Marshall performance evaluation of coarse stone matrix asphalt utilizing water-cooled nickel slag aggregate in sustainable development

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Abstract. This study investigates the potential use of water-cooled nickel slag as a partial replacement for coarse aggregates in Stone Matrix Asphalt (SMA) mixtures and evaluates its impact on mixture performance. The research varies asphalt content levels 6%, 6.25%, 6.5%, 6.75%, and 7% with 100% of the coarse aggregates replaced by nickel slag. Marshall mix design tests were conducted to assess the mixtures' stability, flow, and volumetric properties, including Voids in the Mixture (VIM) and Voids in Mineral Aggregate (VMA). The results indicate that Marshall stability increases in a parabolic trend with asphalt content, peaking at 807.48 kg for 6.25% asphalt content. The Marshall flow values at all asphalt content levels 3.8 mm, 3.4 mm, 2.2 mm, 2.5 mm, and 2.9 mm, respectively comply with specification requirements. Volumetric analysis shows that as asphalt content increases, VIM decreases slightly 4.17%, 4.12%, 4.10%, 4.06%, and 4.03% but remains within the acceptable range of 3–5%. Conversely, VMA increases with asphalt content, yielding values of 17.15%, 17.44%, 17.05%, 18.04%, and 18.33%, all of which exceed the minimum requirement of 17%. This supports sustainable infrastructure development by reducing reliance on natural aggregates.

1 Introduction

Indonesia is the world's largest nickel producer, with an output of 1.6 million metric tons in 2022 far surpassing the Philippines (330 thousand metric tons) and Russia (220 thousand metric tons). The global nickel reserves are estimated at 139.4 million metric tons, with Indonesia holding the largest share at 52%. About 90% of these reserves are concentrated in Morowali (Central Sulawesi), Sorowako (South Sulawesi), Kolaka and Konawe (Southeast Sulawesi), and Tanjung Buli (North Maluku) [1].

The growing demand for electric vehicles, which rely on nickel-based lithium batteries, has fueled the expansion of Indonesia's nickel mining industry. This sector plays a key role in national economic growth by creating jobs and generating state revenue; however, it also produces significant environmental waste, particularly nickel slag, which has accumulated to

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about 13 million metric tons annually. To address this problem, the Ministry of Environment and Forestry has made changes to waste management rules by taking nine types of waste off the hazardous and toxic (B3) list, such as iron slag, steel slag, nickel slag, mill scale, electric arc furnace (EAF) dust, PS ball, fly ash bottom ash (FABA) from coal-fired power plants, spent bleaching earth (SBE), and foundry sand [12].

Stone Matrix Asphalt (SMA) offers a promising solution for road construction in Indonesia, as it is a flexible pavement developed in Germany in the mid-1960s [2]. Known for its high resistance to rutting, flexibility, and durability, SMA was introduced in Indonesia in the 1990s but remains rarely used. Its potential to prevent road damage, particularly cracking and rutting, makes it worth considering, as SMA derives its strength from a skeleton of coarse aggregate, while a mastic blend of fine aggregate, filler, and high asphalt content fills the voids to enhance load-bearing capacity [2]. A full-scale trial conducted by the Public Works Research and Development Center in 2010 tested SMA with cellulose fibers on the Jatibarang–Palimanan road in West Java, and with a compacted thickness of approximately 5 cm, the pavement has remained in satisfactory condition [3], demonstrating SMA's durability and long-term performance.

