International Journal of Technology 15(6) 1613-1631 (2024)
Received July 2024/ Revised August 2024/ Accepted November 2024

International Journal of Technology

http://ijtech.eng.ui.ac.id

Comprehensive Characteristics of High-Performance Concrete with Nickel Slag as Fine and Coarse Aggregate

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Abstract. This study aimed to determine the effect of using nickel slag as an alternative aggregate for high-performance concrete. To achieve the aim, nickel slag aggregate with particle sizes of 0/5 mm and 10/20 mm was considered, using X-ray Diffraction (XRD) to analyze the compounds and minerals contained in the slag content. The investigation incorporated up to 20% Ground Granulated Blast-furnace Slag (GGBFS) as a cement substitute, while systematically replacing natural aggregate with nickel slag at a varying proportions of 0%, 20%, 40%, 60%, 80%, and 100%. The experimental result showed that Mix 2 combination achieved the highest compressive strength of 69.43 MPa. This outcome exceeded the reference concrete by 11.56% and fulfilled the classification of high-performance concrete. Additionally, XRD testing of Mix 2 samples identified the dominant compounds as $C_6H_6O_2$, (Fe, Mg)SiO_3, and SiO_2. The results signified the promising potential of using nickel slag aggregate in concrete production, suggesting significant economic benefit for the construction industry. The outcome of this study could contribute to the growth of construction industry and reassure stakeholders about the financial viability of the project. Finally, this potential for high-performance concrete using nickel slag aggregate would create more opportunities for the future of construction industry.

Keywords: Compressive strength; Construction; Granulated blast-furnace slag; High-performance concrete; Nickel slag aggregate

1. Introduction

Indonesia is considered a country with largest nickel reserve in the world, amounting to approximately 52% of the global reserves according to the latest data from Ministry of Energy and Mineral Resources in 2020 (Radhica, 2023). However, the production capacity of nickel in the country remains limited, at around 1 million metric tons, contributing only

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doi: 10.14716/ijtech.v15i6.7184

about 37.04% to the total global nickel production.

This limitation often becomes a focal point of concern, specifically with the continuously increasing demand for industrial raw materials in the international market, such as electric vehicle batteries and other green technologies. Anticipating the constantly rising demand, Indonesian government has taken proactive measures, such as implementing a policy banning the export of raw minerals in early 2020. Despite the challenges, these measures show the commitment of government to maintaining a reliable global supply of nickel. Government plays a crucial role in managing nickel reserves of the country, providing essential context for the study and signifying its broader implications (Radhica, 2023; U.S.G.S., 2022). Therefore, this policy aims to stimulate growth in the local processing industry, improve domestic economic value, and safeguard nickel reserves for the sustainable development of the national economy. The strategic steps reflect unwavering commitment of Indonesia to harness its natural resource potential while prioritizing the need to address the increasing global environmental concerns. The initiatives of government to promote the use of nickel slag in various industries such as construction are crucial, creating opportunities for a more sustainable future and reassuring stakeholders about the commitment of the country to responsible development.

The introduction of policy prohibiting export of unprocessed minerals is expected to stimulate growth in nickel production sector in Indonesia. However, the rise in nickel production requires a corresponding increase in the generation of nickel waste. The waste produced during nickel smelting process typically consists of solid or agglomerated substances. Solid waste and nickel slag can generate up to fifty times more nickel products than the quantity created during refining nickel. This potential for increased productivity is a promising aspect of the policy change (Aprianto and Triastianti, 2018). The amendment shows the importance of concerted efforts to mitigate the environmental impact of nickel waste through study and technological innovation.

This study aims to develop the use of nickel slag and reduce its negative environmental impact. Waste handling systems should be performed correctly to avoid provoking ecological problems (Oksri-Nelfia, Akbar, and Astutiningsih, 2020; Mustika, Salain, and Sudarsana, 2016). In addition, the slag shows potential for effective use in concrete production, replacing coarse as well as fine aggregate and a substitute for cement. The study signifies that incorporating nickel slag in concrete can improve properties such as compressive strength, pulse velocity, and stiffness while reducing Poisson's ratio compared to traditional concrete mixes (Amir *et al.,* 2022). Combining the slag with fly ash in concrete mixtures has further improved mechanical strength and durability, particularly in marine environments (Ahmad *et al.,* 2022). Moreover, nickel slag powder shows promise as a cement substitute in high-performance concrete, with favorable split tensile strength values observed in studies (Nabiilah, Nelfia, and Astutiningsih, 2019). The material composition, containing 41.47% Silica (Si) and 30.44% Ferro (Fe), renders it suitable for cement substitution (Aprianto and Triastianti, 2018; Sugiri, Saloma, and Yulianti, 2007).

Despite the future application of nickel slag in Indonesia, international studies show its broad applicability in concrete buildings (Saha and Sarker, 2020) conducted a comprehensive review of the global use of the materials, signifying its efficacy in improving mechanical properties and durability under several climatic conditions. Similarly, (Nuruzzaman *et al.,* 2020) tested high-strength self-compacting concrete such as ferronickel slag as fine aggregate in Australia, finding significant improvements in compressive strength and workability. (Saha and Sarker, 2017b) study showed the sustainability of incorporating ferronickel slag into concrete, signifying its environmental benefits in waste reduction and conserving resources. (Sun, Feng, and Chen, 2019) found that ferronickel slag improved compressive strength and chloride ion resistance in concrete in Taiwan, allowing it to be appropriate for coastal applications (Han *et al.,* 2023).

Additionally, the material proved the cost-effectiveness and durability of nickel slag in large-scale infrastructure projects in the Middle East, implying its global value as an environmentally friendly construction material.

Previous studies used nickel slag to replace cement and aggregate in concrete compositions. Consequently, using the material to replace aggregate has often been restricted to a single material category. There is a scarcity of studies that use nickel slag to replace all categories of aggregate, including fine and coarse in top-notch concrete. Based on accumulating evidence, recent studies have shown that nickel slag can replace all forms of aggregate in high-quality concrete. However, further results and experimentation are still needed to fully optimize the use of the material in different types of concrete groups to guarantee its efficacy and sustainability in the building sector.

