



Environmental Sustainability of Nickel Waste Utilization in Porous Asphalt: Toward Green and Circular Road Infrastructure

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Abstract

The rapid development of road infrastructure in Indonesia has increased the demand for construction materials while intensifying environmental challenges. This study examines the potential of nickel waste as a byproduct of nickel smelting widely available in Indonesia as a partial replacement for coarse aggregate in porous asphalt mixtures. The research evaluates both the technical performance and environmental implications of this substitution, contributing to sustainable construction and circular economy discussions. Laboratory tests assessed parameters such as stability, flow, void content, and the Marshall Quotient, following Bina Marga and SNI standards. Results indicate that nickel waste can satisfy several technical requirements, achieving an optimal asphalt content of 5.5%, which also supports waste reduction and potential cost savings. However, because nickel slag contains heavy metals, effective environmental risk management such as leaching control and stabilization is essential. The findings suggest that incorporating nickel waste is not merely a technical adjustment but a strategic move toward resource efficiency, industrial symbiosis, and sustainable infrastructure governance. By reclassifying industrial waste as a productive input, this research highlights opportunities for policy reform, procurement innovation, and collaborative efforts among government, industry, and academia. Ultimately, the study concludes that adding nickel waste to porous asphalt mixtures can enhance road performance, minimize ecological impacts, and advance Indonesia's green infrastructure agenda, provided that appropriate regulatory and environmental safeguards are implemented.

Introduction

Road pavement development in Indonesia is a crucial aspect of efforts to improve connectivity and mobility and support the country's economic growth (Nawir et al., 2023; Haryono et al., 2025; Kuncoro et al., 2024). Roads are the basic infrastructure that forms the backbone of land transportation in Indonesia, so their role cannot be underestimated. Road pavement is a crucial part of Indonesia's transportation infrastructure. With a growing population and rapid economic growth, the need for good and safe roads is increasing (Kang, 2023; Kongkuah et al., 2022; Jie et al., 2023). Road pavement is the foundation of the land transportation system, connecting various regions in Indonesia and enabling the movement of goods and people. One of the main challenges in road pavement development in Indonesia is its unique geography. Indonesia consists of thousands of islands, making building an equitable and efficient road network a complex task. Furthermore, the tropical climate and high traffic density in several major cities

place additional pressure on road pavements. Therefore, careful planning and effective management are essential.

The Indonesian government has taken various steps to improve road infrastructure throughout the country. Major programs such as the National Strategic Program for Inter-City and Inter-Regency Road Development (PSN PKA) have been launched to improve and expand the road network. Investment in road infrastructure not only improves connectivity between regions but also has the potential to increase Indonesia's economic competitiveness globally. Furthermore, the use of the latest technology in road pavement construction is also a key focus. (Ministry of Public Works and Public Housing, 2017) Innovations such as the use of modified asphalt and more efficient construction techniques can help improve road quality and extend their lifespan. These measures are crucial for reducing long-term maintenance costs and improving road user safety.

In the context of road pavement development in Indonesia, it is important to remember that good road infrastructure is a long-term investment that will support economic growth and public welfare. Proper maintenance and wise planning will be key to the success of building a robust and sustainable road pavement. (Basnet et al., 2023; Lungu, 2023; Kothari et al., 2022) The quality of construction materials plays a crucial role in influencing the performance of road pavements in Indonesia. There are several aspects that explain the relationship between material quality in construction and development. Development is a continuous effort aimed at improving people's living standards and general welfare (Graham, 2021; Lestari & Arumi, 2024; Mahardhani, 2023) The increasing development in Indonesia has reduced green areas. In addition, the large number of industrial and construction activities have become a major source of environmental problems and contribute significantly to the depletion of natural resources. Along with this, improving the quality, efficiency, and productivity of every development activity, especially those related to the physical sector, is absolutely necessary, such as the building sector that uses concrete, which is currently experiencing a significant increase. These activities are quite large, so waste is also produced every day. On the other hand, the lack of public awareness of the environment is a problem that must be addressed. Because of the need for aggregates in the mixture. Waste is the result of industrial waste that has little economic value and has a negative impact on the environment if not managed properly. This makes waste a serious problem that needs to be addressed, so that it is hoped that it can reduce the effects of pollution caused to the community. One of the results of waste disposal is nickel waste. Nickel waste or slag is an industrial waste material resulting from the smelting or burning of nickel ore at very high temperatures. The form of slag visually resembles aggregate. used as a stockpile or discarded and not utilized so that it has little economic value. Nickel waste or slag contains iron, because the slag is the result of burning nickel ore containing iron which then undergoes corrosion and will be carried in the slag. Therefore, nickel slag has the advantage of being able to withstand heat longer. The use of nickel waste in substituting hollow asphalt mixtures has been widely studied, where hollow asphalt is a flexible asphalt pavement mixture, where water can seep into the wearing course vertically and flow horizontally (Darshan & Kataware, 2024; Al-Taher et al., 2024; Zhou et al., 2025). Hollow asphalt is a type of asphalt mixture whose aggregate composition is uniformly gradated, with a higher percentage of coarse aggregate than fine aggregate. This asphalt mixture uses a mixed gradation, with coarse aggregate being the dominant ingredient.

