Assessing the Mechanical Properties of Standard Concrete Using Byproducts from Nickel Ore Refinement

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Abstract
The research centered on examining the incorporation of fly ash, bottom ash, and nickel slag in standard concrete production. The study investigated how altering the proportion of fly ash added to cement weight in regular concrete mixtures, along with utilizing bottom ash and nickel slag as aggregates, influences concrete properties, particularly its compressive strength and workability. The objective was to assess the characteristics of waste aggregates, specifically nickel slag and bottom ash, as concrete-making materials, and to evaluate the impact of fly ash as an additive on the workability and compressive strength of concrete using waste aggregates from nickel ore processing compared to conventional aggregates. Findings indicated that waste materials (nickel slag and bottom ash) are viable and recommended for use in concrete mixtures. The addition of fly ash as a concrete additive enhanced the workability of fresh concrete, evidenced by increased slump test values as the fly ash percentage increased in both natural aggregate and waste material concrete mixes. Concrete compressive strength improved with increasing fly ash percentage as an additive, reaching a peak of 32.35 MPa at 20% fly ash variation, surpassing the strength achieved with natural aggregate (28.88 MPa) at the same fly ash addition level.

Keywords: Normal concrete, Nickel slag, Bottom ash, Fly ash, Concrete compressive strength, Concrete workability

1. Introduction.

Concrete is an essential material in the construction industry. Its robustness and longevity make it the preferred option for numerous construction projects and infrastructure development. Nevertheless, the growing need for concrete has resulted in environmental issues owing to the energy-consuming methods involved in its production, particularly in cement manufacturing and the processing of natural aggregates. These procedures not only require substantial resources but also generate significant carbon emissions, thus contributing to climate change [1]–[4].

To mitigate environmental impact, the construction industry is exploring eco-friendly alternatives. A promising approach involves incorporating industrial byproducts as supplements or replacements in the production of concrete. Waste materials from nickel ore processing, including fly ash, bottom ash, and nickel slag, have potential as substitutes for traditional concrete components, such as sand and crushed stone [5]–[8].

Research has shown that adding fly ash, a waste product from coal-fired power plants, can improve concrete quality. The findings indicate that incorporating fly ash not only reduces the amount of cement required but also improves the concrete's resistance to various environmental conditions while increasing its strength and longevity [9]–[11]. Partially substituting cement with fly ash in concrete mixtures has been demonstrated to enhance the workability, durability, and strength of concrete. A study examining high-quality concrete revealed that replacing 15% of cement with fly ash resulted in increased overall compressive strength and density of the concrete while maintaining the same water requirement as conventional concrete to achieve the desired slump value [12]. Furthermore, fly ash functions as a pozzolanic substance, enhancing the long-term strength of concrete by improving its microstructure and reducing its permeability. By reducing permeability and enhancing resistance to harsh environmental conditions, fly ash enables the production of high-strength and durable concrete that is suitable for demanding applications [13]–[15].

Furthermore, incorporating fly ash into concrete manufacturing addresses environmental issues by decreasing the carbon emissions linked to cement production. As cement manufacturing ranks among the top sources of CO2 emissions, substituting a portion of cement with fly ash can substantially lower the environmental impact of building projects [16]. The amalgamation of these advantages leads to enhanced sustainability in construction methods and reduced expenses for major infrastructure developments [17]–[19].

Industrial by-products, such as bottom ash and nickel slag, have significant potential as substitutes for aggregates in concrete mixtures. Bottom ash possesses properties that enable it to serve as a partial replacement for sand in concrete, whereas nickel slag can be utilized in place of coarse aggregates. This presents an opportunity to create concrete that is both cost-effective and environmentally sustainable [20].