Study by (Nuruzzaman *et al.,* 2020) investigated the use of nickel slag as coarse aggregate, with varying compositions of 0%, 20%, 40%, and 60%. The result reported that the highest compressive strength achieved was 65.78 MPa, observed at a composition of 40% Ferro Nickel Slag (FNS). Additionally, the maximum tensile strength recorded was 4.96 MPa for FNS40 composition. The study included evaluations of sportive properties and RCPT (Rapid Chlorite Penetration Test). Significantly, the lowest tensile strength, measured at 8.0 x 10^{-3} mm/s0.5, was observed for FNS40 composition, showing relatively poor performance. RCPT results for this composition were categorized as very low, signifying potential durability concerns.

Recent investigations have shown that ferronickel slag can potentially replace fine and coarse aggregate. (Zhang *et al.,* 2020b) described that incorporating this slag rather than natural aggregate in high-performing concrete improved mechanical properties such as compressive strength. (Sun, Feng, and Chen, 2019) found that ferronickel slag used as fine aggregate significantly increased the durability and strength of concrete. Further studies validate using the material as coarse and fine aggregate. The process shows that this industrial by-product can improve concrete characteristics when used in appropriate ratios (Nuruzzaman, Kuri, and Sarker, 2022; Zhang *et al.,* 2020b). Further studies signify that the combined application of ferronickel slag as coarse and fine aggregate may increase the mechanical properties of concrete. Adding the material in both forms in high-performance concrete significantly increased compressive strength, showing the combined effects of this dual method (Ernawan *et al.,* 2023). Following this discussion, an investigation by (Han *et al.,* 2023) described that using a combination of ferronickel slag as both fine and coarse aggregate increased compressive and flexural strengths and improved the entire workability of concrete mixture. Study by (Saha and Sarker, 2017a) and (Nuruzzaman *et al.,* 2024) showed that the material might improve compressive and flexural strength, proving the possibility of using nickel slag for different concrete applications.

Improving scalability of ferronickel slag has been a significant focus of recent studies. (Ngii *et al.,* 2021) investigated methods to handle nickel slag for application in concrete. Based on the results of (Jaganmohan, 2024), largest nickel reserves globally are in Indonesia, with 55 million metric tons, followed by Australia, 24 million metric tons, and Brazil, 16 million metric tons. According to this finding, the most significant nickel production during 2023 was in Indonesia, with a production of 1.8 million metric tons, followed by Philippines, which produced 400 thousand metric tons, and New Caledonia, which produced 230 thousand metric tons. Signifying the importance of standardizing these procedures for improving accessibility, (Huang, Wang, and Shi, 2017) and (Saha and Sarker, 2016) showed that cooperation between mining and construction industries could potentially overcome logistical optimization constraints as well as source difficulties. (Han *et al.,* 2023) and (Ojha and Singh, n.d.) described that innovative methods were also found to improve the general quality of ferronickel slag, increasing its long-term economic potential. Finally, (Edwin *et al.,* 2016) and (BPK RI, 2014) signified that inspiring local policies could facilitate using nickel slag in buildings. Although the availability and scalability of the material remained challenging, continuing studies and strategic methods have created opportunities for its increasingly broad application in environmentally friendly construction.

This study explores the feasibility of incorporating nickel slag as a partial or complete replacement for all types of aggregate in concrete production, including fine and coarse. The physical, chemical, and mineralogical characteristics of the material were comprehensively examined to assess its suitability for such applications. The study included comprehensive testing of physical and mechanical properties as well as durability aspects of concrete, consisting of workability, compressive strength, tensile strength, permeability, X-ray diffraction (XRD), and Fourier-Transform Infrared Spectroscopy (FTIR). During this study, testing was conducted on samples aged for 28 days, with the composition of nickel slag used, substituting up to 0%, 20%, 40%, 60%, 80%, and 100% of the total required amount for each coarse and fine aggregate.

2. Materials and Methods

2.1. Material

Binder material used was cement OPC, which was from Semen Tiga Roda industry, and Ground Granulated Blast Furnace Slag (GGBFS), produced by PT. Krakatau Semen Indonesia (KSI). Table 1 showed the characteristics of binder used in this study. The chemical composition of this binder was assessed through X-ray fluorescence (XRF) using EPSILON 5 analyzer tool, following the standard test method reviewed in (ASTM, 2013b) for chemical analysis of metal samples, and the results were shown in Table 2. The superplasticizer (SP) used in this study was Sika Viscocrete 3115N, which described the density in Table 1.

Table 1 Density of Ordinary Portland Cement, GGBFS, and Superplasticizer

Material	Density (g/cm^3)
OPC Type 1 Tiga Roda	3.13
GGBFS	2.83
Superplasticizer	1.05

Table 2 Chemical Composition of Binders

Chemical Composition	OPC (Oksri-Nelfia, Akbar, and Astutiningsih 2020)	GGBFS	Nickel Slag (Nelfia, Rahmawati, and Astutiningsih 2021)
CaO	63.2	44.71	24.71
Al_2O_3	4.96	14.74	9.69
SiO_2	18.45	35.93	41.24
Fe_2O_3	2.86	1.02	1.71
SO_3	2.18	0.55	0.90
MgO	3.52	0.28	19.29
K_2O	0.31	0.29	0.17
Na_2O	0.15	0.02	0.24
LOI	3.42	1.98	-
TiO_2	-	0.33	0.26
Mn_2O_3	-	0.14	0.83
IR	-	0.32	-
C_3S	68.72	-	-
C_3A	8.3	-	-
C_4AF	8.7	-	-

Nickel slag used in this investigation was obtained from Southeast Sulawesi, Indonesia. The physical characteristics of the material varied by area depending on differences in ore composition, smelting methods, and cooling process. Moreover, nickel slag used in this study was obtained from PT-Growth Java in Cilegon, Indonesia, which processed lateritic nickel ores from Southeast Sulawesi. Lateritic ores included substantial amounts of iron and aluminum, producing nickel slag with elevated iron oxide levels, affecting its structural performance. Consequently, the material deriving from sulfide ores, such as those in Russia or Canada, had higher levels of sulfur and magnesium, causing variances in mineralogical properties as well as leaching behavior (Putera *et al.,* 2023).