Previous research on the use of nickel slag waste includes Manguma (2020) examining the effect of nickel slag use on the residual strength index of HRS-WC mixtures. Kamba & Rachman (2018) examined the Marshall Characteristics Test of Semi-Gap-Graded HRS

Mixtures Using Nickel Slag. Kusuma & Rachman (2018) studied the Characteristics of Nickel Slag in Semi-Gap-Graded HRS-Base Mixtures. Demmalino et al. 2019 examined nickel slag as an aggregate replacement in HRS-Base mixtures. Other research on the use of waste includes Datu et al. 2019, researching The Effect of Additional Sugar Palm Fibers on the Durability of Mixed Laston AC-WC. Tandibua et al. (2020) researched the Study of Laston BC Durability and Permeability Using Coconut Shell Addition Materials. Alpius (2018) researched the Effects of Additional Rattan Fiber on Hot Rolled Sheet Wearing Course (HRS-WC) Stability.

Nickel waste, particularly waste from laterite nickel mining, is a large-scale solid waste product that remains undermanaged in Indonesia. As the country with the world's largest nickel reserves, Indonesia faces serious challenges related to the accumulation of nickel processing waste, including overburden, tailings, and slag (Yulianto & Prasetyo, 2021). This material is generally stockpiled or dumped in open areas, which in turn causes environmental problems such as soil and water pollution (Al-Wabel, 2022; Khan et al., 2024; Rouhani et al., 2023). In the context of infrastructure sustainability, utilizing nickel waste as a substitute material in porous asphalt mixtures presents a promising alternative. Porous asphalt is a type of pavement designed to increase road surface permeability, reduce rainwater runoff, and improve surface drainage (Chen et al., 2024; Zheng et al., 2022; Chen et al., 2022). This technology is highly suitable for urban areas prone to flooding and supports green infrastructure principles (Wang et al., 2024; Lee et al., 2021; Štrbac et al., 2023). The use of nickel waste as a partial aggregate replacement in porous asphalt offers multiple benefits. First, it reduces the volume of industrial waste that must be handled. Second, it has the potential to extend the service life of roads due to the specific physical and mechanical properties of nickel waste, such as surface roughness and compressive strength (Iqbal et al., 2025; Amakye et al., 2021; Wen et al., 2021). Third, it provides a new direction for a more environmentally friendly circular economy in the road construction sector (OECD, 2022). However, a significant challenge arises in ensuring that nickel waste meets the technical and environmental requirements of applicable specifications. In Indonesia, all state road works must adhere to the Bina Marga technical specifications, which include requirements for aggregate gradation, Marshall stability value, void content, and weathering resistance (Ministry of Public Works and Housing, 2021). Therefore, any alternative material, including nickel waste, must be evaluated for its performance against these standards (Bartzas et al., 2021).

Another important aspect to consider is the potential environmental impact of nickel waste utilization. Despite its adequate physical strength, nickel waste is known to contain heavy metals such as nickel, cobalt, and chromium, which have the potential to pollute the environment through leaching, especially when the material is continuously exposed to rainwater (Puspitasari et al., 2020). If not managed properly, this potential pollution can be counterproductive to sustainability goals (KLHK Research and Development Agency, 2021). Therefore, it is crucial to design environmental risk mitigation schemes through stabilization, encapsulation, or waste washing technologies before applying it as aggregate in road mixes. Furthermore, SNI-based leaching tests or the Toxicity Characteristic Leaching Procedure (TCLP) method must be conducted to ensure that heavy metals in the waste do not exceed government-set environmental quality standards (PP No. 22 of 2021; Kurniawan et al., 2022).

Previous studies have shown that the use of waste materials such as fly ash, steel slag, or glass waste in asphalt mixes has yielded positive results in terms of structural strength and reduced carbon footprint (Hartono & Mulyadi, 2018). This opens up significant opportunities for further research on nickel waste, particularly in tropical contexts like Indonesia, which has specific weather characteristics and traffic loads (Nasution et al., 2024; Ramadan et al., 2025).

Furthermore, the economic aspects of nickel waste utilization cannot be ignored. This waste is generally available in large quantities around mining sites and does not have high commercial value (Jawadand & Randive, 2021; Nevskaya et al., 2021). Therefore, its use in road projects can reduce construction costs while creating added value from industrial waste. However, this approach can only be implemented if its safety and technical performance have been scientifically proven and accepted by regulations (Ahmed et al., 2023; Demi et al., 2023).

Globally, road construction based on recycled materials and industrial waste has been widely implemented in developed countries as part of green road initiatives. The use of mining waste in Australia, Japan, and South Korea shows an increasing trend, in line with strengthening regulations and awareness of the carbon footprint of construction (UNEP, 2020; Mori & Kimura, 2021). Indonesia needs to follow suit by conducting comprehensive scientific studies to support the development of similar policies.

Although the discourse on the use of industrial waste in road construction has grown significantly, research specifically highlighting the application of nickel waste in porous asphalt mixtures remains very limited, particularly that referring to Indonesian technical standards such as the Highways Specification. Many previous studies have focused on the use of mining waste as a road foundation layer or as an aggregate substitute in conventional concrete, while research into its application in porous road surfaces has been limited. This gap presents both a challenge and an opportunity for civil engineering academics and practitioners to develop new studies that are more applicable, responsive to tropical climate conditions, and relevant to Indonesia's local resource potential.