Research on Stone Matrix Asphalt (SMA) mixtures and some other hot-mixed asphalts continues to advance, exploring alternative materials to enhance performance. For example, a study by Febe [4], Utilization of Sorowako Nickel Waste in Coarse Stone Matrix Asphalt Mixes, found that nickel waste meets Bina Marga (2018) standards and is suitable for road pavement mixes. The Marshall SMA test was conducted with asphalt contents of 6.00%, 6.25%, 6.50%, 6.75%, and 7.00%, met the 2018 General Highway Specifications [5]. "Evaluation of HMA Modified with Titan Polymer," a study by HM Alnaqib and RW Bazuhair in 2023, shows that a mixture with 3% Titan7205 works as well as or better than a mixture with other polymer additives used in this study [6]. Researchers Kadhim and Al-Busaltan (2024) looked into how adding palm leaf fibers (PLF) to hot mix asphalt (HMA) affects how resistant it is to cracking. They found that PLF helps keep HMA from cracking. Also, their results suggest that the indirect tensile strength (ITS) test by itself is not enough to figure out how a mixture will behave, since it depends a lot on peak load to measure crack resistance. More comprehensive indices, such as the cracking tolerance (CT) index, provide a more accurate evaluation [7]. Coelho et al. (2024) found that HMA with 40% RFNS had an average elastic modulus of 6,323 MPa using the Marshall method and a visual inspection after four years showed the pavement remained in excellent condition [8]. Silveira et al. (2024) observed a deformation of 5.3 mm in anti-dust-treated mixtures under a 33 kg load, compared to 7.76 mm in stabilised reject–emulsion mixtures. Similarly, anti-dust-treated mixtures of reject soil and emulsion deformed 4.16 mm, versus 6.99 mm for stabilised ones [9]. This study evaluates the reuse of iron ore waste from Samarco Mineração S.A. in road construction. Mixing 50% waste with PRS improved strength by 130% and met Brazilian sub-base standards. LCS showed moderate gains at 20% waste, but performance declined with higher amounts. The results support using inert mining waste as a sustainable pavement material [10].

The industrial sector needs sustainable and advanced technologies to efficiently convert waste into valuable resources, reducing both environmental pollution and waste management burdens. However, while industrial waste continues to accumulate, high-quality aggregates for road construction are becoming increasingly scarce. In regions such as Sulawesi, Papua, and Kalimantan, road construction materials often have to be imported, leading to higher costs and longer processing times, and this scarcity remains a key factor in road construction delays. In line with these challenges, nickel slag waste, if not properly managed, can also cause environmental pollution; therefore, research is needed to explore its potential as an aggregate substitute in Stone Matrix Asphalt (SMA) and to evaluate whether its performance and volumetric properties, as tested through the Marshall test, meet the 2018 Bina Marga specifications. Accordingly, this study aims to assess the stability, flow, and volumetric characteristics of SMA mixtures incorporating nickel slag and to determine the optimum asphalt content for different variations.

The findings are expected to enrich empirical data on the feasibility of nickel slag as an alternative material for road construction. Additionally, this research supports sustainable pavement engineering by repurposing industrial waste, aligning with global efforts to reduce environmental impact and the government's initiative to develop road infrastructure in remote, underdeveloped, and frontier regions.

2 Research Methodology

2.1 Materials

This study utilizes key materials for the Stone Matrix Asphalt (SMA) mixture, including asphalt, fine and coarse aggregates, fillers, and stabilizing agents. The binder used is 60/70 penetration asphalt supplied by PT Pertamina Indonesia, with asphalt content varying between 6%, 6.25%, 6.5%, 6.75%, and 7% aligning with SMA requirements of 6% to 7%.

Crushed stone (CS) from Bili-Bili serves as the fine aggregate, while nickel slag (NS) is used as a full (100%) replacement for coarse aggregate. The NS is sourced from water-cooled nickel slag produced by PT Huadi Nickel Alloy in Bantaeng Regency, Sulawesi. Portland Composite Cement (PCC) from Semen Tonasa is used as the filler material, and a natural stabilizing agent, 6 mm long palm fiber, is incorporated at 0.03% of the total mix weight. These materials are selected based on their availability, suitability for SMA applications, and because they have the potential to enhance the mechanical performance of asphalt mixtures.