This study comprehensively analyzed the chemical and physical properties of nickel slag, verifying the effectiveness as a substitute for fine and coarse aggregate in concrete across geographic sources. Previous investigations confirmed that the material from different locations was efficiently used as building materials (Saha and Sarker, 2020; Zhang *et al.,* 2020b; Wu *et al.,* 2018; Lee *et al.,* 2015).

The analysis included the use of two nickel slag aggregate including fine (0/5 mm), which replaced natural fine, and coarse (10/20 mm), as substitute for natural coarse. The particle size of the material was categorized based on sieve size. Moreover, the fractions of 0- 5 mm and 10 - 20 mm represented particles that passed through 5 mm and 20 mm sieves, respectively, with the lower number showing the minimum size as well as the upper number the maximum amount.

During the investigation, the experiment derived natural coarse aggregate from Quarry of Mount Holcim, Bogor. Following the discussion, natural fine was obtained from Quarry of MBS, Bogor. The specifications of the characteristics of nickel slag and natural aggregate were shown in Table 3. In addition, the chemical composition of the slag was obtained through XRF as shown in Table 2.

Table 3 Physical Characteristics of Aggregates

Materials	Specific gravity	Water absorption (%)	Content weight (kg/m^3)	Fineness Modulus
Natural Fine Aggregate	2.51	2.78	1487.01	3.12
Nickel Slag Fine Aggregate	3.06	0.91	2034.97	2.8
Natural Coarse Aggregate	2.6	1.68	1489.76	-
Nickel Slag Coarse Aggregate	2.95	0.86	1588.41	-

The specific gravity and water absorption of ferronickel slag were determined using (ASTM, 2015a) (coarse) and (ASTM, 2015b) (fine aggregate). Sieve analysis determined the particle size distribution of ferronickel slag according to (ASTM, 2014). Nickel slag and GGBFS were industrial solid wastes polluting the environment. Therefore, the potential for leaching or the leaching of heavy metals in industrial solid waste was determined by testing Toxicity Characteristic Leaching Procedure (TCLP). The standard method for TCLP testing was published by (EPA, 1992). The following results obtained during this process were shown in Table 4. The concentrations of Heavy metals in leachate were compared with legal limits, including those set by U.S. Environmental Protection Agency (EPA) for hazardous waste categorization. The legal limit of EPA for nickel in leachate was 5 mg/L (EPA, 1990). However, TCLP result for nickel from nickel slag was 7.47 mg/L, above this restriction. The results showed that concrete using the slag material required further treatment or incorporation to avert environmental pollution from nickel leaching and might not be immediately appropriate for use in groundwater-sensitive places.

The level of other elements, including lead (Pb), arsenic (As), cadmium (Cd), and hexavalent chromium (Cr), remained lesser than individual respective regulatory thresholds. The lead content in nickel slag was 0.06 mg/L, which was less than threshold of

EPA of 5 mg/L. These results signified that the primary concerns of the material were related to nickel leaching while leaching risks for other analyzed metals were minimal. Although nickel slag concrete had potential for various applications, the elevated nickel content was mitigated to guarantee environmental safety and obedience to regulatory standards. Additional investigation into treatment methodologies or other applications with less leaching hazards was required (Astuti *et al.*, 2024; Wanta *et al.*, 2022).

Table 4 Toxicity Characteristic Leaching Procedure (TCLP) of Nickel Slag and GGBFS

Parameters	Nickel Slag	GGBFS
Antimony (Sb)	< 0.04	0.4
Arsenic (As)	< 0.07	< 1
Barium (Ba)	0.03	-
Beryllium (Be)	< 0.03	-
Boron (B)	0.05	-
Cadmium (Cd)	< 0.01	2.27
Hexavalent Chromium (Cr)	< 0.01	<3
Copper (Cu)	< 0.01	46.35
Lead (Pb)	0.06	1.87
Mercury (Hg)	< 0.018	< 0.2
Molybdenum (Mo)	< 0.01	-
Nickel (Ni)	7.47	< 1
Selenium (Se)	< 0.13	16.98
Silver (Ag)	< 0.03	-
Tributyltin Oxide	< 0.02	-
Zinc (Zn)	0.22	53.28
Cobalt (Co)	-	< 2
Thallium (Ti)	-	< 0.5
Vanadium (V)	-	134.90

2.2. Mix Proportion

Concrete used ACI 211.4R-93 standard because the type of concrete pursued aims to be included as high-performance concrete. The composition of the standard concrete mix used a cement-water ratio (w/c+p) of 0.317. Moreover, natural fine with a specific gravity (SSD) of 2.51 kg/m^3, fineness modulus of 3.12, and natural coarse aggregate with a particular gravity (SSD) of 2.60 kg/m^3 were used. The composition of concrete mixture had a targeted compressive strength of fc' = 60 MPa. During this process, concrete was created by substituting the cement mass with GGBFS up to 20% and substituting nickel slag of 0%, 20%, 40%, 60%, 80%, and 100%, respectively, of the required totality of the type of aggregate.

The names as well as compositions of each planned mixture used were shown in Figure 1 and explained as follows:

a. aRef was a reference concrete in which the mixture used 100% OPC, natural fine aggregate, as well as natural coarse, water, and 1% superplasticizer of the total weight of the binders.
b. Mix 1 consisted of concrete with 80% OPC, 20% GGBFS, 20% nickel slag fine aggregate, 80% natural fine, 20% nickel slag coarse, 80% natural coarse, water, and 1% superplasticizer of the total weight of binders.
c. Mix 2 was concrete with 80% OPC, 20% GGBFS, 40% nickel slag fine aggregate, 60% natural fine, 40% nickel slag coarse, 60% natural coarse, water, and 1% superplasticizer of the total weight of binders.

d. Mix 3 comprised concrete with 80% OPC, 20% GGBFS, 60% nickel slag fine aggregate, 40% natural fine, 60% nickel slag coarse, 40% natural coarse, water, and 1% superplasticizer of the total weight of binders.
e. Mix 4 was concrete with 80% OPC, 20% GGBFS, 80% nickel slag fine aggregate, 20% natural fine, 80% nickel slag coarse, 20% natural coarse, water, and 1% superplasticizer of the total weight of binders.
f. Mix 5 consisted of concrete with 80% OPC, 20% GGBFS, 100% nickel slag fine aggregate, 100% nickel slag coarse, water, and 1% superplasticizer of the total weight of the binders.