This research seeks to bridge this gap by integrating two main approaches: technical and environmental. From a technical perspective, this study assesses the extent to which nickel waste can meet the stability, porosity, and durability parameters required by the State Highways Agency (Bina Marga) standards. From an environmental perspective, analysis of heavy metal leaching and potential pollution are crucial aspects that cannot be ignored. This combination of approaches is expected to provide a strong scientific basis for encouraging the development of new regulations that are more accommodating to road material innovation. The results will not only provide benefits at the project scale but also contribute to the formulation of national technical policies in the road infrastructure sector. In the context of public policy, the results of this study indicate that the use of nickel waste as an aggregate substitute in porous asphalt aligns with the national sustainable development agenda. However, such innovation will not develop without affirmative support from policymakers. Therefore, strategic steps are needed, such as developing technical guidelines, providing incentives for applied research, strengthening collaboration between local governments, academics and industry players, and conducting limited field trials to evaluate performance in real-world conditions.

The role of institutions such as the Regional Infrastructure Development Agency (BPIW), the Research and Development Center of the Ministry of Public Works and Public Housing (PUPR), and technical units at the regional level is crucial in designing an implementation framework that can be adopted nationally. Universities are also encouraged to actively participate through collaborative research schemes and community-based innovation, especially in regions with active nickel mining activities. Collaboration with the private sector, such as mining companies and road contractors, can open up opportunities for large-scale implementation with a direct impact on waste management and project efficiency.

Furthermore, affirmative policies that prioritize the use of local and environmentally friendly materials need to be integrated into the LKPP e-catalog system or other government procurement instruments. This will accelerate technological adaptation and expand market

opportunities for waste substitute materials such as nickel. The existence of derivative regulations from Government Regulation No. 22 of 2021 and synergy with energy transition and low-carbon development policies will make the use of nickel waste not only technically and scientifically legitimate, but also constitutionally and strategically sound in the long term.

Therefore, it can be concluded that the use of nickel waste in porous asphalt mixtures is not simply an innovative idea in materials engineering, but also a reflection of a commitment to the transformation towards green construction. Going forward, further research needs to focus on developing optimal mixture formulas, safe heavy metal stabilization technologies, and evaluating long-term performance through field monitoring. Only with an integrated approach between research, regulation, and implementation can nickel waste utilization become a new pillar in realizing strong, sustainable, and locally resource-based national road infrastructure.

This research is relevant given the national push to build green infrastructure in line with the Sustainable Development Goals (SDGs), particularly Goal 9 (Industry, Innovation, and Infrastructure) and Goal 12 (Responsible Consumption and Production) (Bappenas, 2022). In this context, utilizing nickel waste as a substitute for road aggregates demonstrates the principles of sustainable development. To explore this potential, this research focuses on evaluating the performance of porous asphalt substituted with nickel waste, both from a technical perspective (compressive strength, stability, permeability) and from an environmental perspective. The assessment was conducted in accordance with the Bina Marga technical specifications, the primary standard for national road construction in Indonesia (Ministry of Public Works and Public Housing, 2021).

Furthermore, this research seeks to address public and stakeholder concerns about the potential environmental hazards of industrial waste use. This is achieved through an analysis of the potential for heavy metal leaching, the chemical stability of the material, and the possibility of technological interventions to prevent contamination (Wang et al., 2024; Wang et al., 2021; Ma et al., 2022). This study also attempts to determine the effect of nickel waste substitution on the performance of porous asphalt, particularly in meeting the porous characteristics required for managing stormwater runoff. This aspect is crucial in the context of urban resilience in the face of climate change and increasing intensity of extreme rainfall (World Bank, 2021). In this study, nickel waste will be used as an aggregate substitute in road pavement layers, specifically in porous asphalt mixtures. The use of nickel slag as a coarse aggregate substitute in porous asphalt mixtures is an alternative or solution that can be used for procuring coarse aggregate material, which is expected to be economically feasible and reduce potential negative impacts, such as environmental pollution.

Methods

The method used in this research was an experiment conducted in the laboratory. This research method involves creating a specific number of test specimens and using specific variables, which are then tested to obtain data.

Time and Location of the Research

The research began in June and was located at the Civil Engineering Laboratory of Fajar University Makassar, Jalan Prof. Abdulrahman Basalaman (former Racing Center) No. 101, Karampuang, Panakukang, Makassar City, South Sulawesi 90231, Indonesia.

Research Tools and Materials

The research tools used were divided into three categories: asphalt testing tools, aggregate testing tools, and supporting tools. The asphalt testing tools used included penetration,

ductility, specific gravity, softening point, flash point, and fire point tests, as well as Marshall and Cantabro tools to determine the stability and durability of the mixture. For aggregate testing, sieves according to Bina Marga specifications, scales, ovens, soaking tanks, and aggregate specific gravity testers were used. Supporting tools included a heating stove, mixing pan, thermometer, spatula, rags, a mortar, a pestle, a heating pan, and additional scales.

The materials used consisted of coarse aggregate, fine aggregate, filler, petroleum asphalt, and nickel waste as a substitute material in the mixture. All materials were tested for their characteristics to ensure compliance with SNI standards before being used in the mixture.