Coal-fired power plants generate a byproduct called bottom ash, which shows significant promise as a partial or complete substitute for sand in concrete. Utilizing bottom ash in this manner can alleviate the reliance on natural sand, a resource that is becoming scarce and is extensively used in construction [21]–[23]. Studies indicate that incorporating bottom ash as a sand replacement in concrete can enhance its strength properties, including compressive, split-tensile, and flexural strengths, despite a minor reduction in concrete workability. An experiment demonstrated that substituting 20% of sand with bottom ash resulted in concrete with superior strength compared to standard concrete without any replacement, although there was a slight decrease in processability [24]–[26].

The utilization of bottom ash presents significant environmental advantages, including the reduction of industrial waste and decreased necessity for extensive natural sand mining. Studies indicate that substituting up to 30% of sand with bottom ash is feasible without substantially compromising the concrete quality. This approach offers an eco-conscious and sustainable solution, simultaneously mitigating waste impact and reducing dependence on increasingly scarce natural resources. By integrating bottom ash as an alternative to sand in concrete production, high-quality standards can be maintained while fostering more environmentally responsible and sustainable construction practices [27]–[30].

In terms of appearance, nickel slag particles have a shape similar to the rocks utilized as coarse aggregates in concrete mixtures (fig. 1), while bottom ash particles resemble natural sand (fig. 2), which is used as a fine aggregate in such mixes [31], [32]. Despite being industrial by-products, nickel slag and bottom ash share properties with aggregates commonly used in concrete production, although they serve distinct purposes in concrete mixtures. Nickel slag, a byproduct of nickel refinement, possesses a granular structure similar to that of the coarse rock used as a coarse aggregate in concrete [34]. Research indicates that incorporating nickel slag into concrete can yield advantages, particularly in terms of enhancing its strength. However, excessive use, such as replacing 50% of coarse aggregates with nickel slag, can compromise concrete quality. Therefore, it is advisable to limit the use of nickel slag to lower proportions to maintain optimal concrete strength [34]–[37].

In contrast to fly ash, bottom ash, a byproduct of coal combustion in power plants, bears a closer resemblance to natural sand and is frequently utilized as a fine aggregate in concrete mixtures. The lighter and more porous nature of bottom ash makes it particularly suitable for lightweight concrete or concrete that needs enhanced resistance to water and chlorides. Studies indicate that substituting up to 30% of natural sand with bottom ash can yield concrete with satisfactory strength, particularly for lightweight concrete applications that do not demand high structural integrity. Incorporating bottom ash in concrete production also offers environmental benefits by recycling industrial waste that is challenging to decompose naturally [31], [38].

Figure 1. Nickel slag

Cement-like in appearance (fig. 3), fly ash consists of fine, gray particles. Waste disposal sites at nickel ore processing smelters typically contain nickel slag waste, whereas steam power plant disposal areas often house both bottom ash and fly ash. These three materials - nickel slag, fly ash, and bottom ash - are waste products generated during various stages of nickel ore processing, including power generation and ore treatment. Due to their limited utilization and inefficient processing, these byproducts are generally regarded as low-value waste materials with minimal economic significance [31]. Proper and thorough research is expected to boost the economic potential of these waste materials by incorporating them into concrete mixtures.

Figure 2. Bottom ash

Figure 3. Fly ash

The present study investigates the application of fly ash, bottom ash, and nickel slag in conventional concrete production. This research examines how adjusting the fly ash content relative to cement weight in standard concrete mixtures, as well as incorporating bottom ash and nickel slag as aggregate substitutes, influences concrete properties, with a focus on compressive strength and workability. The primary objective is to formulate concrete compositions that exhibit high strength and durability while promoting sustainability and minimizing environmental consequences. The objective of this research is to investigate the properties of waste aggregates, specifically nickel slag and bottom ash, as potential materials for concrete production. Additionally, the study seeks to examine how the incorporation of fly ash as an additive in concrete affects its workability and compressive strength when using waste aggregate derived from nickel ore processing, in comparison to conventional aggregate.

