Research on various slags has demonstrated improvements in Marshall stability, including Basic Oxygen Furnace (BOF), steel slags [6, 23], and NS, which achieved high stability values in the dense gradation of asphalt mixtures [12]. The Marshall flow value escalates with the increment of asphalt in the mixture, as demonstrated in all SMA mixes depicted in Figure 7. The NS content in the mix increases the latter's flow value. The SMA CS values ranged from 2.122 mm - 4.020 mm, SMA NS 50 2.475 mm - 4.461 mm, and SMA NS 100 3.137 mm - 4.999 mm. The specifications for the flow values are in the range of 2 mm - 4.5 mm; therefore, the flow of SMA SN 100 at 6.75% and 7% asphalt content exceeds the requirements. The flow value reflects the mixture's deformation under load. An increase in flow with a higher NS content suggests reduced stiffness but greater deformability. In SMA mixtures, this is not necessarily unfavorable, as performance depends on maintaining a balance between flexibility and stability. Similar findings in prior studies suggest that a higher flow may indicate improved resistance to traffic-induced damage [24].

B. Microstructural Evaluation with SEM and EDX Test

1) SEM Test

The surface morphology and texture of coarse aggregates for SMA mixtures, specifically CS and NS, were examined using SEM.



(a). CS raw ×5000 (b). CS overlay ×5000 (moderates crack)

(c). NS raw ×5000 (d). NS overlay ×5000 (moderates crack)

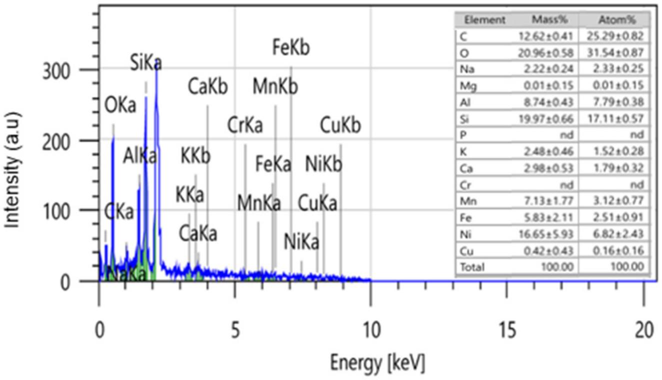
Fig. 9. SEM images of CS and NS.

The SEM observations reveal that NS aggregates possess a rougher surface than CS, with irregularities at ×5000 magnification enhancing bonding with asphalt and improving stone-on-stone contact and deformation resistance, as shown in Figure 9. This is supported by quantitative measurements, where NS recorded a roughness index of 35.7 ± 4.1, significantly higher than CS (25.9 ± 3.5), indicating greater potential for mechanical interlocking. The rough surface of NS facilitates better adhesion and load transfer, enhancing the resistance to traffic loading and elevated temperatures. Nevertheless, NS showed a higher global crack density (0.28 mm/mm²) compared to CS (0.20 mm/mm²), attributable to abundant micro-porosities that may increase moisture susceptibility. Conversely, CS appeared smoother and denser but exhibited larger macro-cracks at ×5000 magnification. The macro-crack analysis confirmed this, with CS reaching a total length of 21µm-23 µm and a width of 0.8 µm–1.2 µm, whereas NS displayed fewer and smaller cracks (<10 µm, width <0.5 µm). Thus, CS is more prone to macro-crack propagation under cyclic loading, while NS is more affected by micro-porosity. These observations align with [25, 26], where it was reported that steel slag provides stronger asphalt mortar matrices than natural aggregates, such as basalt and limestone.

Complementary aggregate property assessments corroborate the SEM results. NS exhibited greater specific gravity, reduced water absorption, and enhanced the abrasion resistance relative to CS, hence affirming its long-term stability. While CS aggregates possess dense and angular traits conducive to mixture stability, their elevated water absorption and abrasion rates indicate increased susceptibility to weathering and surface deterioration over time.

2) *XRD Test*

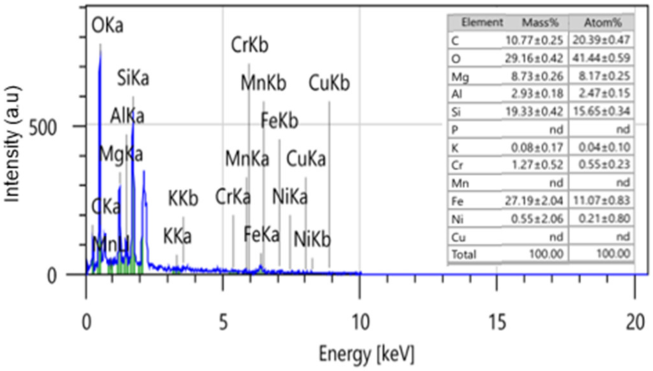
The XRD test results indicate the chemical element content in NS and CS aggregates to identify the dominant crystalline components in each aggregate. This information is necessary to comprehend the mineralogical properties that affect aggregate performance in asphalt mixture applications. Figures 10 and 11 present the test results for NS and CS, respectively.