Data Collection Techniques

Research data was collected in two forms: primary and secondary data. Primary data was obtained through a series of laboratory tests on the mixture's constituent materials, including examination of the physical properties of coarse aggregate, fine aggregate, filler, and asphalt. This testing aims to ensure the materials meet the quality standards stipulated in the Indonesian National Standard (SNI). Secondary data was obtained from various supporting documents, such as previous research journals, research institute reports, Bina Marga technical specifications, and data from relevant government agencies, particularly the Ministry of Public Works and Public Housing.

Work Steps

The research steps were carried out in several stages. The first stage was a literature review aimed at gathering information regarding material specifications, previous research results, and the technical standards used. The second stage was the preparation of tools and materials, including the selection, transportation, and preparation of test materials in the laboratory. The third stage was material characteristic testing to determine the suitability of aggregates, fillers, and asphalt to SNI standards, including tests for specific gravity, water absorption, abrasion, and silt content. The fourth stage was the preparation of test specimens. Once the materials met the requirements, a porous asphalt mixture was prepared with variations in nickel waste substitution of 0%, 25%, 50%, 75%, and 100%. Three test specimen samples were prepared for each content variation, resulting in a total of 15 samples. The fifth stage was testing the test specimens using the Marshall method to obtain the mixture's characteristic parameters.

Testing of Test Specimens

Test specimens were tested to determine the mechanical and physical characteristics of the porous asphalt mixture with nickel waste substitution. The parameters tested included:

Optimum Asphalt Content (OAS): determined based on the calculated design asphalt content and validated through a Marshall test with several variations in asphalt content. Marshall Stability: measures the mixture's ability to withstand deformation due to traffic loads. Flow: measures the magnitude of vertical deformation when the test specimen is subjected to loads. Marshall Quotient (MQ): indicates the ratio between stability and flow, thus describing the stiffness of the mixture. Void in Mixture (VIM): measures the percentage of air voids in the compacted mixture. Void in Mineral Aggregate (VMA): determines the volume of voids between aggregate grains in the mixture that can be filled with asphalt. Void Filled Bitumen (VFB): calculates the percentage of VMA effectively filled with asphalt. All tests refer to SNI 06-2489-1991 and the General Specifications for Highways (2018/2020)

Research Flowchart

The research flow begins with a literature review, preparation of tools and materials, testing of material characteristics, creation of test specimens, Marshall testing, and analysis of the results and recommendations for mixture formulations.

Conceptual Framework

The conceptual framework of this research emphasizes the relationship between the independent variable, namely the percentage of nickel waste substitution in the porous asphalt mixture, and the dependent variable, the technical performance of the road surface, as tested using Marshall parameters. Furthermore, the environmental risks of nickel waste use are also considered through heavy metal leaching tests (TCLP/SPLP) to ensure the sustainable use of this material. The research results are expected to produce recommendations for mixture formulations that not only meet technical standards but are also environmentally friendly.

Results and Discussion

Results of Aggregate Physical Properties Tests

The series of aggregate physical properties tests used in this study generally met the standards required for aggregate performance and characteristics testing. Testing was conducted in the Civil Engineering Laboratory of the Faculty of Engineering, Fajar University.

Physical Properties of Coarse Aggregate (Chipping)

The results of the coarse aggregate physical properties tests were conducted in accordance with the Indonesian National Standard (SNI) testing method. The coarse aggregate used in this study was chipped material from a stone crusher from Bili-bili. The tests showed that the aggregate characteristics met the requirements for use as a component in asphalt mixtures. The results of these tests are shown in Table IV.1.

Table 1. Data on the Results of Testing the Physical Properties of Coarse Aggregates (Chipping)

Test	Formula	I	II	Average	Specification
Bulk Specific Gravity (Sd)		2.76	2.73	2.75	Min. 2.5
SSD Specific Gravity (Ss)		2.80	2.77	2.78	
Apparent Specific Gravity (Sa)		2.86	2.84	2.85	
Water Absorption (SW)		1.20	1.40	1.30	Max. 3%

Source: Primary data, 2025

Physical Properties of Fine Aggregate (Sand)

The results of the physical properties of fine aggregate were conducted in accordance with the Indonesian National Standard (SNI) testing methods. The fine aggregate used in this study was sand from a company in Bili-bili. Testing showed that the aggregate's performance met the requirements for asphalt mixtures. The test results are shown in Table 2.

Table 2. Data on the Results of Testing the Physical Properties of Fine Aggregate (Sand)

Test	Formula	I	II	Average	Specification
Bulk Specific Gravity (Sd)		2.49	2.63	2.56	Min. 2.5
SSD Specific Gravity (Ss)		2.56	2.66	2.61	
Apparent Specific Gravity (Sa)		2.69	2.70	2.70	
Water Absorption (Sw)		3.09	1.01	2.05	Max. 3%

Source: Primary data, 2025

Nickel Slag Waste Sediment

The results of the physical properties of the Nickel Slag waste sediment were conducted in accordance with the Indonesian National Standard (SNI) testing method. The Nickel Slag waste sediment used in this study was sourced from PT. Obsidian Stainless Steel. Most of the test results indicated that this material's performance met the requirements as a component in asphalt mixtures as a coarse aggregate. However, if the test results did not meet specifications, such as sludge content, the aggregate was washed with clean water until the sludge content was below the required threshold. This was followed by retesting the washed aggregate material or handling. However, if the absorption test results did not significantly exceed the threshold or required specifications, no handling was performed.

