High-Quality Composite Concrete Based on Eco Materials from Nickel Slag Waste as an Implementation of Sustainable Infrastructure

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ABSTRACT

The nickel processing industry produces a large amount of solid waste in the form of nickel slag, which has the potential to pollute the environment if not properly managed and utilized. This study evaluates the use of nickel slag as a partial substitute for coarse aggregate in the production of high-strength concrete. Tests were conducted using cylindrical specimens with a diameter of 10 cm and a height of 20 cm, with variations in nickel slag content of 25%, 50%, and 75% of the total coarse aggregate. Based on the compressive strength test results, it was found that a 50% nickel slag composition was the most optimal variation, producing an average compressive strength of 46.31 MPa, which is an increase of 10.18% compared to the control concrete at 42.03 MPa. This improvement is influenced by the physical and chemical characteristics of the nickel slag, such as its rough surface that enhances interlocking between aggregate particles, as well as the presence of silica compounds that act as pozzolanic materials.

Keywords-Nickel slag; high-strength concrete; coarse aggregate; compressive strength

I. INTRODUCTION

Aggregate consumption in the construction industry is projected to increase significantly, which could have serious impacts on the natural aggregate ecosystem. Aggregates are a key component of the concrete matrix, accounting for approximately 60%–80% [1]. To reduce dependence on natural aggregates as the primary source in concrete production, synthetic aggregates derived from industrial waste present a viable alternative for the construction sector. In the context of infrastructure development in the new Indonesian Capital City (IKN), the main challenge lies in the limited availability of natural material resources in the Balikpapan region. Balikpapan relies on supplies of natural materials, such as coarse and fine aggregates, from outside Kalimantan, particularly Sulawesi. This dependence arises from the low quality of aggregates in Kalimantan, which do not meet the required specifications. Consequently, natural resource reserves in Sulawesi are increasingly depleted due to overexploitation [2], leading to rising material costs and environmental degradation. Therefore, the use of aggregates derived from industrial waste offers a promising alternative to both natural and synthetic aggregates. The growth of Indonesia's nickel industry has driven production to 1.6 million metric tons in 2022, accounting for approximately 48% of the global output, as reported by the Ministry of Energy and Mineral Resources [3]. Sulawesi, particularly the Morowali region in Central Sulawesi, serves as one of the country's major nickel production centers. This increase in production has simultaneously generated substantial amounts of nickel slag waste, estimated at nearly 1 million tons/year [4]. In line with Law No. 32 of 2009 on Environmental Protection and [29] on the Management of Hazardous and Toxic Waste (B3), industrial waste must be handled through reuse and recycling to reduce environmental impacts [5]. However, nickel slag is still predominantly disposed of in landfills without proper utilization, despite its considerable potential for various applications, especially in construction. Therefore, developing alternative construction materials, particularly those incorporating nickel slag into concrete mixtures is essential.

Furthermore, the development of the IKN emphasizes the implementation of smart and sustainable infrastructure concepts, thus prioritizing the need for high-performance concrete. High-performance composite concrete is specifically designed to exhibit superior durability and mechanical performance compared to conventional concrete [6]. This type of concrete often utilizes industrial byproducts, such as nickel slag, recycled materials, and chemical additives, to achieve improved performance characteristics. Industrial waste, such as iron slag, steel slag, ground granulated blast slag, fly/bottom ash, palm oil waste, rubber waste, ceramic waste, and so on, can be used as substitutes for natural aggregates in concrete mixes [7-13]. This waste can improve the performance and mechanical properties of concrete. It has also been shown that nickel slag can improve concrete's abrasion resistance. Furthermore, it can increase the latter's compressive strength. However, so far the research has been limited to the use of nickel slag in road structures, paving blocks, concrete blocks, and as embankments with low to medium quality concrete, without reviewing in depth the use of waste in the need for high quality concrete and the durability of concrete in extreme environmental conditions, such as those that will be faced in the IKN [17-22]. The use of nickel slag in concrete mixtures can support the resilience of national infrastructure in the field of material technology and construction engineering [23], while contributing to efforts to reduce carbon emissions.

