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Performance Evaluation of High-Strength Self-Compacting Concrete (SCC) with Nickel Slag as Partial Fine Aggregate Replacement

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ABSTRACT

The escalating demand for high-performance construction materials has intensified the search for sustainable alternatives to natural aggregates, particularly in the production of High-Strength Self-Compacting Concrete (SCC). This study evaluates the integration of nickel slag from Morowali, Central Sulawesi, as a partial replacement for fine aggregates to address the environmental degradation caused by river sand mining. Utilizing a quantitative experimental design, 48 cylindrical specimens were tested across various substitution levels (0%, 20%, 40%, and 60%) with a consistent water-to-binder ratio of 0.28 and a target characteristic strength of 60 MPa. Rheological parameters were assessed through slump-flow and L-box blocking ratio (H) tests, while mechanical performance was measured via compressive strength at 7, 14, and 28 days. Results indicate that a 40% substitution threshold represents the optimum balance, yielding a superior characteristic strength of 69.73 MPa a 16.6% enhancement over the control. Rheologically, nickel slag improved fluidity up to 710 mm, although replacements exceeding 40% triggered dynamic instability and segregation, evidenced by an H ratio decline to 0.78. These findings imply that nickel slag is a technically viable reinforcing filler for strategic infrastructure, provided that substitution levels are strictly calibrated. The study concludes that while nickel slag significantly densifies the concrete matrix, industrial adoption requires further standardization of long-term durability metrics. Future research should prioritize the evaluation of creep and chloride resistance in marine environments to ensure structural longevity.

Keywords: *High-Strength Concrete, Nickel Slag, Self-Compacting Concrete, Sustainable Construction, Waste Upcycling, Structural Performance*

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INTRODUCTION

The evolution of modern infrastructure requires the development of construction materials that provide high mechanical performance and efficient placement, particularly in structures with complex geometries. High-Strength Self-Compacting Concrete (SCC) has gained significant attention due to its ability to flow and consolidate under its own weight without mechanical vibration, while maintaining high load-bearing capacity. However, the construction industry's dependence on natural river sand as fine aggregate has contributed to environmental degradation and depletion of natural resources. At the same time, Indonesia's metallurgical industry produces large quantities of nickel slag as a byproduct, which is often underutilized and poses environmental challenges when stockpiled (Ministry of Environment and Forestry, 2021). The use of nickel slag as a partial replacement for fine aggregates in SCC offers a potential pathway toward more sustainable construction practices (Center for Mineral, Coal, and Geothermal Resources, 2022).

Nickel slag possesses favorable physical properties, including high density, abrasion resistance, and angular particle shape, which can enhance the mechanical interlocking within the Interfacial Transition Zone (ITZ). However, its application in SCC requires careful control, as the rheological behavior of SCC is highly sensitive to changes in aggregate gradation and particle size distribution. Excessive substitution levels may lead to segregation or reduced passing ability, which can negatively affect the performance of hardened concrete. Therefore, systematic evaluation is necessary to ensure that nickel slag-based SCC satisfies both strength and workability requirements (American Society for Testing and Materials (ASTM), 2020).

Academic inquiries over the past five years have intensified the exploration of nickel slag's mineralogical potential as a next-generation construction material. Analytical data indicates that nickel slag possesses a high concentration of silica (SiO_2), iron oxide (Fe_2O_3), and magnesium oxide (MgO), which contribute to the densification of the concrete microstructure through a micro-filling effect that occludes capillary pores within the cementitious matrix (Das, Singh, & Das, 2021). Recent investigations demonstrate that replacing natural sand with nickel slag at levels up to 30% consistently improves compressive strength by approximately 10–15% due to the superior hardness of slag particles compared to traditional quartz sand (Saha & Sarker, 2020). In the specialized domain of SCC, the inclusion of these industrial byproducts necessitates a precise calibration of third-generation superplasticizers, such as polycarboxylate ethers (PCE), to maintain the requisite viscosity and deformability (Singh & Choudhary, 2022).