The determination of the Optimum Asphalt Content (OAC) was carried out based on the calculation of the planned asphalt content (Pb). From the design calculation, the value of Pb obtained was 5.5%. To establish the variation, two asphalt content levels below and two levels above the calculated value were selected using intervals of P-0.5%, P-1.5%, P+0.5%, and P+1.5%. This approach resulted in four variations of asphalt content, namely 4%, 5%, 6%, and 7%. The formula used to calculate the planned asphalt content is expressed as:

$$P=0.035a+0.045b+K(c)+FP = 0.035a + 0.045b + K(c) + FP=0.035a+0.045b+K(c)+F$$

where PPP represents the approximate asphalt content of the mixture, aaa is the percentage of aggregate retained on sieve No. 8, bbb is the percentage of aggregate passing sieve No. 8 and retained on sieve No. 200, and ccc is the percentage passing sieve No. 200. The factor KKK is taken as 0.15 for 11–15% passing sieve No. 200, 0.20 for ≤ 5% passing sieve No. 200, and 0.18 for 6–10% passing sieve No. 200, while FFF ranges from 0–2% depending on the aggregate standard, with a value of 0.7–1 commonly applied if no data is available. By substituting the values into the equation, the calculation is shown as follows:

$$P=0.035(85) +0.045(5) +0.18(10) +0.5=5.5\%P = 0.035(85) + 0.045(5) + 0.18(10) + 0.5 = 5.5\%P=0.035(85) +0.045(5) +0.18(10) +0.5=5.5\%$$

Thus, the planned asphalt content was determined to be 5.5%, which served as the reference for preparing the OAC variations.

Table 3. Optimum Asphalt Content 4%

Sieve No.	Opening (mm)	Gradation Spec. Min	Gradation Spec. Max	% Passing	% Retained	Total (g)
1 1/2	36.10	100	100	100.00	0.00	0.00
1	25.40	90	100	100.00	0.00	0.00
3/4	19.00	73	90	84.98	15.02	172.99
1/2	12.50	55	76	69.68	15.30	176.26
3/8	9.50	45	66	50.13	19.55	225.22
4	4.75	28	39.5	34.83	15.30	176.26
8	2.36	19	26.8	20.67	14.17	163.20
16	1.18	12	18.1	13.58	7.09	81.70
30	0.60	7	13.6	12.23	1.35	15.55
50	0.30	5	11.4	10.73	1.50	17.28
100	0.15	4.5	9	7.58	3.15	36.29
200	0.075	3	7	4.28	3.30	38.02

Pan	Filler	–	–	0.00	4.28	49.25
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Total Aggregate Weight = 100% = 1152 g

Asphalt Pen 60/70 (4%) = 48 g

Total Weight (Aggregate + Asphalt) = 1200 g

Table 4. Optimum Asphalt Content 5%

Sieve No.	Opening (mm)	Gradation Spec. Min	Gradation Spec. Max	% Passing	% Retained	Total (g)
1 1/2	36.10	100	100	100.00	0.00	0.00
1	25.40	90	100	100.00	0.00	0.00
3/4	19.00	73	90	84.98	15.02	171.19
1/2	12.50	55	76	69.68	15.30	174.42
3/8	9.50	45	66	50.13	19.55	222.87
4	4.75	28	39.5	34.83	15.30	174.42
8	2.36	19	26.8	20.67	14.17	161.50
16	1.18	12	18.1	13.58	7.09	80.85
30	0.60	7	13.6	12.23	1.35	15.39
50	0.30	5	11.4	10.73	1.50	17.10
100	0.15	4.5	9	7.58	3.15	35.91
200	0.075	3	7	4.28	3.30	37.62
Pan	Filler	–	–	0.00	4.28	48.74

Total Aggregate Weight = 100% = 1140 g

Asphalt Pen 60/70 (5%) = 60 g

Total Weight (Aggregate + Asphalt) = 1200 g

Table 5. Optimum Asphalt Content 6%

Sieve No.	Opening (mm)	Gradation Spec. Min	Gradation Spec. Max	% Passing	% Retained	Total (g)
1 1/2	36.10	100	100	100.00	0.00	0.00
1	25.40	90	100	100.00	0.00	0.00
3/4	19.00	73	90	84.98	15.02	169.39
1/2	12.50	55	76	69.68	15.30	172.58
3/8	9.50	45	66	50.13	19.55	220.52
4	4.75	28	39.5	34.83	15.30	172.58
8	2.36	19	26.8	20.67	14.17	159.80
16	1.18	12	18.1	13.58	7.09	79.99
30	0.60	7	13.6	12.23	1.35	15.23
50	0.30	5	11.4	10.73	1.50	16.92
100	0.15	4.5	9	7.58	3.15	35.53
200	0.075	3	7	4.28	3.30	37.22
Pan	Filler	–	–	0.00	4.28	48.22