2.2 Mixed Design

The mixture gradation follows coarse SMA curve with a nominal maximum aggregate size (NMAS) of 19 mm, as specified in SNI 8129:2015 [11]. The SMA standards follow the General Requirements for Roads and Bridges by the Directorate General of Highways (2018, Revision 2) (Ministry of Public Works and Public Housing, 2020) [12]. With these limits, an upper and lower bound is defined for each aggregate size and, in this research, the middle-value gradation has been chosen to obtain an optimum and balanced AC. This is satisfied by adjusting the mixture so it falls in the high-performance pavement range. The coarse aggregate was 100% nickel slag and fine aggregate, copper slag.

(a) (b)

Fig. 1. (a) Palm Fiber and (b) Nickel Slag as Coarse Aggregate

2.3 Test Preparation

The mixture was made in 5 asphalt grades, with 3 (three) test specimens for each binder proportion to obtain the optimum binder proportion based on the strength and flexibility of the mixture. Fine aggregate, coarse aggregate, and nickel slag are manually mixed with the appropriate grade of emulsified asphalt until a uniform mixture is achieved. The compact is then formed using a Marshall compactor to produce cylindrical samples for volumetric, stability, and flow testing. Furthermore, the compaction step follows standard procedures, where pressure is applied at a rate of 5 cm/min in a room maintained at 25°C, and subsequently, the samples are stabilized under conditions that closely simulate those in the field to ensure greater accuracy of results. Finally, all tests are conducted in a controlled environment to minimize the influence of external factors.

The test data will also be used to evaluate the influence of the various asphalt contents on SMA mixture performance. Statistical assessment of multiple regression on statistical variability of the mechanical properties at different asphalt levels is included as well. The results will contribute to predicting a performance-optimized amount of asphalt to achieve the durability and structural performance in SMA mixes.

Fig. 2. Test Specimen of Stone Matrix Asphalt Mixture

2.4 Equipment and Testing

The performance of hot mix SMA with different nickel slag contents is determined using Marshall method (SNI 2489:2018) [13] according to several index. Figure 3 shows the test specimen installed in the UTM machine.

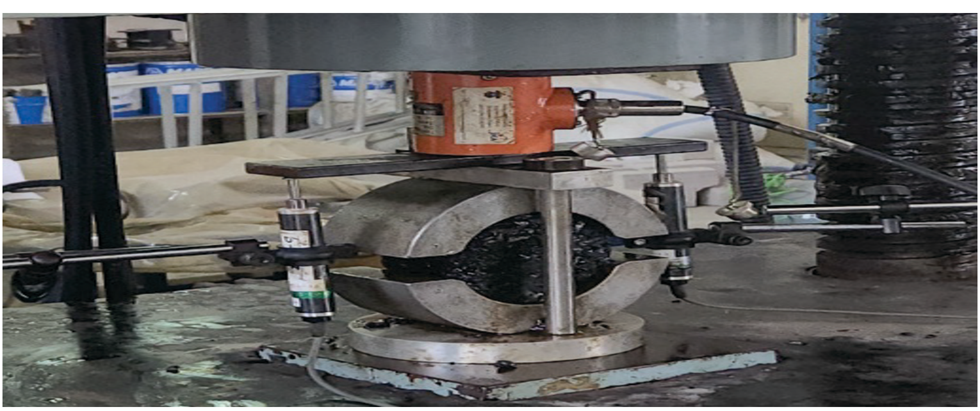

Fig. 3. Marshall Test Using a Universal Testing Machine

The stability of the compacted sample is assessed by creating the 'stable number' from the maximum load obtained when the sample fails during testing in a UTM fitted with a load cell. This value is indicative of the resistance to mixture rutting under traffic loads. The flow is evaluated through the vertical deformation of the sample under load using Linear Variable Differential Transformer (LVDT) and gives information on the plasticity of the mix and its behavior under traffic.