II. MATERIALS

The aggregates used in this study consisted of fine aggregate and coarse aggregate from crushed stone. The coarse aggregate had a maximum particle size of 20 mm and was sourced locally from the banks of the Palu River in Sunju Village, Marawola Subdistrict, Sigi District, Palu, Central Sulawesi. The nickel slag was obtained as a by-product from the nickel smelting process of Gunbuster Nickel Industry (GNI), a nickel processing industry located in Morowali, Central Sulawesi. Initially in the form of large lumps, the slag was crushed to approximate the size of natural coarse aggregate and sieved using a ¾-inch (19 mm) sieve to achieve a maximum particle size of 20 mm. Portland Composite Cement (PCC) produced by Semen Tonasa was used as the binder. In addition, a Type F admixture (Consol Flow 206), in accordance with [24], classified as a High-Range Water Reducer (HRWR), was incorporated into the mixture. This admixture was intended to improve the workability of the concrete without increasing the water content.

Fig. 1. Nickel Slag.

TABLE I. AGRREGATE PHYSICAL TESTING

Testing	Specification	CA	SN	Unit
Moisture content	0.5 - 2	1.2	1.36	%
Specific gravity	2.4 – 2.7	2.66	2.72	gr/cm^3
Bulk density	1.6 – 1.9	1.96	1.62	gr/cm^3
Abrasion	Max 30%	19.6	1.83	%
Sieve analysis	Max 10 - 40	max 20	max 20	-

The aggregate gradation in this study followed procedures for designing normal concrete mixtures according to [27]. The aggregate gradation proportions were determined based on the upper and lower standard limits, with the midpoint value selected to ensure compliance with aggregate usage standards. Based on Table I, the nickel slag had a specific gravity of 2.72 g/cm³, a bulk density of 1.62 g/cm³, an abrasion value of 1.83%, a water content of 1.36%, and a water absorption of 1.25%. In comparison, natural coarse aggregate had a specific gravity of 2.66 g/cm³, a bulk density of 1.96 g/cm³, an abrasion value of 19.6%, a water content of 1.21%, and a water absorption of 1.37%.

TABLE II. NICKEL SLAG CHEMICAL TESTING

Compounds / elements	Laboratory test results	Unit
Silica (SiO_2)	29.78	(%)
Alumina (Al_2O_3)	0.78	(%)
Calcium Oxide (CaO)	5.53	(%)
Iron (Fe)	52.06	(%)
Chromium (Cr)	3.34	(%)
Sulfur (S)	5.32	(%)
Manganese (Mn)	1.65	(%)
Nickel (Ni)	0.69	(%)
Titanium (Ti)	0.35	(%)
Potassium (K)	0.19	(%)
Zinc (Zn)	0.18	(%)
Copper (Cu)	0.05	(%)
Vanadium (V)	0.03	(%)

The nickel slag used in this study contained 29.78% silica (SiO_2), 52.06% iron (Fe), 0.78% alumina (Al_2O_3), 3.34% chromium (Cr), 5.53% calcium oxide (CaO), 1.65% manganese (Mn), 5.32% sulfur (S), along with trace amounts of other elements. The high proportions of iron and silica indicate that the slag has the potential to enhance concrete performance, as silica can contribute to secondary hydration reactions that improve the formation of Calcium Silicate

Hydrate (C–S–H), the primary strength-giving compound in concrete.

III. METHODS

The preparation of concrete specimens was carried out in accordance with [28]. The materials used included fine aggregate, coarse aggregate, cement, nickel slag, water, and a Type F superplasticizer. The fine aggregate was sourced from Palu and classified as Zone II, while the coarse aggregate had a maximum size of 20 mm. The nickel slag was obtained from Morowali, Central Sulawesi. The superplasticizer was a Type F admixture (Consol Flow 206) with a dosage of 0.5% of the cement weight, intended to improve the workability of the concrete mixture. The high-strength concrete mixture in this study was designed for a volume of 1 m³, with a target compressive strength of 42 MPa. The mix composition utilized coarse aggregate with a maximum size of 20 mm, and fine aggregate classified within Zone II. The detailed proportions of the concrete mix are outlined in Table III.