2. Methods.

2.1. Materials.

This study utilized various materials, including industrial byproducts (nickel slag and bottom ash), supplementary components such as fly ash, Portland Composite Cement (PCC), and water. Additionally, conventional aggregates were employed as a benchmark, with crushed stone serving as the coarse aggregate and sand as the fine aggregate.

The nickel slag material originates from the waste produced by PT Virtue Dragon Nickel Industry's (VDNI) nickel smelter in Southeast Sulawesi Province, Indonesia. Additionally, the fly ash and bottom ash are byproducts from VDNI's Coal Power Plant (PLTU), also located in Southeast Sulawesi Province, Indonesia.

The research utilizes a target gradation method that adopts a standardized material gradation specification for aggregates with a maximum size of 20 mm, as outlined in SNI-03-2834-2000. [39].

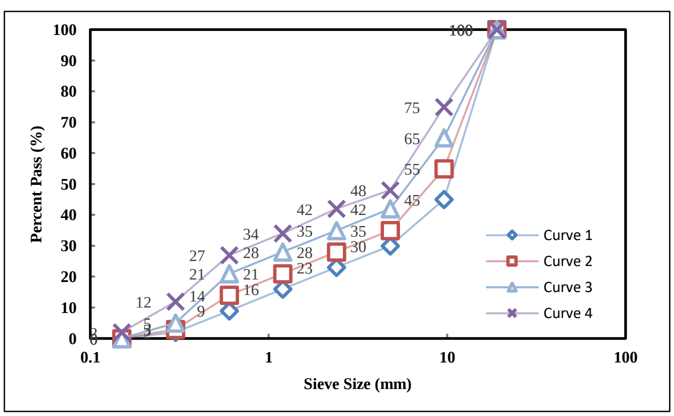

Figure 4. Size distribution curve for target aggregate featuring a maximum grain dimension of 20 mm

2.2. Research Procedure.

The investigation initiated with the assembly of essential materials for sample production. These included nickel slag serving as coarse aggregate, bottom ash functioning as fine aggregate, fly ash, cement, and water. Natural aggregate, consisting of crushed stone and river sand, was also prepared as a control substance. Subsequently, the investigators performed a series of laboratory analyses to assess the aggregates' properties. These evaluations encompassed tests for moisture and mud content, volume weight determination, sieve analysis of both coarse and fine aggregates, specific gravity measurement, water absorption assessment, and abrasion testing for coarse aggregate materials.

In the concrete mix design, the aggregate gradation was established and formulated by weight ratio to conform to the specifications for a maximum aggregate size of 20 mm. The weight composition of each component in the mixture was determined using a conventional concrete mix design approach with natural aggregates, followed by adjustments to the volume weight between natural and waste materials. All materials were combined under saturated surface-dry (SSD) conditions. A cement-water ratio of 0.5 was utilized in the concrete mixture, while fly ash additions to cement weight ranged from 0% to 50%, increasing in 10% increments. These fly ash dosages were classified from low to high, as depicted in Table 1.

Table 1. Efficiency factor for fly ash incorporation in concrete mixes [40]

Percentage of fly ash weight in concrete mix to cement weight	Classification
< 15	Low
15-30	Medium
30-50	High
> 50	Very High

Cylindrical concrete samples measuring 10 cm in diameter and 20 cm in height were utilized for the study. The properties of Portland Composite Cement (PCC) were not examined, as it was presumed that the cement employed was standard and met the necessary requirements. Material testing for the concrete mixture was conducted using appropriate SNI methods for each specific test, while the assessment of fresh concrete workability followed the guidelines outlined in SNI 1972-2008. [41] and concrete compressive strength tested based on SNI 1974-2011 [42]. Concrete compressive strength tested at 28 days.

3. Results

3.1. Natural Material Inspection Results.

3.1.1. Coarse Aggregate Inspection Results (Crushed Stone).

Table 2 displays the findings from the analysis of coarse aggregate (crushed stone) properties. The test outcomes for the characteristics of the coarse aggregate (crushed stone) are in compliance with the standards outlined in ASTM C33 .