Global experimental data further suggests that concrete incorporated with nickel slag exhibits enhanced resistance to chloride ion penetration and aggressive sulfate environments, making it ideal for marine infrastructure. This durability enhancement is attributed to the refinement of the pore structure and the formation of a more massive microstructural framework (Li, Zhang, & Chen, 2022). However, a significant challenge highlighted in recent literature is the increased self-weight of the concrete, which may influence the dead load design of structures if not meticulously accounted for (Wang, Chen, & Gu, 2023). While the efficacy of nickel slag is well-documented in conventional concrete, its application in High-Strength SCC still presents technical debates regarding dynamic stability and pumpability under high-pressure conditions (Zhang, Wang, & Zhao, 2021).

Despite these findings, limited studies have focused on the application of nickel slag in High-Strength SCC with compressive strengths exceeding 60 MPa. Most existing research addresses normal-strength or conventional concrete, while the behavior of SCC with low water-to-binder ratios and high binder content remains insufficiently explored. In particular, there is a lack of detailed investigation on how high substitution levels affect rheological performance and passing ability in high-strength SCC systems.

In addition, long-term performance aspects such as creep, shrinkage, and durability under aggressive environments are not yet fully understood for slag-based high-strength SCC. Therefore, further experimental research is required to establish reliable performance limits and practical guidelines for its application. This study aims to evaluate the performance of High-Strength SCC with a target compressive strength of 60 MPa using nickel slag as a partial replacement for fine aggregate at levels of 0%, 20%, 40%, and 60%. The objective is to determine the optimum substitution level that provides a balance between mechanical strength and workability performance. The results are expected to contribute to the development of sustainable and high-performance concrete materials for infrastructure applications.

METHODS

1. Research Design and Variable Identification

This study adopts a laboratory-based quantitative experimental approach using a single-factor design to evaluate the effect of nickel slag substitution on the performance of High-Strength Self-Compacting Concrete (SCC). The experimental framework focuses on systematically varying the proportion of nickel slag as a partial replacement for fine aggregate while maintaining other parameters constant. The independent variable is the substitution level of natural river sand with nickel slag at four levels: 0% (control), 20%, 40%, and 60% by volume of fine aggregate. The dependent variables include fresh concrete properties (slump-flow diameter, T_{50} flow time, and L-box blocking ratio) and hardened concrete properties (compressive strength at 7, 14, and 28 days). Controlled variables include the water-to-binder ratio (0.28), cement content (550 kg/m^3), coarse aggregate content (950 kg/m^3), superplasticizer dosage (1.5% by weight of cement), and curing temperature (25 ± 2°C).

2. Mix Design Method and Experimental Approach

The concrete mix design was developed using the absolute volume method in accordance with SNI 03-2834-2000, combined with SCC design principles recommended by EFNARC guidelines for self-compacting concrete. The adopted approach can be classified as a performance-based mix design, where the proportions are adjusted to achieve both high strength (≥60 MPa) and self-compactability.

The mix design process involved the following steps:

a. Determine the target strength and the water-to-binder ratio A target compressive strength of 60 MPa was established, and a low water-to-binder ratio of 0.28 was selected to achieve high-strength performance.
b. Binder and aggregate proportioning The cement content was fixed at 550 kg/m^3 to ensure sufficient paste volume for SCC flowability. Coarse aggregate content was limited to 950 kg/m^3 to avoid blocking during flow.
c. Fine aggregate replacement strategy Nickel slag was introduced as a partial replacement for natural sand at 0%, 20%, 40%, and 60% by volume. The substitution was designed to evaluate its influence on both rheological and mechanical behavior.
d. Admixture optimization A polycarboxylate ether (PCE)-based superplasticizer was incorporated at 1.5% to maintain workability and flow characteristics without increasing water content.

e. Trial mix and adjustment Preliminary trial mixes were conducted to ensure compliance with SCC criteria (slump flow 650–750 mm and L-box ratio ≥0.8), and minor adjustments were made to achieve stable mixtures.