Total Aggregate Weight = 100% = 1128 g

Asphalt Pen 60/70 (6%) = 72 g

Total Weight (Aggregate + Asphalt) = 1200 g

Table 6. Optimum Asphalt Content 7%

Sieve No.	Opening (mm)	Gradation Spec. Min	Gradation Spec. Max	% Passing	% Retained	Total (g)
1 1/2	36.10	100	100	100.00	0.00	0.00
1	25.40	90	100	100.00	0.00	0.00
3/4	19.00	73	90	84.98	15.02	167.59
1/2	12.50	55	76	69.68	15.30	170.75
3/8	9.50	45	66	50.13	19.55	218.18
4	4.75	28	39.5	34.83	15.30	170.75
8	2.36	19	26.8	20.67	14.17	158.10
16	1.18	12	18.1	13.58	7.09	79.14
30	0.60	7	13.6	12.23	1.35	15.07
50	0.30	5	11.4	10.73	1.50	16.74
100	0.15	4.5	9	7.58	3.15	35.15
200	0.075	3	7	4.28	3.30	36.83
Pan	Filler	–	–	0.00	4.28	47.71

Total Aggregate Weight = 100% = 1116 g

Asphalt Pen 60/70 (7%) = 84 g

Total Weight (Aggregate + Asphalt) = 1200 g

From the various compositions of optimum asphalt content that were prepared and tested in the laboratory, experimental results were obtained as presented in Table IV.7 (Optimum Asphalt Content Test Results). Subsequently, to determine the most representative value of the optimum asphalt content (KAO), the average value from the series of tests was calculated and summarized in Table IV.8 (Determination of Mean Optimum Asphalt Content).

Table 7. Results of Optimum Asphalt Content Testing

Testing Indicators	Result 1	Result 2	Specifications
Stability	993.51	1009.28	Min. 800
(Flow)	2.42	2.37	≤ 4
Marshall Quotient (MQ)	311.21	325.80	Min. 300
Void in Mixture (VIM)	3.67	5.30	3–5 %
Void in Mineral Aggregate (VMA)	11.54	13.23	Min. 15
Void Filled Bitumen (VFB)	68.80	65.43	Min. 65

Table 8. Determination of the Middle Value of Optimum Asphalt Content (OAC)

Asphalt Content (%)	Stability	Flow	Marshall Quotient (MQ)	VIM	VMA	VFB
5,0						
5,5						
6,0						
Specification	Min. 800	≤ 4	Min. 300	3–5%	Min. 15	Min. 65

The results of the optimum asphalt content test according to Marshall parameters show that there are several characteristics that meet and do not meet the specifications used, for example,

in the VIM value characteristics, all asphalt content meets the requirements. Based on the VMA characteristics, all asphalt content used meets the technical requirements. Regarding VFB performance, there are no fixed design criteria. In terms of flow characteristics, all asphalt content meets the specifications. Based on its stability properties, asphalt content of 5%, 6%, 7 meets the requirements, asphalt content of 4% does not meet the requirements. Meanwhile, according to the specifications on the MQ value, asphalt content of 4%, 5%, 6% and 7% does not meet the required design criteria. To obtain the optimum asphalt content, the test results were as follows: Optimum Asphalt Content (OAC) = 5/6 = 5.5% From the calculation results using the above midpoint, the optimum asphalt content used in this study was 5.5%.

Combined Aggregate Gradation

The mix gradation and mix design in this study adhere to the open gradation standards required by the National Highways Agency (SNI). The percentage of each aggregate used in this study, 85% coarse aggregate: 15% fine aggregate, was then multiplied by the aggregate percentages previously used. The results were then added to obtain the mix composition or mix design. Table IV.10 shows that the combined design created and obtained from this study falls within the specification interval required by the National Highways Agency (SNI). Therefore, an optimal mix is expected. The aggregate composition was determined by sieve (weighing based on sieve size). This method of determining aggregate proportions does not group aggregate fractions (coarse aggregate, fine aggregate, and filler) as with the by-portion method, but rather by weighing based on the composition of each sieve size used in this study. The determination of total composition using the by-sieve method is shown below:

Table 9. Sieve Analysis and Gradation of Combined Aggregates for Asphalt Concrete Wearing Course (AC-WC)

Sieve Number	1 1/2	No. 1	3/4	No. 4	No. 16	No. 50	No. 100
Crushed Stone (% Passing)	100	82.33	43.3	100.00	100.00	100.00	
85% Batch	85	85	69.98	54.68	0.00	0.00	0.00
Sand (% Passing)	100	100	100	90.50	71.50	50.50	
15% Batch	15	15	18	13.58	10.73	7.58	
Combined Aggregate	100	100	84.98	69.68	13.58	10.73	
Specification	100	90–100	73–90	55–76	12–18	5–14	