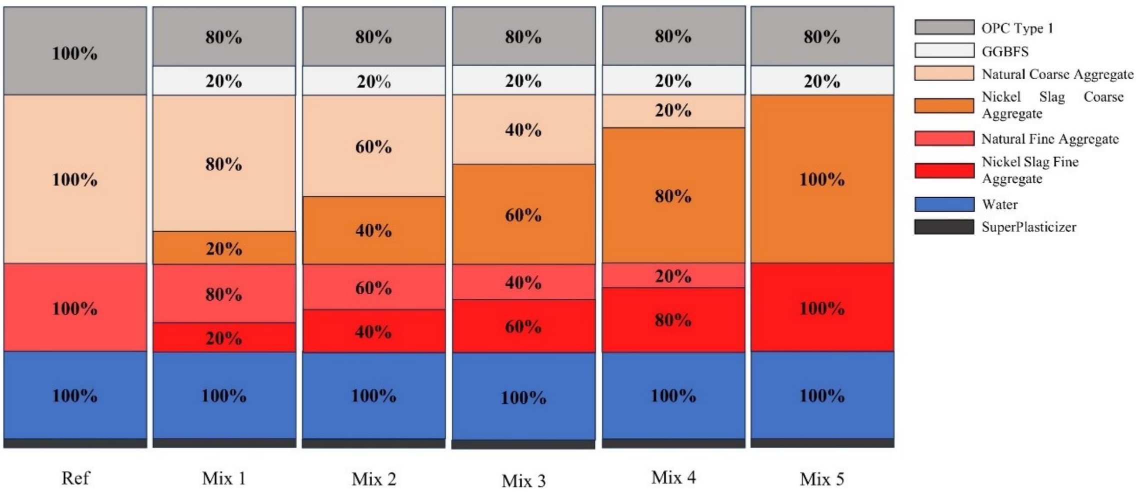

Figure 1 Composition of Concrete Mixes, Including Variations in Binder Proportion (OPC and GGBFS), Aggregate Types (Nickel Slag and Natural Aggregates), and 1% superplasticizer dosage

Table 5 Mix Design of the studied concrete (in kg/m³)

Mix id	Binders		Fine aggregate		Coarse aggregate		Water	SP
	OPC	GGBFS	Natural	Nickel Slag	Natural	Nickel Slag		
Ref	638.95	0,00	460.69	0.00	1013.04	0.00	202.63	6.38
Mix 1	511.16	127.79	368.55	92.14	810.43	202.61	202.63	6.38
Mix 2	511.16	127.79	276.41	184.27	607.82	405.21	202.63	6.38
Mix 3	511.16	127.79	184.27	276.41	405.21	607.82	202.63	6.38
Mix 4	511.16	127.79	92.14	368.55	202.61	810.43	202.63	6.38
Mix 5	511.16	127.79	0.00	460.69	0.00	1013.04	202.63	6.38

According to Table 5, the quantity of cement used in this concrete reference was 581.52 kg/m³. This quantity remained in the permissible limits for concrete mixes since the material did not exceed 593 kg/m³, as stated in ACI standards 211.4R-08 (ACI 211.4R-08, 2008).

2.3. *Test Methods*

During this study, compressive strength referred to (ASTM, 2021a) C39 standard. Compressive strength of concrete samples aged 28 days was evaluated using 2000 kN digital concrete compression machine manufactured by MBTES. Following this discussion, tensile solid strength referred to (ASTM, 2020) C1583 standard. Tensile strength was tested on samples aged 28 days using the same compressive strength tools from MBTES brand.

Testing the permeability of concrete in this study used gas or air permeability method. This test referred to (UNI, 2005) 11164 standard applying controls Mod. 58-E0031 tool. The examination used the pressure of oxygen gas passing through concrete to measure the permeability coefficient. Porosity testing conducted in this investigation aimed to determine the percentage of pores in concrete, which was referred to (ASTM, 2021b) C642-90 standard.

XRD was used to identify the crystal structure of a mineral by using the diffraction in the crystal lattice. During the study, ASTM D934-13 standard provided methodologies to conduct XRD analysis, permitting accurate determinations of crystalline phases in ferronickel slag or related materials. Comprehensive sample preparation, precise tool calibration, and accurate database reference were essential for reliable findings. This process led to a diffraction pattern that reflect the crystal structure. Relating to the process, the instrument used was Shimadzu XRD-7000 type. A diffractometer with a Cu source that had a wavelength of χ = 1.54 À at a scanning speed of 2s/step and a diffraction angle between 5° and 50° was used for conduction testing, as XRD was based on Bragg's law. The specimens used in this experiment were first smoothened, and each specimen passed No. 200 sieve. The tested sample consisted of conventional/Ref concrete, and concrete test specimens achieved the highest compressive strength.

During this investigation, FITR measured infrared absorption by a material with its molecular vibrations. The tool used for the process was Infrared Spectrophotometer data acquisition frequency, where FTIR spectrometry took 5 seconds, ranging from 400 cm^{-1} to 4000 cm^{-1} with a spectral resolution of 1 cm^{-1}.

3. Results and Discussion

3.1. Workability

Workability testing in this study was conducted using slump test method, which was referred to (ICONTEC, 2018) NTC 396 or (ASTM, 2015c) C143/C143M-15. The test was conducted using Abrams cone apparatus with dimensions of 150 mm in height and 100 mm in diameter. Following the completion of slump test, concrete was poured into a cylindrical formwork with a diameter of 100 mm and a height of 200 mm. After 24 hours, concrete was then extracted from the formwork and placed in curing bath for a full day before the desired age was achieved.