Furthermore, the volumetric characteristics of the mixture are investigated. Excluded action in the mixture, VIM for both compacted sample the about the compacted sample space in the way It all and enters to amount of the air air void content in the compacted sample which, it air void space in of the air void to density and material density and durability. VMA is tested to verify acceptable binder content and stability of the mixture. For further durability assessment, VFA is examined to see how well the binder fills voids. The measurements obtained are compared with relevant specifications in order to confirm that the mix complies with the performance requirements for strong, durable and good quality road pavements.

3 Results And Discussion

3.1 Material Properties

Physical property tests are crucial to determine how aggregate will contribute to the performance of the SMA mix. In SMA, the coarse exhibits a strong framework where the load is carried while the fine fills the aggregates voids and it binds with the asphalt to form a stable mix. The coarse and fine aggregate test results are given in Table 1 and Table 2, respectively.

Table 1. Test Results for Coarse Aggregate Characteristics

Testing	Spesification	Coarse Aggregate Test Results	
		Local	Nickel Slag
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

Table 2. Test Results of Fine Aggregate Characteristics

Testing	Spesification	Test Results
Sand Equivalent Value	Min. 12 %	96,20 %
Material Passing Sieve No. 200	Maks. 1 %	0,40 %

Its reported summary by test results of physical properties of the material verifies that all gross aggregate indexes even such for local aggregate and NS all satisfy the requirement of SMA mixture. Nickel slag exhibits superior abrasion resistance, with a lower abrasion value than crushed stone (CS). Additionally, NS has a higher specific gravity, while CS has greater water absorption.

Local aggregate is also little more cuboid in shape than NS, as indicated by its lower flat, elongated, and angular indices. These characteristics enhance interlocking and stability within the mix. Both CS and NS from PT. Huadi Nickel-Alloy meet the criteria for use as coarse aggregates in SMA, demonstrating their suitability for high-performance, long-lasting road pavements.

The asphalt material test results, shown in Table 3, confirm that the Pertamina-produced asphalt used in the mix meets the required specifications for SMA binders. Additionally, the specific gravity test of the filler Semen Tonasa brand Portland Composite Cement (PCC) yields a value of 3.11, indicating compatibility with the asphalt binder in meeting SMA performance criteria.

Table 3. Asphalt Characteristics Test Results

Testing	Specification	Result
The specific gravity of bitumen	≥ 1,0	1,158
Penetration 25 0C (0.1 mm)	60 – 70	65,6
Softening Point (0C)	≥ 48	53,4
Ductility of bitumen 25 0C (cm)	≥ 100	128,67
Flashpoint (0C)	≥ 232	268

Selecting the right binder and filler is crucial for ensuring the stability, durability, and overall performance of the pavement. Further evaluation under varied environmental conditions could provide deeper insights into their long-term effectiveness in SMA applications. Optimizing binder-filler interaction may also enhance the mix's resistance to moisture damage and fatigue cracking. Future research should explore the impact of alternative fillers on SMA's mechanical properties to improve sustainability and cost efficiency.

3.2 Marshall's Stability and Flow

The Marshall test results indicate a significant improvement in the performance of the Stone Matrix Asphalt (SMA) mixture as the percentage of nickel slag in the coarse aggregate increases. The stability values, measured in kilograms, are presented in Figure 4.

Additionally, the flow value, which represents the plastic deformation of the mixture under load, follows a parabolic trend with increasing nickel slag content, as also shown in Figure 4.