Source: Primary data, 2025

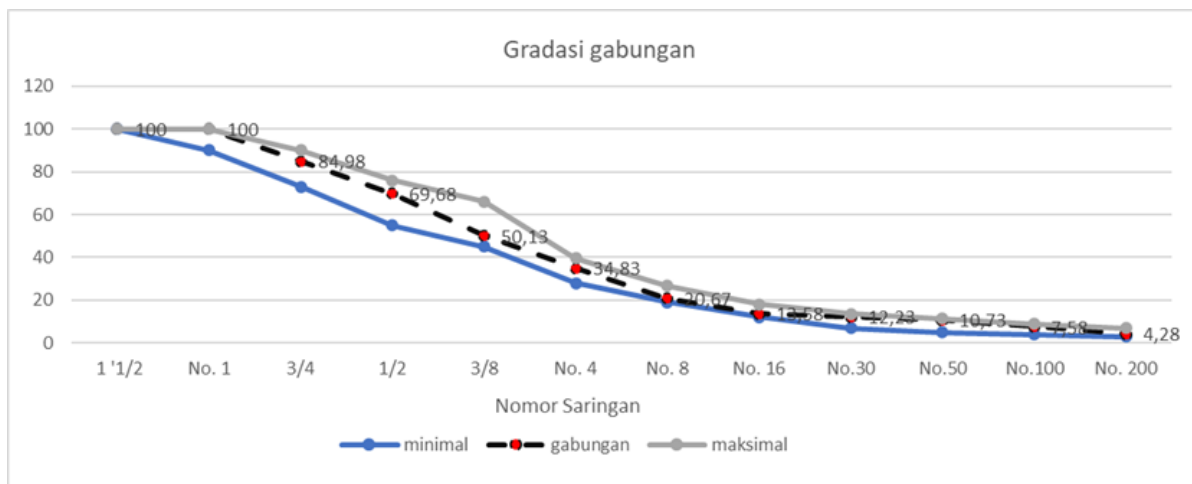


Figure .1 Combined Aggregate Gradation Curve

Source: Primary data, 2025

After screening to determine the composition of coarse aggregate, fine aggregate and filler based on the composition of each sieve size used in accordance with Bina Marga, the test results were obtained as in Table IV. 10 and Figure 1, the percentage value between coarse aggregate and fine aggregate is 85%: 5%: 10%. The aggregate composition uses coarse aggregate and fine aggregate as well as filler, meaning that the aggregate is held on each sieve and then separated according to the sieve size specified in the specifications used.

Preparation of Test Specimens

The hollow asphalt mixture has an optimum asphalt content of 5.5% and an asphalt penetration of 60/70. The calculations can be found in the appendix. Furthermore, the mixture weight and aggregate obtained for the optimum asphalt content are as follows.

After obtaining the optimum asphalt content, the next step is to determine the proportions of normal aggregate and nickel slag waste sediment. The following table shows the ratio of normal aggregate to nickel slag waste sediment for the mixture with the Bina Marga specifications:

Table 10. Proportion of normal aggregate mixture and 0% Nickel Slag waste sediment

Sieve Size (mm)	Sieve Number	% Passing	Specification Limits (%)
19.0	3/4"	100.00	100
12.5	1/2"	95.21	90–100
9.5	3/8"	86.70	73–90
4.75	No. 4	68.21	55–76
2.36	No. 8	45.05	–
1.18	No. 16	28.15	12–18
0.60	No. 30	18.10	–
0.30	No. 50	10.73	5–14
0.15	No. 100	7.58	–
0.075	No. 200	5.21	4–8

Table 11. Proportion of normal aggregate mixture and 25% Nickel Slag waste sediment

Sieve Size (mm)	Sieve Number	% Passing	Specification Limits (%)
19.0	3/4"	100.00	100
12.5	1/2"	95.21	90–100
9.5	3/8"	86.70	73–90
4.75	No. 4	68.21	55–76
2.36	No. 8	45.05	–
1.18	No. 16	28.15	12–18
0.60	No. 30	18.10	–
0.30	No. 50	10.73	5–14
0.15	No. 100	7.58	–
0.075	No. 200	5.21	4–8

Table 12. Proportion of normal aggregate mixture and 50% Nickel Slag waste sediment

Sieve Size (mm)	Sieve Number	% Passing	Specification Limits (%)
19.0	3/4"	100.00	100
12.5	1/2"	95.21	90–100
9.5	3/8"	86.70	73–90

4.75	No. 4	68.21	55–76
2.36	No. 8	45.05	–
1.18	No. 16	28.15	12–18
0.60	No. 30	18.10	–
0.30	No. 50	10.73	5–14
0.15	No. 100	7.58	–
0.075	No. 200	5.21	4–8

Table 13. Proportion of normal aggregate mixture and 75% Nickel Slag waste sediment

Sieve Size (mm)	Sieve Number	% Passing	Specification Limits (%)
19.0	3/4"	100.00	100
12.5	1/2"	95.21	90–100
9.5	3/8"	86.70	73–90
4.75	No. 4	68.21	55–76
2.36	No. 8	45.05	–
1.18	No. 16	28.15	12–18
0.60	No. 30	18.10	–
0.30	No. 50	10.73	5–14
0.15	No. 100	7.58	–
0.075	No. 200	5.21	4–8

Implications for Sustainable Construction Management

The implications of this research go beyond laboratory findings and place them into the context of a greater managerial quandary of finding a balance between infrastructure expansions and sustainable development. In Indonesia, road construction is not just an engineering project, but a managerial strategy that has a direct influence on economic competitiveness, environmental stability, and social welfare (Leweherilla, 2022; Ministry of Public Works and Public Housing, 2017). This research provides an alternative approach to material strategy through the introduction, by proving the possibility of using nickel waste as an alternative aggregate in porous asphalt, not only in operational but also in institutional implications in construction management. Nickel waste in road mixtures demonstrates what the principle of the circular economy, that is, to turn industrial by-products into productive resources, is, and, therefore, is consistent with international sustainability frameworks (Ellen MacArthur Foundation, 2020; OECD, 2022).