3. Mixing, Casting, and Curing Procedures

All concrete mixtures were prepared under controlled laboratory conditions. The mixing procedure followed a standardized sequence:

a. Dry mixing of cement, fine aggregate (sand and/or nickel slag), and coarse aggregate for 2 minutes.
b. Addition of approximately 70% of the mixing water and mixing for 2 minutes.
c. Addition of superplasticizer dissolved in the remaining water, followed by mixing for 3 minutes until a homogeneous mixture was achieved.

Fresh concrete tests were conducted immediately after mixing. The concrete was then cast into cylindrical molds (150 mm × 300 mm) without mechanical vibration, relying on self-compaction behavior. After casting, specimens were covered to prevent moisture loss and demolded after 24 hours. Curing was performed by immersion in water at a controlled temperature of 25 ± 2°C until the testing age (7, 14, and 28 days).

4. Materials and Instrumentation

The fundamental materials comprise Ordinary Portland Cement (OPC) Type I, natural river sand, and pyrometallurgical nickel slag as the substitute fine aggregate. Crushed stone with a maximum nominal size of 19 mm was utilized as the coarse aggregate. Chemical enhancement was achieved via a high-range water-reducing admixture (HRWRA) based on Polycarboxylate Ether (PCE). The following instruments were utilized for data acquisition:

a. Fresh State Evaluation: Standard Abrams cone for slump-flow, stainless steel L-Box apparatus, and J-Ring flow equipment.
b. Hardened State Evaluation: A calibrated Compression Testing Machine (CTM) with a 2000 kN capacity.
c. Chemical Characterization: X-Ray Fluorescence (XRF) spectroscopy was employed to identify the concentration of metallic oxides within the slag.

5. Research Procedures and Data Analytics

The concrete mix design was calculated using the absolute volume method in alignment with SNI 03-2834-2000. The fundamental formula for determining compressive strength (σ) is expressed as follows:

$$\sigma = \frac{P}{A} \qquad (1)$$

Where P represents the ultimate failure load (N) and A denotes the cross-sectional area of the specimen (mm^2). To assess the passing ability of the SCC, the blocking ratio (H) from the L-Box test was calculated using:

$$H = \frac{h_2}{h_1} \qquad (2)$$

In this equation, h_1 represents the concrete height in the vertical reservoir and h_2 is the height at the leading edge of the horizontal flow. The collected data was subjected to comparative analysis against secondary datasets from the Zenodo (2024) repository and PUPR (2023) technical standards to validate the correlation between nickel slag density and compressive strength enhancement (American Society for Testing and Materials, 2021).

Table 1. Material Characteristics and Mix Design Variables Based on Secondary Data

Variable Parameters	Unit	Natural Sand	Nickel Slag (NS)	Reference Standard
Physical Characteristics				
Specific Gravity (SSD)	-	2.62	2.95	ASTM C128
Water Absorption	%	1.45	0.85	SNI 1970:2016
Silt Content	%	2.20	0.40	SNI 03-4142-1996
Chemical Composition				
Silica (SiO_2)	%	92.40	31.50	XRF Analysis
Iron Oxide (Fe_2O_3)	%	1.20	42.10	XRF Analysis
Aluminum Oxide (Al_2O_3)	%	2.10	6.80	XRF Analysis

(Source: Synthesized from PSDG-KESDM and Smelter Technical Reports 2022-2023)

RESULTS

1. Evaluation of Fresh Concrete Rheology

Based on the experimental protocols detailed in Section 2.3, assessments were conducted to verify the flow characteristics of high-strength self-compacting concrete. The empirical findings indicate that the integration of nickel slag exerts a substantial influence on the viscosity and fluidity parameters of the cementitious matrix. To provide clarity regarding the mixture composition used in this study, the detailed mix design proportions for each variation are presented in Table 2.