TABLE III. CONCRETE MIX PROPORTIONS

Information	Binder	Watter	Fine	Coarse	Unit
Propotion (1m^3)	553.8	205	551.71	1024.61	Kg
1 sample (0.00157 m^3)	0.87	0.31	0.87	1.62	Kg
Sf 1.2	1.04	0.37	1.05	1.94	Kg

After determining the mix proportions for each variation, the mixing process was carried out using a concrete mixer. The fresh concrete obtained from the mixer was subjected to a slump test to evaluate its consistency. According to [27], the proposed slump value for structural concrete is 10 cm ± 2 cm, indicating the ability of the mixture to flow and fill the mold without segregation. The fresh concrete was then cast into prepared molds and compacted using a combination of rodding and tapping methods. Cylindrical specimens with a diameter of 100 mm and a height of 200 mm were used for the compressive strength test.

IV. RESULTS AND DISCUSSION

A. Specimen Weight

The average weight of the test specimens for each variation reflects the density of the concrete and correlates with the compressive strength results. For the control concrete (0% nickel slag), the average specimen weight was 3.91 kg, derived from three samples weighing 3.93 kg, 3.92 kg, and 3.89 kg. The 25% nickel slag substitution (SN 25%) yielded an average specimen weight of 3.95 kg, based on individual weights of 3.95 kg, 4 kg, and 3.9 kg. For the 50% substitution (SN 50%), the average specimen weight increased further to 4.03 kg, with sample weights of 4 kg, and 4.04 kg. The highest average specimen weight was recorded for the 75% substitution (SN 75%) at 3.89 kg, based on weights of 4.06 kg, 3.84 kg, and 3.85 kg. The highest specimen weight was achieved at 50% slag substitution, which also corresponded to the highest compressive strength. This suggests that the optimal proportion of nickel slag contributes to a denser and more compact internal structure, leading to improved mechanical performance. Conversely, the slight reduction in specimen weight at 75% substitution reflects a decrease in concrete density, which correlates with the reduction in compressive strength observed for this variation.

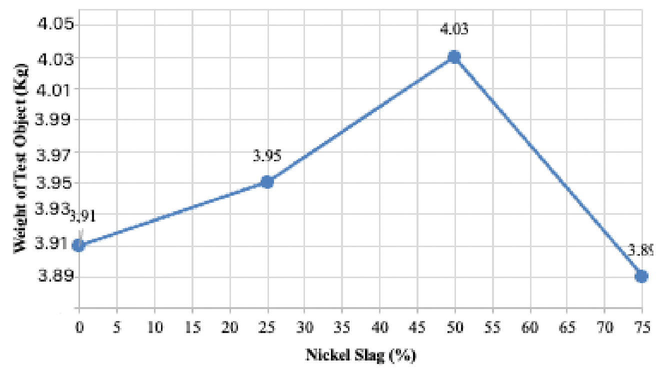


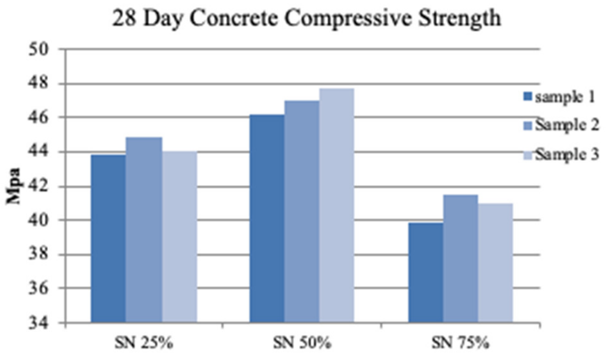
Fig. 2. Weight of specimen.