Table 2. Inspection results of coarse aggregate characteristics (crushed stone)

	Test Type	Result	Spec.	Unit
1.	Specific gravity			
	- Dry basic	2.57	-	-
	- SSD	2.58	-	-
	- Apparent	2.60	-	-
	- Absorption	0.37	max. 3	%
2.	Abrasion test	26.36	max. 40	%
3.	Loose unit weight	1.31	-	gr./cm^3
4.	Solid unit weight	1.51	-	gr./cm^3
5.	Clay content	0.16	max. 1	%

6.	Moisture content	0.38	-	%

3.1.2. Fine Aggregate Inspection Results (Sand).

Tests were conducted on the properties of fine aggregate (river sand) to assess its specific gravity, moisture content, mud content, volume weight, and aggregate gradation size. Table 3 displays the outcomes of these tests on the fine aggregate (river sand) characteristics. The overall results of the fine aggregate (river sand) property tests were found to comply with the standards outlined in ASTM C33.

Tabel 3. Inspection results of fine aggregate characteristics (river sand)

	Test Type	Result	Spec.	Unit
1.	Specific gravity			
	- Dry basic	2.49	-	-
	- SSD	2.56	-	-
	- Apparent	2.68	-	-
	- Absorption	2.74	max. 3	%
2.	Loose unit weight	1.38	-	$gr./cm^3$
3.	Solid unit weight	1.55	-	$gr./cm^3$
4.	Clay content	2.64	max. 5	%
5.	Moisture content	2.74	-	%

A fine aggregate gradation test was performed to assess the gradation of sand. The results of this analysis are displayed in Figure 5, which illustrates the gradation of the fine aggregate (sand).

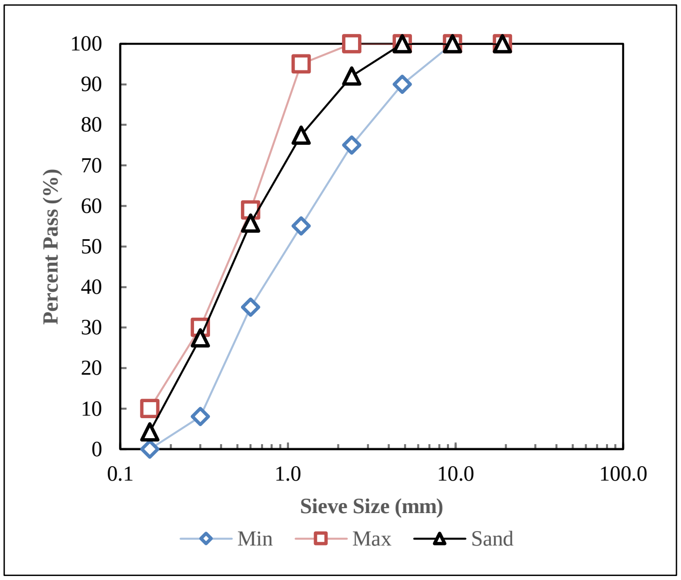

Figure 5. Gradation of fine aggregate (sand)

According to the experimental findings, the sand particles utilized as fine aggregate fall within the category of region II, which is classified as relatively coarse sand in accordance with SNI 03-2834-2000 gradation standards [39].

3.2. Waste Material Inspection Results.

3.2.1. Coarse Aggregate Inspection Results (Nickel Slag).

Table 4 presents an examination of the characteristics of nickel slag, a byproduct of smelter operations, when utilized as a coarse aggregate material. The analysis reveals that the specific gravity, absorption value, wear resistance, and mud content of the nickel slag aggregate conform to the standards set forth by SNI and ASTM C33 specifications.