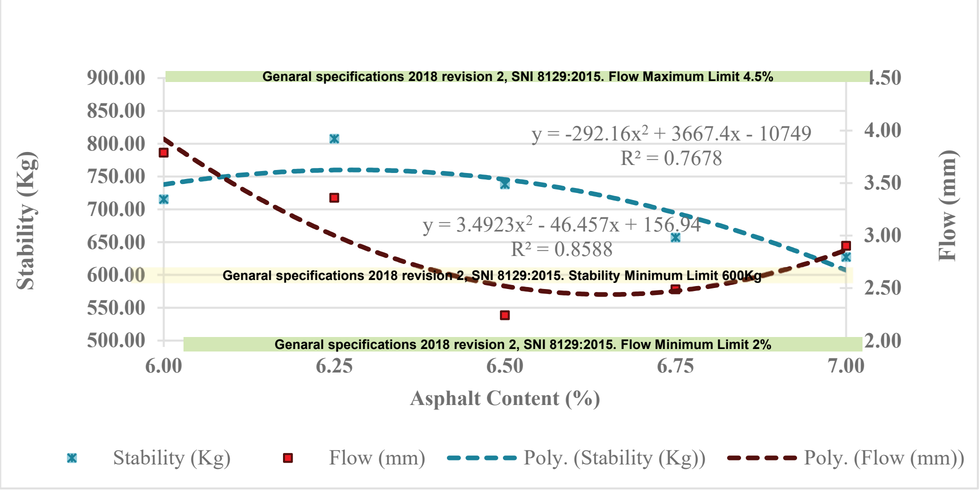

Fig. 4. Marshall Stability and Flow Test Results

The Marshall test results indicate a notable improvement in the performance of Stone Matrix Asphalt (SMA) mixtures as the percentage of nickel slag used to replace coarse aggregates increases. As shown in Fig. 4, stability values (kg) exhibit an upward trend with increasing asphalt content, reflecting enhanced structural strength. Likewise, flow values, representing the mixture's plastic deformation under load, follow a parabolic trend as nickel slag content increases, also illustrated in Figure 4.

In terms of asphalt content, stability increases from 6% to 6.25%, reaching a peak, before gradually declining as asphalt content rises to 7%. Conversely, flow values decrease as asphalt content increases up to 6.5%, then rise again toward 7%. This pattern aligns with the principle that adding asphalt improves internal cohesion and aggregate interlock, enhancing stability up to an optimum point. Beyond this point, excess asphalt forms a thicker coating around aggregates, reducing interlocking and consequently lowering stability. Importantly, stability values at all asphalt content levels exceed the specified minimum of 600 kg, and flow values remain within the acceptable range of 2 mm to 4.5 mm.

These findings emphasize the potential of nickel slag as an effective and sustainable alternative material to improve the performance of SMA mixtures in road pavement applications. The test results show that mixture flexibility decreases as asphalt content increases up to 6.5%. This is because, with the addition of asphalt, the free spaces within the mixture and inside the particles of the nickel slag are filled, which results in increased stiffness. However, when the asphalt content is increased to 7%, the mixture becomes more flexible because excess asphalt acts to reduce the stiffness. The reduction in stiffness may compromise the structural integrity of the pavement under heavy traffic loads.

Therefore, the determination of the optimum asphalt content is important in striking a balance between stiffness and flexibility for the achievement of durable and high-performance SMA pavements. Moreover, the study highlights the importance of selecting an adequate proportion of nickel slag to enhance the mechanical performance. Future research should focus on long-term performance evaluations, including fatigue resistance and moisture susceptibility, to validate the durability of SMA mixtures with nickel slag.

3.3 Volumetric Properties

As the nickel slag content increases, noticeable changes occur in the volumetric properties of SMA mixtures, particularly in Voids in the Mineral Aggregate (VMA) and Voids in the Mixture (VIM). Figure 5 presents the VIM and VMA results, illustrating these variations.

As shown by Figure 5, VIM value declines with the rising content of asphalt. This is due to the fact that asphalt binds and fills the voids between nickel slag particles and reduces air pockets in the mixture. The reduction of air voids densifies the mixture, and this can be beneficial to stability and durability. However, if VIM is reduced too much, the mixture will become too dense and lack flexibility. In addition, higher asphalt content may form a thicker asphalt film around aggregate particles that fills internal voids but reduces interlocking of aggregates at the expense of the structural integrity of the mix.