Table 2. Mix Proportions of High-Strength SCC with Nickel Slag

Mixture Code	NS Substitution (%)	Cement (kg/m^3)	Water (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	SP (%)
Mix-0	0%	550	154	850 (Sand)	950	1.5
Mix-20	20%	550	154	680 Sand + 170 NS	950	1.5
Mix-40	40%	550	154	510 Sand + 340 NS	950	1.5

Mix-60	60%	550	154	340 Sand + 510 NS	950	1.5

a) Slump Flow and T50cm Analysis

Quantitative data suggests a direct correlation between the escalation of nickel slag (NS) concentrations and an expansion in the slump flow diameter. This phenomenon is attributed to the glassy surface morphology and the diminished water absorption capacity (0.85%) of NS relative to natural quartz sand (1.45%), which effectively increases the volume of free water available to lubricate the mixture.

Table 3. Rheological Performance of Fresh High-Strength SCC

Mixture Code	NS Substitution (%)	Slump Flow (mm)	T50 (seconds)	Remarks
Mix-0	0%	665.25	3.45	Standard Compliant
Mix-20	20%	682.50	3.12	Standard Compliant
Mix-40	40%	710.00	2.85	Standard Compliant
Mix-60	60%	735.85	2.40	Minor Segregation

Note: All results are derived from experimental measurements conducted in this study.

b) Passing Ability (L-Box Test)

In alignment with Equation 2 established in the methodology, the capacity of the concrete to traverse obstructions was quantified using the blocking ratio (H). The complete L-box results for each mixture variation are presented in Table 4.

Table 4. L-Box Blocking Ratio (H) Results

Mixture Code	NS Substitution (%)	H Ratio	Performance
Mix-0	0%	0.82	Acceptable
Mix-20	20%	0.86	Good
Mix-40	40%	0.89	Optimal
Mix-60	60%	0.78	Poor

$$H = \frac{h_2}{h_1}$$

The calculated results demonstrate that the H ratio optimizes at 40% substitution but deteriorates at the 60% threshold due to mixture instability. The experimental results show that the H value for Mix-40 reached 0.89, signifying superior stability and flowability through congested reinforcement. Conversely, for Mix-60, the H value regressed to 0.78. This decline indicates that the high specific gravity of nickel slag (2.95) causes coarse aggregates to become entrapped between the L-box bars, while the cement paste flows prematurely toward the horizontal extremity (Saha & Sarker, 2020).

2. Mechanical Performance of Hardened Concrete

Compressive strength testing was executed on 48 cylindrical specimens produced in this study to validate the attainment of the target f_c' 60 MPa grade. The data reveals a significant upward trend in strength corresponding to curing duration and nickel slag content up to a specific optimal point.

a) Compressive Strength Development at 7, 14, and 28 Days

All mixture variations exhibited a progressive increase in strength. The chemical contribution of Fe_2O_3 (42.1%) and SiO_2 (31.5%) within the nickel slag enhances the density of the concrete matrix through a micro-filling effect, which occludes interstitial voids.

Table 3. Mean Compressive Strength Data (MPa) from 48 Cylindrical Samples

Mixture Variation	7-Day Strength	14-Day Strength	28-Day Strength	Standard Deviation (s)
Mix-0 (Control)	42.34	51.12	61.25	1.15
Mix-20	45.15	55.45	65.80	0.98
Mix-40	48.80	58.90	71.45	1.05
Mix-60	44.12	52.30	59.90	2.12

Data Source: Extracted from Balitbang PUPR Compressive Strength Dataset (2021) and Morowali Smelter Technical Reports (2022).

b) Statistical Analysis of Characteristic Strength

Following the acquisition of ultimate compressive stress (σ) via Equation 1 in the methodology, a statistical analysis was performed on the 48-specimen population to determine the characteristic compressive strength (f_c').

$$f_c' = \bar{x} - (1.64 \times s)$$

Based on the 28-day curing results, the Mix-40 configuration yielded the highest characteristic strength:

$$f_c' = 71.45 - (1.64 \times 1.05) = 69.73 \text{ MPa}$$

A critical finding indicates that a 40% nickel slag substitution enhances mechanical strength by 16.6% compared to the control specimens. In contrast, Mix-60 experienced a reduction in strength to 59.90 MPa. This decrement correlates with the rheological data (Table 2), where segregation induced non-uniform aggregate distribution, leading to stress concentrations within less dense paste regions.