Table 4. Inspection results of nickel slag characteristics

	Test Type	Result	Spec.	Unit
1.	Specific gravity			
	- Dry basic	2.69	-	-
	- SSD	2.70	-	-
	- Apparent	2.71	-	-
	- Absorption	0.17	max. 3	%
2.	Abrasion test	21.53	max. 40	%
3.	Loose unit weight	1.42	-	gr./cm^3
4.	Solid unit weight	1.61	-	gr./cm^3
5.	Clay content	0.09	1	%
6.	Moisture content	0.16	-	%

The measured specific gravity of nickel slag indicates its relatively high density, ranging from 2.69 to 2.71. Coarse aggregate used in concrete typically has a specific gravity between 2.5 and 2.7, as specified by ASTM C33 [43]. Consequently, nickel slag fulfills the specific gravity requirements, demonstrating its capacity to enhance concrete strength without causing excessive compression [44].

3.2.2. Fine Aggregate Inspection Results (Bottom Ash).

Table 5 indicates that the bottom ash exhibits an absorption value of 4.80%, which surpasses the conventional maximum threshold of 3%. This heightened water absorption capacity could potentially influence the performance of the bottom ash in various applications, particularly in concrete mixtures, where excessive water retention might compromise the long-term strength of the final product. Conversely, the material passing through sieve no. 200 is a mere 0.09%, well below the 5% limit set by ASTM-C33. This low percentage suggests an optimal particle size distribution, with the majority of the material being coarse enough to be retained by the sieve. Thus, despite concerns raised by the elevated absorption rate, the particle size characteristics of the bottom ash align with established standards, rendering it potentially viable for select construction purposes.

Tabel 5. Inspection results of fine aggregate (bottom ash) characteristics

	Test Type	Result	Spec.	Unit
1.	Specific gravity			
	- Dry basic	2.31	-	-
	- SSD	2.42	-	-
	- Apparent	2.59	-	-

	- Absorption	4.80	max. 3	%
2.	Loose unit weight	1.31	-	gr./cm^3
3.	Solid unit weight	1.51	-	gr./cm^3
4.	Clay content	0.09	max. 5	%
5.	Moisture content	0.16	-	%

Results from the comprehensive sieve analysis reveal that the particles of bottom ash fall into the region II category, which is defined as coarse sand by the SNI 03-2834-2000 standard. This classification implies that the bottom ash possesses a particle size distribution similar to that of coarse sand, making it suitable for use in construction projects where such materials are needed. [39].

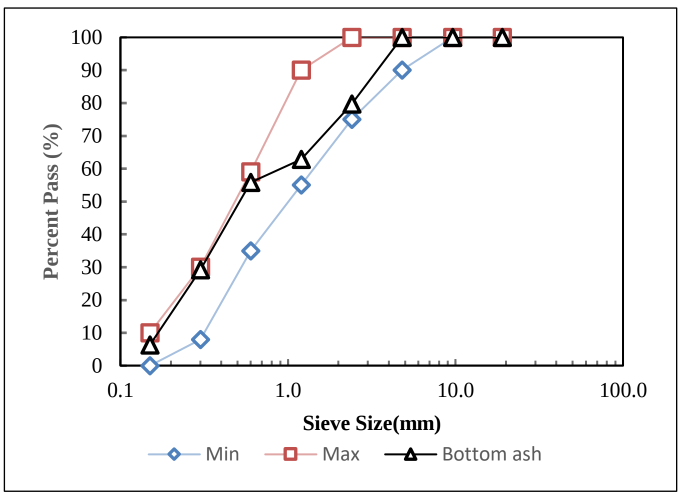

Figure 6. Gradation of fine aggregate (bottom ash)

Tabel 6. Design of material requirements for mixing concrete with normal aggregate