B. Compressive Strength Test Method

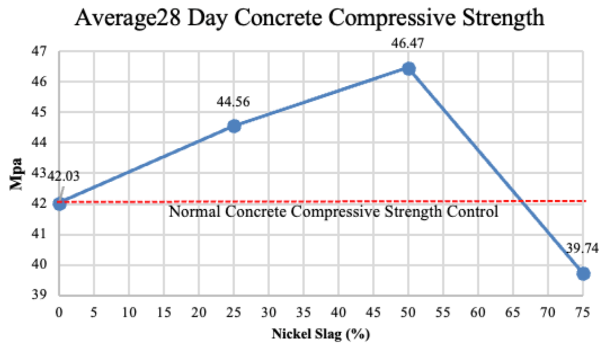
The compressive strength test was carried out to assess the ability of concrete to resist maximum compressive loads prior to failure. This test was conducted to observe the influence of various nickel slag substitution levels on the mechanical performance of concrete and to determine the optimum proportion that produces the highest compressive strength. Visual documentation of the testing procedure and a comparison of the compressive strength results for each variation are shown in Figures 3 and 4.

Fig. 3. Compressive strength testing.

The results of concrete compressive strength testing at 28 days showed that the compressive strength value varied depending on the percentage of nickel slag coarse aggregate used in the mixture. Control concrete without nickel slag had an average compressive strength of 42.03 MPa, with an average test specimen weight of 3.91 kg. At a variation of 25% nickel slag, the compressive strength increased to 44.23 MPa, an increase of 5.23%, with a test specimen weight of 3.95 kg, and reached its peak at a variation of 50%, with a compressive strength of 46.31 MPa, an increase of 10.18%, with a test specimen weight of 4.03 kg. This increase in compressive strength can be correlated with the increase in concrete density, as reflected in the weight of the test specimen, which also increased. This indicates that the distribution of nickel slag aggregate in the mixture at proportions of 25% and 50% can fill the voids between the aggregates more effectively, resulting in a denser and more solid internal structure of the concrete.



(a)



(b)

Fig. 4. (a) (b) Compressive strength testing.

The increase in compressive strength is also influenced by the physical properties of the aggregates used. Nickel slag has a higher specific gravity of 2.717 g/cm³ compared to natural coarse aggregate at 2.660 g/cm³, indicating that nickel slag particles are denser and more compact. This contributes to higher concrete density, which is directly associated with improved strength and durability. Aggregates with higher specific gravity typically possess greater internal strength and lower porosity, enhancing the bonding between the concrete components and reducing the air voids within the mix. In addition, the abrasion value of nickel slag coarse aggregate is 18.4%, which is lower than that of natural coarse aggregate at 19.6%. A lower abrasion value signifies higher hardness and better resistance to friction or mechanical wear, thereby contributing to increased compressive strength. The rough and angular surface texture of nickel slag further enhances mechanical interlocking between the aggregate and the cement paste, resulting in stronger bonding and a more integrated concrete matrix. From a chemical perspective, the relatively high silica content of nickel slag (29.78%) also plays a beneficial role. Silica can undergo pozzolanic reactions with calcium hydroxide released during cement hydration, forming additional C–S–H, the primary strength-forming compound in concrete. This contributes to the improvement of both the microstructure and compressive strength of the concrete.

However, at a 75% substitution level, the compressive strength decreased to 41.78 MPa, which is 0.59% lower than the control concrete, accompanied by a reduction in specimen weight to 3.89 kg. This decline indicates that the excessive use of nickel slag leads to the formation of additional voids, resulting in lower concrete density. When the proportion of nickel slag exceeds the optimal limit, the aggregate gradation becomes imbalanced, causing uneven particle distribution and the creation of gaps within the concrete matrix. The compressive strength is strongly influenced by the internal density and the quality of the bond between the cement paste and the aggregates. Poor aggregate gradation or non-ideal surface texture increases porosity and weakens inter-particle bonding, thus reducing the concrete's load-bearing capacity. Higher porosity disrupts material continuity, making the concrete more susceptible to failure under compressive forces. This observation aligns with the results of this study, where the reduced density of specimens at 75% substitution corresponded to lower compressive strength. Although the silica content in nickel slag still contributes to the hydration process, the excessive proportion of slag physically disrupts the concrete's structural compactness, leading to a less dense and suboptimal concrete matrix.