Conversely, Figure 5 also shows that Voids in Mineral Aggregate (VMA) values are greater with higher asphalt content. This may be described by the characteristics of materials used, such as the absorption capacity of nickel slag and the hardness of the asphalt binder. The angular shape and rough surface texture of nickel slag can reduce void spaces between particles so that the asphalt will fill these voids and lead to high VMA values.

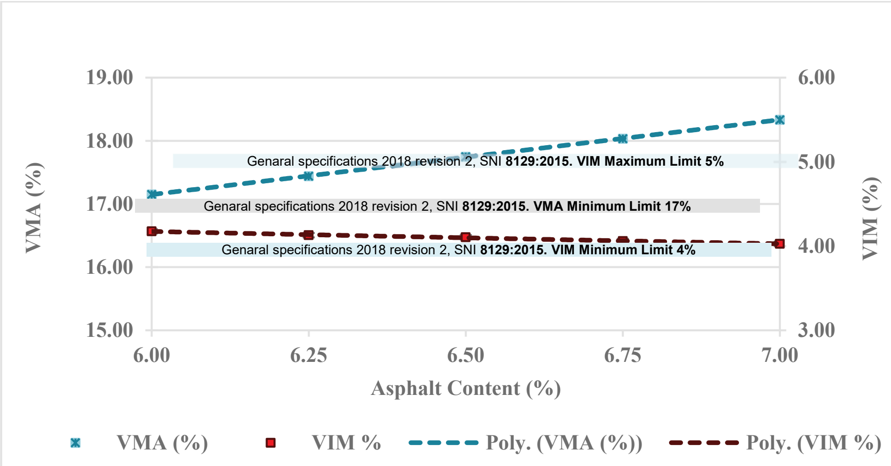

Fig. 5. VIM and VMA Test Results of Using Nickel Slag in SMA

4 Conclusion

The study is helpful for the researchers and engineers to have a better understanding of the role the nickel slag played on SMA mixture performance properties (stability and volumetric properties).

1. The mixture incorporating 100% nickel slag achieved an optimum asphalt content of 6.25%, yielding a stability of 807.48 kg, a flow of 3.36 mm, a VIM of 4.13%, and a VMA of 17.43%, all of which conform to the specified requirements.
2. The asphalt content significantly influences the mechanical properties and volumetric characteristics of asphalt mixtures:
   a. Stability increases with asphalt content up to an optimum level due to the improved coating and bonding between aggregates. Beyond this point, excessive asphalt causes the mix to become too plastic, reducing interlock and consequently lowering stability, forming an inverted parabolic trend.
   b. Flow values increase with asphalt content because the thicker asphalt film enhances mixture flexibility. However, excessive asphalt results in excessive deformation and rutting susceptibility, while insufficient asphalt produces a brittle and stiff mix with low flow.
   c. The voids in mix (VIM) decrease as asphalt content increases, since the asphalt fills the intergranular voids. High VIM may lead to oxidation and cracking, whereas very low VIM may cause bleeding due to insufficient air voids.
   d. Similarly, the voids in mineral aggregate (VMA) initially increase with asphalt content because of slight separation between aggregates. When the asphalt content continues to increase, the VIM reduction dominates, resulting in a gradual decrease in total VMA.
3. An asphalt content of 6.25% is recommended for Stone Matrix Asphalt (SMA) mixtures with 100% nickel slag replacing coarse aggregate. This composition demonstrates optimal performance while offering notable environmental and economic benefits. The use of nickel slag reduces industrial waste and conserves natural aggregates, contributing to environmental protection and resource sustainability. At the same time, utilizing local slag materials lowers construction and transportation costs, especially in regions reliant

on imported aggregates. Overall, nickel slag emerges as a sustainable and economically viable alternative that supports both durable road infrastructure and a circular economy.

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