Sample Code	**Cement (gram)**	**River Sand (gram)**	**Crushed Stone (gram)**	**Water (gram)**	**Fly Ash (gram)**	**Fly Ash (%)**	**(c+p) (gram)**	**W/(c+p)**	**Number of Samples**
1	2	3	4	5	6	7	8	9	10
N1.FA0.	1810.49	3265.07	5215.63	905.24	0.00	0.00	1810.49	0.50	3
N2.FA10.	1810.49	3265.07	5215.63	995.77	181.05	10.00	1991.53	0.50	3
N3.FA20.	1810.49	3265.07	5215.63	1086.29	362.10	20.00	2172.58	0.50	3

N4.FA30.	1810.49	3265.07	5215.63	1176.82	543.15	30.00	2353.63	0.50	3
N5.FA40.	1810.49	3265.07	5215.63	1267.34	724.19	40.00	2534.68	0.50	3
N6.FA50.	1810.49	3265.07	5215.63	1357.86	905.24	50.00	2715.73	0.50	3

Tabel 7. *Design of material requirements for mixing concrete with waste aggregate*

Sample Code	Cement (gram)	Bottom Ash (gram)	Nickel Slag (gram)	Water (gram)	Fly Ash (gram)	Fly Ash (%)	(c+p) (gram)	W/(c+p)	Number of Samples
1	2	3	4	5	6	7	8	9	10
L1.FA0.	1810.49	2709.56	5684.66	905.24	0.00	0.00	1810.49	0.50	3
L2.FA10.	1810.49	2709.56	5684.66	995.77	181.05	10.00	1991.53	0.50	3
L3.FA20.	1810.49	2709.56	5684.66	1086.29	362.10	20.00	2172.58	0.50	3
L4.FA30.	1810.49	2709.56	5684.66	1176.82	543.15	30.00	2353.63	0.50	3
L5.FA40.	1810.49	2709.56	5684.66	1267.34	724.19	40.00	2534.68	0.50	3
L6.FA50.	1810.49	2709.56	5684.66	1357.86	905.24	50.00	2715.73	0.50	3

3.2.3. Fly Ash Inspection Results.

This study presents the findings from an analysis of the chemical constituents found in the fly ash sample employed.

Tabel 8. *Chemical composition of fly ash*

Compound	m/m%	Compound	m/m%
SiO_2	35.89	Si	16.78
Fe_2O_3	28.10	Fe	19.65
CaO	27.11	Ca	19.38
Al_2O_3	7.01	Al	3.71
K_2O	1.08	K	0.90
TiO_2	0.45	Ti	0.27
SrO	0.151	Sr	0.128
BaO	0.084	Ba	0.075
ZrO_2	0.048	Zr	0.036
Nb_2O_5	0.0302	Nb	0.0211
MoO_3	0.0225	Mo	0.0150
SnO_2	0.0087	Sn	0.0069
In_2O_3	0.0079	In	0.0065
RuO_4	0.0076	Ru	0.0058
Sb_2O_3	0.0071	Sb	0.0059

This research examined the properties of fly ash through specific gravity testing. Fly ash particles, when used as a cement additive, share similarities with cement particles. The fly ash analyzed in this investigation exhibited a specific gravity of 2,960.

XRF (X-Ray Fluorescence) analysis was conducted to ascertain the chemical composition of fly ash. The results of this examination are presented in Table 8. Laboratory examination results reveal that the chemical makeup of fly ash is primarily composed of three oxides: SiO_2 at 35.89 m/m%, Fe_2O_3 at 28.10 m/m%, and CaO at 27.11 m/m%.

Fly ash is Type C when its calcium oxide (CaO) content exceeds 18%, indicating more alkali metals and basic compounds that enhance pozzolanic characteristics. A byproduct of coal burning in power facilities, fly ash is divided into Type C and Type F. Type C is derived from sub-bituminous coal or lignite, while Type F comes from bituminous or anthracite coal. [45].

3.3. Mixed Design.

Before formulating the concrete mix design, the materials were processed to achieve the desired gradation for concrete mixtures with a maximum aggregate size of 20 mm (fig. 4). Table 9 displays the intended gradation and combined composition of coarse and fine aggregates in the concrete mix, which was applied to both standard and waste aggregates.