Figure 2 showed the results of slump test during the investigation. The slump value predominantly increased by 4% to 6%, except for Mix 3, which decreased by 2%. This outcome supported the results of (Edwin *et al.,* 2019), where a slump value increase was observed in nickel slag concrete. Additional studies supported this result and signified that as the percentage of nickel slag in concrete mix increased, the slump value also increased, reflecting improved workability. Moreover, investigations into using the slag material as a fine aggregate in concrete showed varying effects on slump values across different mixtures, ranging from a decrease of 39.47% to an increase of 55.26% (Ngii *et al.,* 2021). These results implied a positive impact of incorporating nickel slag in concrete, leading to improved workability characterized by higher slump values as the slag content increased.

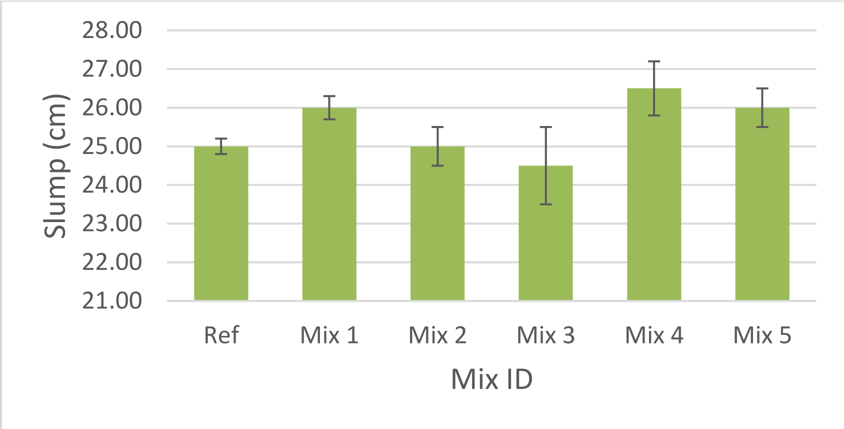

Figure 2 Results of the Slump Test Conducted Using Abrams Cone Apparatus Under Standard Conditions

During the analysis of this study, GGBS significantly affected the workability of concrete. Replacing GGBS had shown to increase the slump of concrete, signifying its impact on the properties of fresh concrete (Ahmad *et al.,* 2020). This observation was supported by a review discussing the use and efficiency of GGBS. (Özbay, Erdemir, and Durmuş, 2016). Khan *et al.* (2014) provided additional insights into the effects of mineral admixtures, including GGBS, on fresh concrete properties.

GGBS, a by-product of iron-making process, served as a high-volume cement replacement, improving the sustainability and strength of concrete. (Onn *et al.,* 2019). The broader effect of GGBS on concrete properties, including structural performance, was shown through an investigation of precast concrete beams with varying GGBS replacement ratios. (Lee *et al.,* 2021). Moreover, incorporating GGBS into concrete improved workability, sustainability, and structural performance, allowing it to be a valuable mineral admixture in concrete production.

3.2. Compressive strength

Compressive strength was tested at 28 days using a Digital Concrete Compression Machine 2000 kN MBTES, and the results for each sample were shown in Figure 3. According to the graph, compressive strength value increased in Mix 2 by 11.56% compared to reference concrete. Meanwhile, the other mixtures decreased by 20.28% compared to reference concrete. This process showed that using nickel slag increased the strength of concrete up to a certain amount (Nuruzzaman *et al.,* 2024; Ahmad *et al.,* 2022; Ngii, Mursidi, and Umar 2020; Nuruzzaman *et al.,* 2020; Edwin *et al.,* 2019). Compressive strength of concretes using nickel slag increased slightly before it decreased. Other studies also signified that concrete mixes containing the slag content showed increased compressive strength and improved workability, achieving higher strength values. (Edwin *et al.,* 2019).

(Dewiandratika, Sukandar, El-Akmam, 2018) signified that concrete strength might decrease with higher nickel slag content due to the larger surface area of the slag per unit volume exposed, potentially leading to inadequate cement content for binding concrete matrix together. These results showed that using nickel slag in concrete formulations improved the strength of the resulting concrete structures. According to (Lee *et al.,* 2015), when the amount of slag in concrete mixtures increased, specifically when the mixtures were older than 365 days, compressive strength also raised. The idea that concrete with a higher nickel slag concentration could eventually have stronger concrete was supported by this study. Some studies showed a positive relationship between the slag content and compressive strength, others proposed potential limitations due to factors such as surface area and cement binding. Therefore, the impact of nickel slag as a substitute for aggregate content on concrete compressive strength was affected by various factors that should be considered in concrete mix design and application.

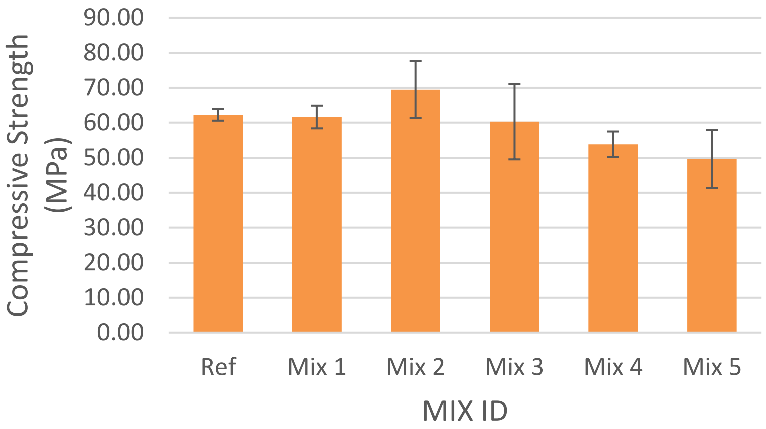

Figure 3 Compressive Strength Results at 28 Days Tested Using a Digital Concrete Compression Machine

3.3. Tensile strength

Tensile strength was tested at 28 days using a Digital Concrete Compression Machine 2000 kN MBTES, and the results for each sample were shown in Figure 4. Based on the graph, tensile strength obtained had increased compared to reference concrete. Following the discussion, optimum tensile strength was at Mix 3, which was 5.27 MPa. This outcome implied that using GGBFS as a substitute for cement and nickel slag as a replacement for coarse and fine aggregate increased tensile strength of concrete. According to (Nuruzzaman *et al.,* 2020; Suwindu, Parung, and Sandy 2020; Sun, Feng, and Chen, 2019), those that experienced an increase in the value of individual tensile strength were compared to reference concrete.