C. Environmental Safety Test

To assess the environmental safety of concrete containing nickel slag, a Toxicity Characteristic Leaching Procedure (TCLP) test was performed. This test aims to evaluate the potential leaching of hazardous heavy metals from the concrete into the surrounding environment, particularly into soil and groundwater, which can pose serious threats to human health and ecological systems. The concrete specimens, prepared using various nickel slag substitution levels, were first crushed to a standardized size to simulate real environmental conditions. The samples were then subjected to a leaching process using a synthetic acetic acid solution that simulates the acidic conditions found in landfills or contaminated soils. The leaching procedure was conducted over a period of 18–20 hours using a rotary agitation device under controlled conditions. The resulting leachate was analyzed to detect the concentrations of heavy metals using X-Ray Fluorescence (XRF) or Atomic Absorption Spectroscopy (AAS). The heavy metal parameters tested included chromium (Cr), nickel (Ni), lead (Pb), cadmium (Cd), and mercury (Hg). The test results were then compared against the maximum allowable concentrations stipulated in [29]. The outcome of the TCLP test is crucial to ensure that the utilization of nickel slag as a partial replacement for coarse aggregate in concrete does not result in environmental contamination. This certifies that such concrete applications are safe and suitable for sustainable, long-term infrastructure development.

TABLE IV. TCLP TESTING

Parameter	Unit	Test method	Result	Remarks
Arsenic (As)	mg/L	[25], [26]	<0.002	Normal
Barium (Ba)	mg/L	[25], [26]	0.176	Normal
Cadmium (Cd)	mg/L	[25], [26]	< 0.002	Normal
Selenium (Se)	mg/L	[25], [26]	< 0.002	Normal
Silver (Ag)	mg/L	[25], [26]	< 0.017	Normal
Chromium (Cr)	mg/L	[25], [26]	< 0.026	Normal
Lead (Pb)	mg/L	[25], [26]	< 0.035	Normal

TCLP testing in this study was conducted on concrete samples with optimum compressive strength, namely with a 50% nickel slag variation. Based on the test results shown in Table IV, all heavy metal parameters were well below the EPA's TCLP regulatory limits. Nickel slag waste in concrete does not cause environmental pollution due to the release of heavy metals. This material is safe for both structural and non-structural applications, with a low risk of toxicity. Therefore, concrete with nickel slag waste can be used as an environmentally friendly alternative material.

V. CONCLUSIONS

This research presents the first innovation in high-quality concrete formulation that utilizes nickel slag waste as a significant substitute for aggregate and/or cement, with a multi-scale characterization approach (micro to macro) and leaching tests to ensure technical performance and environmental safety. The main conclusions of this study are:

- The concrete mix composition for 1 m³ consists of 553.8 kg of binder, 205 kg of water, 551.71 kg of fine aggregate, and 1024.61 kg of coarse aggregate. Furthermore, type F admixture was used at 0.5% of the cement weight, or 2.77 kg.
- A 50% substitution of nickel slag resulted in an optimum compressive strength of 46.31 MPa, a 10.17% increase compared to standard concrete, while a 75% substitution reduced the concrete's strength.
- Nickel slag waste in concrete does not cause environmental pollution; this material is safe for use in both structural and non-structural applications, with a low risk of toxicity.

Future research will focus on further optimizing sustainable concrete mixtures by integrating nickel slag with other industrial by-products, such as palm oil ash and fly ash. Subsequent studies will also evaluate the long-term durability of the proposed concrete under various aggressive environmental conditions and involve the development of small-scale structural prototypes. In addition, large-scale implementation trials will be carried out in IKN construction projects. These research efforts are expected to contribute to the development of advanced eco-friendly construction materials that support smart and sustainable infrastructure in the IKN.

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