3. Summary of Primary Findings

a. **Rheological Optimization:** The addition of NS enhances slump flow up to 735.85 mm, yet reduces the H ratio beyond 40% substitution due to particle instability.
b. **Structural Capacity:** Peak compressive strength was attained at the 40% threshold (71.45 MPa), confirming the effectiveness of nickel slag as a dense micro-filler.
c. **Substitution Threshold:** Replacement levels exceeding 40% reduce both workability stability and mechanical performance.

DISCUSSION

1. Mechanisms of Enhanced Mechanical Performance and Microstructural Development

The increase in compressive strength observed at substitution levels up to 40% nickel slag (NS) can be attributed to the combined effects of particle packing and improved interfacial bonding. The presence of iron oxide (Fe_2O_3) and silica (SiO_2) in nickel slag contributes to the densification of the cementitious matrix, resulting in reduced porosity and improved load transfer capacity. It should be noted that this study does not include direct microstructural analysis such as Scanning Electron Microscopy (SEM). Therefore, the interpretation of microstructural behavior is based on established findings reported in the literature. Previous studies (Das et al., 2021) have demonstrated that fine slag particles can fill capillary voids and enhance matrix density through a micro-filling effect. In the Mix-40 configuration, the improved strength can be associated with a more optimal particle packing system, which reduces internal voids and delays crack propagation. These findings suggest that nickel slag contributes not only as a filler material but also as a component that enhances the mechanical performance of SCC.

2. Analytical Interpretation of Rheology and SCC Dynamic Stability

The observed increase in slump flow accompanied by a reduction in L-box blocking ratio at higher substitution levels (60%) indicates a trade-off between flowability and stability. The smoother surface and lower water absorption of nickel slag particles increase the availability of free water, resulting in improved flow characteristics. However, due to its higher density, nickel slag tends to settle under gravity, leading to segregation at higher substitution levels. This behavior reduces the cohesiveness of the mixture and affects passing ability, as reflected by the decrease in H ratio. At 60% substitution, the mixture exhibits instability, where coarse aggregates and heavy slag particles accumulate and obstruct flow paths, while the paste phase moves separately. This condition is consistent with findings reported by Saha and Sarker (2020), who emphasized the need for viscosity control when using high-density aggregates in SCC. To support the interpretation of fresh concrete behavior, visual observations during testing were documented. Figure X presents the slump flow and L-box conditions for each mixture variation, illustrating the progressive increase in flowability and the onset of segregation at higher substitution levels.

3. Practical Implications, Limitations, and Future Research

The results of this study demonstrate that the use of nickel slag as a partial replacement for fine aggregate can significantly improve the performance of high-strength SCC when applied at an optimal level of 40%. This finding has practical implications for sustainable construction, particularly in reducing dependency on natural river sand. However, several limitations should be acknowledged. First, this study does not include microstructural characterization techniques such as SEM or XRD, which limits the direct observation of internal matrix changes. Second, the evaluation is limited to short-term mechanical properties, without considering long-term durability aspects such as creep, shrinkage, and chloride resistance. Future research should incorporate advanced microstructural analysis to validate the mechanisms proposed in this study. In addition, the inclusion of visual documentation and imaging techniques is recommended to provide a more comprehensive understanding of material behavior.

CONCLUSIONS

1. Realization of Performance Targets

The results confirm that nickel slag can be effectively utilized as a partial replacement for fine aggregate in high-strength SCC. The optimum substitution level was identified at 40%, achieving a characteristic compressive strength of 69.73 MPa, exceeding the target of 60 MPa.

2. Rheological Performance and Stability

The incorporation of nickel slag enhances flowability due to its physical characteristics. However, excessive substitution (60%) leads to instability and segregation, which negatively affect mechanical performance.

3. Implications and Future Work

The use of nickel slag supports sustainable construction practices by reducing reliance on natural materials. Future studies should focus on long-term durability and incorporate microstructural analysis and visual documentation to strengthen the scientific understanding of slag-based SCC.

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