This change as a managerial perspective is not just a replacement of materials but an all-over restructuring of the road construction supply chain. Historically, the use of aggregate procurement has relied on extraction of natural resources, thus increasing ecological degradation and causing social resistance in mining areas (Hartono & Mulyadi, 2018). The fact that nickel slag is implemented as a partial replacement of traditional aggregates provides the sourcing strategy with flexibility, therefore reducing the dependence on virgin materials and at the same time reduces the externalities linked to the disposal of industrial waste (Yulianto and Prasetyo, 2021; Siregar et al., 2022). The managerial reframing is in line with what has been practiced in Japan and Korea where recycled mining wastes have been incorporated in the state infrastructure development with strict quality-assurance policies (Ishikawa, 2015; Mori and Kimura, 2021). The need to institutionalize material innovation to Indonesian managers and policymakers is indisputable: it is necessary not only to technically justify it but also to implement it in policy frameworks that would introduce such options into national procurement principles (Rosyidi & Darmawan, 2020; Ministry of Public Works and Housing, 2021).

However, sustainability is not achievable by substitution only. Nickel waste is rich in heavy metals, which presents an environmental management issue that should be paid special attention (Puspitasari et al., 2020; KLHK, 2021). Otherwise, nickel, cobalt, and chromium residues can be washed into soil and aqueous systems, which will affect ecological integrity and the health goals of the population (Permatasari et al., 2020; Kurniawan et al., 2022). Management thus does not merely deal with the road performance but in collaboration with the design of overall risk-reduction structures. Pre-treatment, washing, or encapsulation as environmental risk management techniques should also become part of the supply chain thus shifting project management priorities towards short-term cost efficiency into lifecycle accountability (Puspitasari, 2022; Sembiring et al., 2023). Such environmental protection symbolizes good green supply chain management practices where hidden environmental dangers are absorbed in planning and procurement (Prayoga, 2023; Wicaksono and Yulianto, 2022).

The benefits of undertaking nickel waste incorporation into road construction, though, must be put into perspective in a strategic and not a strictly transactional paradigm, in terms of economics. Although short-term savings due to a decrease in aggregate procurement are topical, the main managerial benefit lies in the creation of long-term efficiencies that will be supported through improved road quality and extended periods of maintenance (Andika et al., 2019; Ramadhani, 2020). The comparative studies in Australia and South Korea have shown that the systemic benefits attributed to the legitimised use of the industrial by-products outweigh transitory fiscal benefits by a large margin (UNEP, 2020; Mori & Kimura, 2021). The strategic need with respect to Indonesian infrastructural agencies is ensuring that nickel-waste utilisation is integrated into the procurement system like the LKPP e-catalogue so that the contractors can be encouraged to use sustainable materials not as an option but as a matter of default (Bappenas, 2022; Setiawan, Wulandari, 2021).

The current paper shows that sustainable construction cannot be simplified to technical compliance; instead, it should be interpreted as managerial paradigm, which integrates environmental, economic and institutional factors. The use of nickel waste as part of porous asphalt will also help solve the issue of material shortage, waste disposal, and flood resistance at once, thus transforming the value architecture of infrastructural projects (Mulyono, 2006; Sunaryo, 2020; World Bank, 2021). Such a Tri dental conclusion means that waste-to-resource approaches are pillars, as opposed to peripheral innovations to manage twenty-first-century infrastructure systems. The next challenge is that Indonesian policymakers, contractors, and educational institutions collaboratively transfer laboratory achievements to the state implementation settings, with a focus on implementing sustainability in practice, but not on the rhetoric.

Conclusion

The current paper shows that nickel waste can be used successfully as a partial substitute to coarse aggregate in porous asphalt mixes, which provides it with technical viability and strategic value in building sustainable roads in Indonesia. Findings affirm that nickel slag has sufficient mechanical strength, stability and durability to meet various performance requirements as discussed in the Bina Marga specifications, whereas simultaneously addressing the severe challenge of industrial waste build-up in nickel-producing areas. With its ability to improve the quality of roads, on the one hand, and to diminish the environmental impact, on the other hand, this innovation of waste-to-resource turns out to be much more than an engineering solution, as it appears a managerial initiative aligned with the national project of development and the global agenda of sustainability. The implications of these findings on

the overall management of infrastructure projects are wider as it means that these projects cannot be perceived solely in the context of technical efficiency. The use of nickel waste integration is an example of a paradigmatic shift in construction management, where the previous models of extraction, based on virgin aggregates, are replaced by the new ones based on the principles of the regenerative models with the inclusion of the principles of the circular economy. The process of realizing this transition requires purposeful institutional assistance and includes items such as procurement incentives, clear regulatory standards, and joint partnership between government agencies, academic institutions, contractors, and the mining industry. Without this kind of systemic integration, laboratory level advances can be little more than isolated phenomena, of no help in transforming industry practice. At the same time, the research also outlines pressing issues that have to be overcome to allow the sustainable use of nickel waste in road construction projects. The threat of leaching of heavy-metals presupposes the strict environmental risk control, such as the implementation of stabilization technologies and compliance with the SNI-based toxicity testing guidelines. This evidence highlights the fact that the process of sustainable construction cannot be done by material substitution only but by the comprehensive system that would provide the balance between the level of economic efficiency, technical performance, and environmental safety. To managers and policymakers, this reiterates the need to incorporate environmental protection aspects in their procurement procedures and project planning, thus making sustainability sought in a comprehensive and not selective way.

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