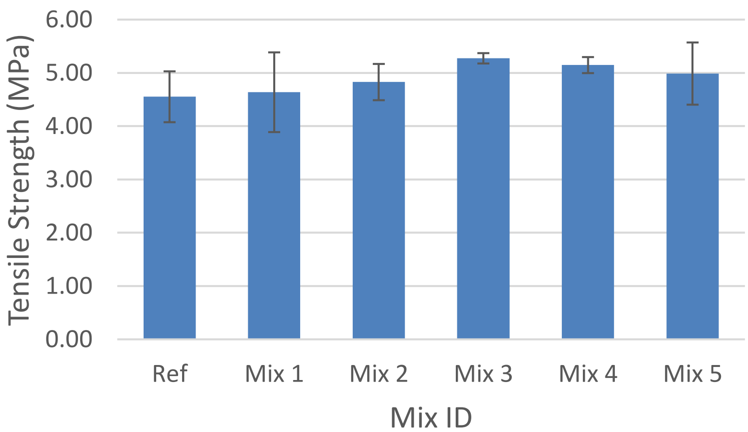

Figure 4 Tensile Strength Results at 28 Days Tested Using a Digital Concrete Compression Machine

3.4. Gas Permeability Coefficient and Porosity

The test was conducted using air permeability type 58-E0031 by Controls. Oxygen gas pressures of 150, 200, 250, 300, and 350 kPa, were used (Lliso-Ferrando *et al.,* 2023). Figure 5 showed the results of testing and calculating concrete permeability coefficient during the study. Based on Figure 5, permeability coefficient for reference concrete was 6.11E-08. The graph showed an increase in the coefficient compared to reference concrete. However, a decrease of 31.06% in the coefficient was observed in Mix 2.

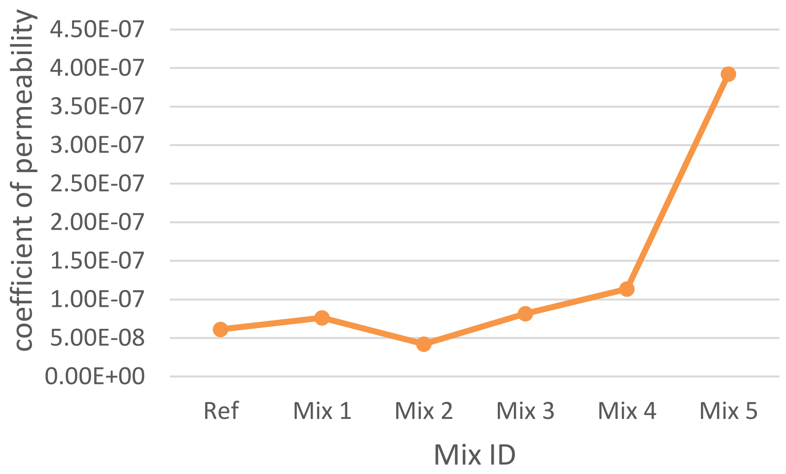

Figure 5 Permeability Coefficient Results Tested Using an Air Permeability Apparatus

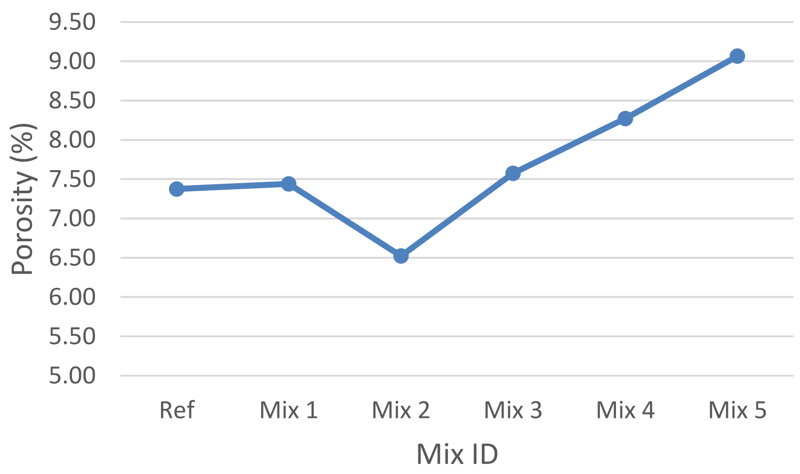

Figure 6 The Results of the Porosity Test Indicate an Increasing Trend Correlated with the Permeability

The results of porosity test conducted in this study were shown in Figure 6. The proportion of porosity showed an upward trend in comparison to permeability. Consequently, Mix 2 reduced porosity percentage by 11.57% compared to reference concrete. The reduction showed a direct proportionality between porosity and permeability coefficient. This process signified that higher porosity values were associated with an increase in permeability coefficient.

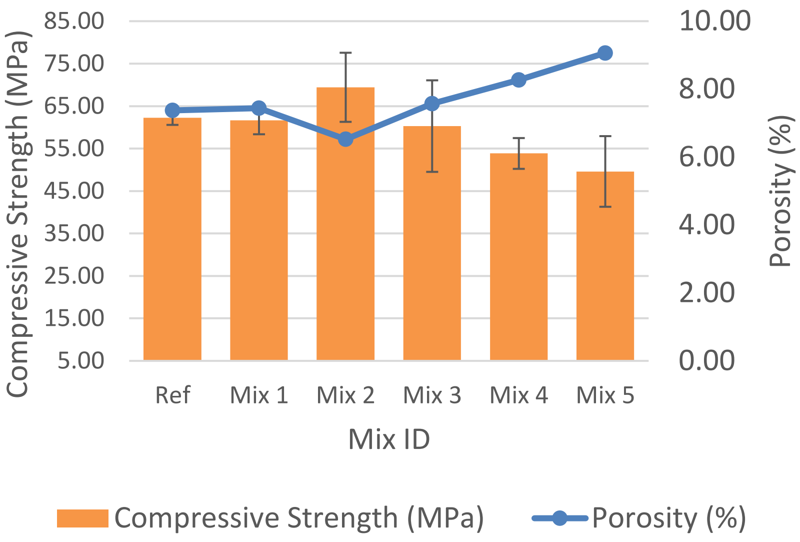

Figure 7 Comparison of Porosity and Compressive Strength

The percentage of porosity was also compared to compressive strength, as shown in Figure 7. According to the Figure, as porosity decreased, compressive strength also increased, showing an inverse correlation between the two properties. Therefore, the outcome was hypothesized that the percentage of porosity was inversely proportional to compressive strength. The presence of more pores in concrete led to a decrease in its compressive strength.