Element	Mass%	Atom%
C	12.62±0.41	25.29±0.82
O	20.96±0.58	31.54±0.87
Na	2.22±0.24	2.33±0.25
Mg	0.01±0.15	0.01±0.15
Al	8.74±0.43	7.79±0.38
Si	19.97±0.66	17.11±0.57
P	nd	nd
K	2.48±0.46	1.52±0.28
Ca	2.98±0.53	1.79±0.32
Cr	nd	nd
Mn	7.13±1.77	3.12±0.77
Fe	5.83±2.11	2.51±0.91
Ni	16.65±5.93	6.82±2.43
Cu	0.42±0.43	0.16±0.16
Total	100.00	100.00

Fig. 10. XRD test of NS.

The EDX analysis of NS aggregates revealed the dominant elements to be Silicon (Si, 19.97%), Nickel (Ni, 16.65%), Aluminum (Al, 8.74%), Manganese (Mn, 7.13%), Iron (Fe, 5.83%), Calcium (Ca, 2.98%), Carbon (C, 12.62%), and Oxygen (O, 20.96%). In comparison, the CS aggregates primarily contained Iron (Fe, 27.19%), Silicon (Si, 19.33%), Aluminum (Al, 2.93%), Magnesium (Mg, 8.73%), Carbon (C, 10.77%), and Oxygen (29.16%). These elements are typically present in compound forms, such as silica (SiO_2), nickel oxide (NiO), aluminum oxide (Al_2O_3), manganese oxide (MnO), iron oxide (Fe_2O_3), and calcium oxide (CaO). Such compounds contribute to the surface structure and roughness of NS aggregates, potentially improving stability and enhancing the asphalt–aggregate bond. However, the presence of carbon indicates possible traces of organic matter, which may weaken adhesion since carbon exhibits low reactivity with asphalt. This aligns perfectly with previous studies on steel slag; the chemical elements in steel slag significantly increase alkalinity, primarily due to calcium hydroxide ($Ca(OH)_2$), dicalcium silicate ($2CaO{\cdot}SiO_2$), and tricalcium silicate ($3CaO{\cdot}SiO_2$). These compounds significantly enhance the chemical bonding between the aggregates and asphalt binder, leading to improved adhesion through their reaction with the binder's functional acid groups [25].



Element	Mass%	Atom%
C	10.77±0.25	20.39±0.47
O	29.16±0.42	41.44±0.59
Mg	8.73±0.26	8.17±0.25
Al	2.93±0.18	2.47±0.15
Si	19.33±0.42	15.65±0.34
P	nd	nd
K	0.08±0.17	0.04±0.10
Cr	1.27±0.52	0.55±0.23
Mn	nd	nd
Fe	27.19±2.04	11.07±0.83
Ni	0.55±2.06	0.21±0.80
Cu	nd	nd
Total	100.00	100.00

Fig. 11. XRD test of CS.

IV. CONCLUSIONS

This study demonstrates that Nickel Slag (NS) has strong potential as a sustainable alternative coarse aggregate in Stone Matrix Asphalt (SMA) mixtures. The Marshall, Scanning Electron Microscope (SEM), and XRD analyses provided an understanding of both the mechanical performance and material characteristics. The mechanical evaluation showed that NS significantly enhances stability, with the highest values obtained at 6.5% asphalt content. At this level, SMA CS (0% NS), SMA NS 50 (50% NS), and SMA NS 100 (100% NS) exceeded the required thresholds, while simultaneously meeting flow, VIM, and VMA specifications. These results indicate that 6.5% asphalt content is optimal for NS-based SMA mixtures, ensuring both stability and durability. The microstructural analysis further confirmed the advantages of NS. The SEM observations revealed that NS aggregates have a rougher surface morphology than CS, with a roughness index of 35.7 ± 4.1 compared to 25.9 ± 3.5, which promotes stronger aggregate interlocking and asphalt adhesion. Although NS exhibited higher global crack density (0.28 mm/mm²) than CS (0.20 mm/mm²) due to micro-porosities, CS showed longer macro-cracks, indicating different modes of weakness. The XRD analysis highlighted the presence of key elements in NS, including Si, Ni, and Al, along with Mn, Fe, Ca, and C. The prevalence of silica and metal oxides is particularly beneficial, as these compounds enhance aggregate stability and improve asphalt–aggregate bonding. Further research should investigate the performance of NS-based mixtures under varied conditions, such as temperature fluctuations, moisture susceptibility, and freeze–thaw cycles. Long-term chemical stability, including potential heavy metal leaching, should also be examined to confirm environmental safety. Addressing these aspects will strengthen the case for NS as a sustainable and durable material in asphalt pavement applications.

DATA AVAILABILITY

The findings of this study can be substantiated by data obtainable from the corresponding author upon a reasonable inquiry.

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