Tabel 9. Design of target gradation and aggregate mix composition

Sieve Size (mm)	Specification			Proportion of Combined Aggregate (%)
	Grada-tion Specifi-cations	Target Grada-tion	Passing Differen-ce	
38.1	100	100	-	Coarse aggregates = 61.5%
19.0	100	100	0	
9.6	55-65	60	40	
4.8	35-42	38.5	21.5	
2.4	28-35	31.5	7	Fine aggregates = 38.5%
1.2	21-28	24.5	7	
0.6	14-21	17.5	7	
0.3	3-5	4	13.5	
0.2	0-0	0	4	
			0	
Total			**100**	

Tables 6 and Table 7 outline the design material specifications for concrete mixing using standard and waste aggregates. The mixture composition for each waste aggregate has been modified by comparing its volume weight to that of natural aggregate within each aggregate size distribution.

3.4. Fresh Concrete Inspection Results.

To assess the workability of concrete, it is necessary to conduct fresh concrete testing using the slump test method. Fig. 7 and fig. 8 illustrate how fly ash impacts the slump value in a fresh concrete mixture.

Figure 7. Slump test

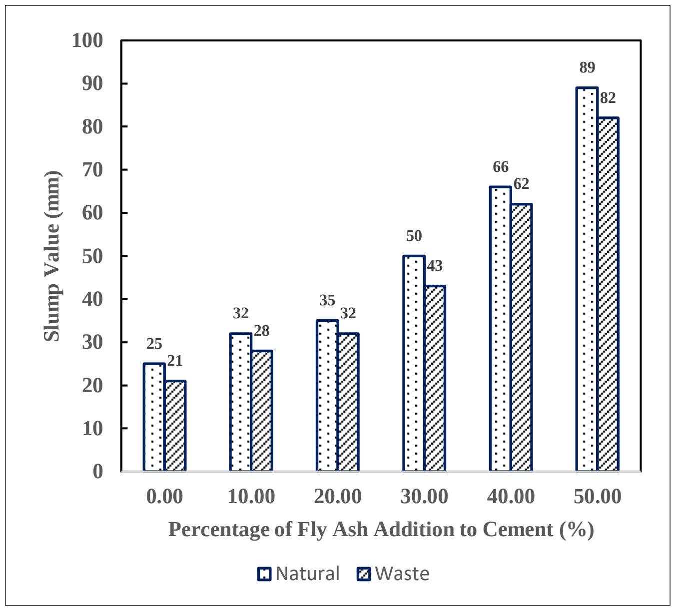

Figure 8. Graph of slump test results

The slump test findings revealed that as the proportion of fly ash in the concrete mix increased, so did the slump value. Higher concentrations of fly ash led to improved workability of the concrete mixture, resulting in a more plastic and cohesive composition.

In comparison to standard concrete, which uses natural crushed stone as coarse aggregate and natural sand as fine aggregate, the slump test values were higher for mixtures utilizing nickel slag waste as coarse aggregate and bottom ash as fine aggregate. This difference was observed when maintaining the same cement-water ratio of 0.5 for both mixtures.

3.5. Compressive Strength Test Results.

Experiments were conducted to evaluate the compressive strength of concrete by varying fly ash additive levels while keeping the water-cement ratio (w/c) constant at 0.5. The incorporation of fly ash into concrete mixtures, whether using standard aggregate materials or waste materials (such as nickel slag for coarse aggregate and bottom ash for fine aggregate), did not decrease cement usage in the mixture. Consequently, increasing fly ash content in the concrete mixture led to a corresponding rise in water content, as illustrated in Table 6 and Table 7. Fig. 9 displays the results of the concrete compressive strength test conducted at 28 days of age.