GGBFS effectively substituted cement in concrete mixes to reduce gas permeability. Investigation showed that incorporating GGBFS in concrete formulations improved durability by decreasing porosity and capillarity, leading to lower gas permeability (Srikanth *et al.,* 2022). Studies signified that GGBFS increased compressive strength of concrete, with optimal replacement levels around 30% to 40% producing the best results (Chi, Chi, and Wu, 2018). Using slag cement containing GGBFS in concrete mixtures with heavyweight aggregate had shown significant improvements in compressive strength and reduced chloride ingress, further increasing durability. (Jóźwiak-Niedźwiedzka *et al.,* 2020). Therefore, using GGBFS as a partial substitute for cement, specifically in combination with slag cement, effectively reduced gas permeability and improved the general performance of concrete structures.

3.5. X-ray Diffraction (XRD)

This study conducted XRD analysis using 2 Theta ranging from 5˚ to 70˚. The samples examined included nickel slag aggregate with particle sizes of 0/5 and 10/20, conventional concrete (Ref), and Mix 2, selected for optimal compressive strength.

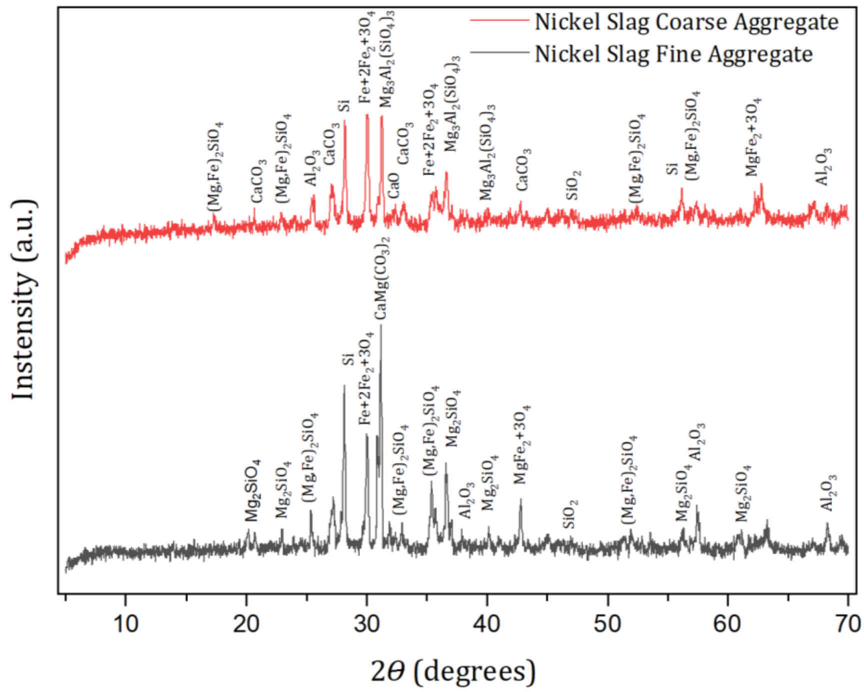

Figure 8 X-ray Diffraction Results of Nickel Slag Aggregate

Figure 8 showed XRD results for nickel slag samples during the study. In the slag fine aggregate, the predominant compounds identified were $CaMg(CO_3)_2$, SiO_2, Mg_2SiO_4, and iron oxide, with a significant peak at 31° as well as a minor peak at 20° (Nuruzzaman, Kuri, and Sarker 2022; Wu *et al.,* 2018). Moreover, the dominant compounds observed in nickel slag coarse aggregate were $Mg_3Al_2(SiO_4)_3$, iron oxide, and SiO_2.

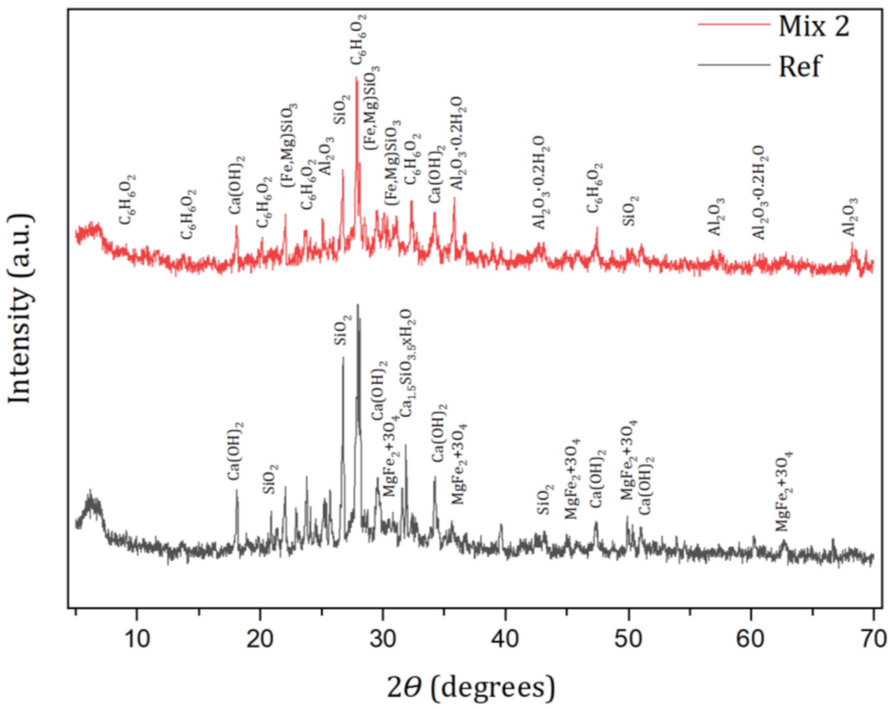

Figure 9 Comparison of X-ray Diffraction (XRD) Results for Concrete Composition Mix 2 and High-Performance Concrete as Reference (Ref)

Figure 9 showed XRD results for reference concrete sample and Concrete Mix 2, which signified optimal compressive strength. In reference concrete, the dominant compounds detected were SiO_2, $Ca_{1.5}SiO_{3.5}$ x H_2O, and $Ca(OH)_2$. Consequently, Concrete Mix 2 showed dominant compounds such as $C_6H_6O_2$, (Fe, Mg) SiO_3, and SiO_2, supporting XRF results signifying the presence of SiO_2 and Al_2O_3 compounds. These silicon-rich compounds in Mix 2, specifically SiO_2 and (Fe, Mg)SiO_3, were significant. Studies showed that the silicate chemicals promoted the formation of a denser matrix, strengthening its mechanical properties and durability by improving the pozzolanic reaction and decreasing pore structure in concrete mixture (Lee *et al.*, 2015).

During the study, an increased SiO_2 percentage in minerals improved compressive strength tests. Solid matrices in concrete from silicon dioxide (SiO_2) and (Fe, Mg)SiO_3 increased strength and durability. This study showed how Mix 2 exceeded reference concrete in compressive strength by 11.56%. The increased microstructure of the compound decreased porosity and improved mechanical interlock, surging stress-splitting resistance as well as tensile strength.

Modifying predominant chemicals improved compressive strength and durability, with no immediate concerns about negative impacts on general performance of concrete. Future studies should prioritize investigating the long-term performance and durability of the materials, with a focus on individual ability to resist freeze-thaw damage and fatigue under dynamic loading conditions. A recent study showed that nickel slag in concrete generally increased durability and mechanical properties by affecting the microstructure (Chi, Chi, and Wu, 2018).

3.6. Fourier-Transform Infrared Spectroscopy (FITR)

Figure 10(A) showed FTIR results of nickel slag aggregate, signifying no substantial difference between nickel slag aggregate with particles sized 0/5 and 10/20. Meanwhile, Figure 10(B) showed FTIR results of reference concrete and Concrete Mix 2. In these ranges, an absorption peak at 977 cm^{-1} signified asymmetric vibrations of Si-O bond in (SiO)4- group. Peaks observed at 3406 cm^{-1} and 1417 cm^{-1} corresponded to the combined bending vibration of water and stretching vibration, respectively (Zhang *et al.*, 2020a).

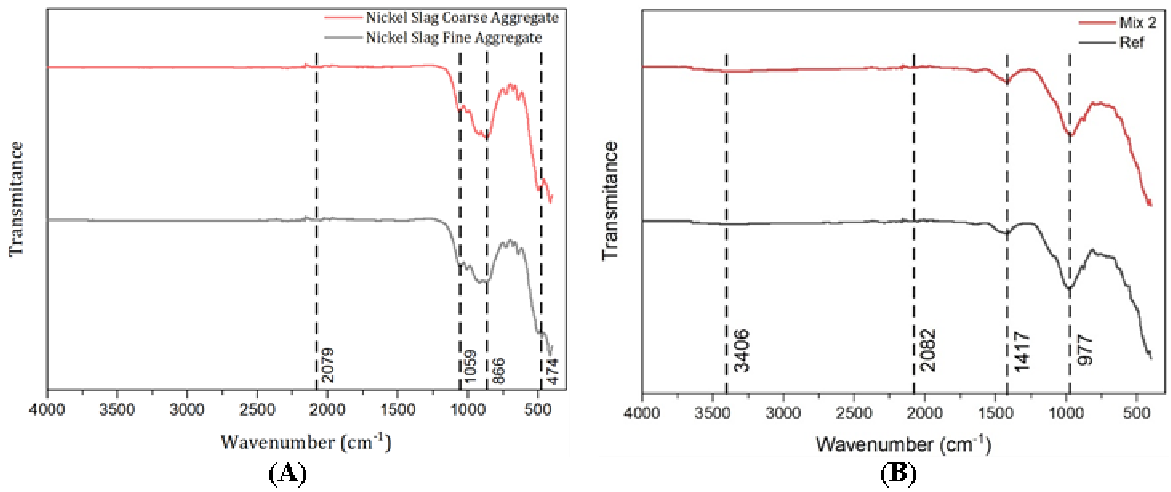

Figure 10 Fourier-Transform Infrared Spectroscopy (FTIR) Results, **(A)** Nickel slag aggregate, and **(B)** Concrete from Mix 2 and High-Performance Concrete as Reference (Ref)

4. Conclusions

In conclusion, the effect of using nickel slag rather than coarse aggregate and partial or complete fine aggregate on high-quality concrete was evaluated. Binders contained OPC and GGBFS as substitutes for Portland cement, and the water-to-binder ratio was 0.317.

Moreover, nickel slag used to replace coarse and natural fine aggregate was 20%, 40%, 60%, 80%, and 100%, respectively. The characteristics of concrete were evaluated by testing compressive and tensile strength, as well as the durability of concrete, which was examined by testing permeability of gas and porosity of concrete. During this study, optimum compressive strength obtained in Mix 2 concrete was 69.43 MPa. The partial substitution of a coarse and fine aggregate of nickel slag as aggregate increased by 11.56% compared to reference concrete, which was interpreted as an improvement in the performance of concrete that used nickel slag. To maintain optimal concrete performance, the use of slag should be limited to recommended levels, as excessive slag content could lead to diminished quality. The percentage of porosity in concrete that used nickel slag as natural fine and coarse aggregate was less than 10%. In addition, the smallest percentage of porosity was found in Mix 2, amounting to 6.52%.

Acknowledgments

The authors are grateful for PT Jaya Beton Indonesia and I-Lab BRIN (National et al. Agency) continuous contribution and support. Indonesian Ministry of Research, Technology, and Higher Education funded this project in 2024 through a competitive grant under Fundamental Research Scheme. The contract numbers are 832/LL3/AL.04/2024, 170/A/LPPM-P/USAKTI/VI/2024.

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