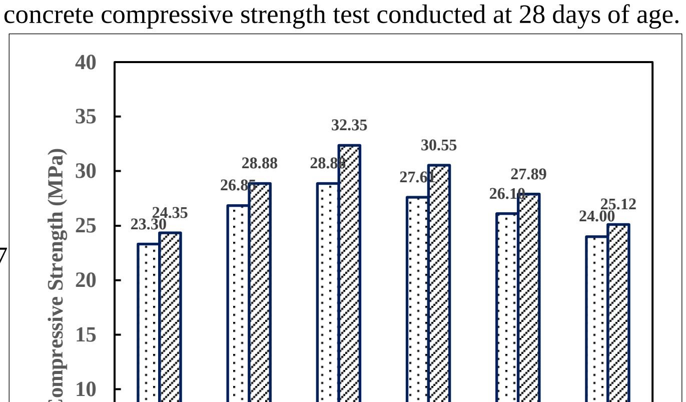

Figure 9. Graph of concrete compressive strength test results

As depicted in fig. 9, concrete made with a combination of coarse aggregate (crushed stone) and fine aggregate (river sand), without fly ash incorporation, achieved a compressive strength of 23.30 MPa. This value is lower than the 24.35 MPa compressive strength observed in concrete samples utilizing waste aggregates, specifically nickel slag and bottom ash.

Results from average concrete compressive strength tests, which employed both natural and waste materials with various fly ash concentrations, show that concrete's compressive strength increases as fly ash levels rise to 20%. However, at 30%, 40%, and 50% fly ash concentrations, the compressive strength values begin to decrease. Interestingly, when fly ash is incorporated at 50% of the cement content, the resulting compressive strength becomes comparable to that of concrete without any fly ash additions.

Figure 10. Compressive strength test

4. Discussion

4.1. Effect of Fly ash Addition on Workability of Fresh Concrete

Research has shown that incorporating fly ash into fresh concrete mixtures enhances the concrete's workability, as evidenced by higher slump test results with increased fly ash content. This improvement occurs because fly ash particles, which are similar in size to cement particles, create a smoother concrete mixture that is easier to manipulate. These small particles act as a lubricant in the concrete mix, increasing its plasticity and cohesiveness, thereby enhancing the overall workability of the concrete. The incorporation of fly ash into fresh concrete mixtures not only improves workability but also offers several additional benefits. The spherical shape of fly ash particles contributes to the "ball-bearing" effect, which reduces friction between aggregate particles and enhances the concrete's flowability. This improved flowability allows for easier pumping and placement of concrete, particularly in complex or congested reinforcement areas. Furthermore, the increased workability achieved through fly ash addition often results in reduced water demand, which can lead to improved strength and durability of the hardened concrete [46]–[48].

The enhanced workability provided by fly ash also has implications for the concrete's finishing characteristics. The smoother, more cohesive mixture allows for easier screeding, floating, and troweling, resulting in a superior surface finish. This is particularly advantageous in applications where aesthetics are important, such as exposed concrete surfaces or decorative concrete work. Additionally, the improved workability can extend the setting time of the concrete, providing contractors with a longer window for placement and finishing operations, especially in hot weather conditions. These combined effects of fly ash on concrete workability contribute to improved construction efficiency, reduced labor costs, and enhanced overall quality of the finished concrete product [49], [50].

The findings indicate that concrete mixtures incorporating waste materials (nickel slag and bottom ash) and varying amounts of fly ash exhibit lower slump values compared to mixtures using natural materials (crushed stone and river sand). This reduction in slump could be attributed to the coarser grains of nickel slag and stronger interparticle bonds within the mixture, resulting in decreased flowability of the fresh concrete and consequently lower slump test values. Similarly, bottom ash, which has sand-like grains but higher absorption rates than river sand, contributes to increased cohesiveness in the fresh concrete mixture. These factors collectively lead to reduced slump values across all variations of fly ash addition in concrete mixtures containing waste materials. When waste materials like nickel slag and bottom ash are added to concrete mixtures, along with varying quantities of fly ash, the concrete's workability undergoes notable alterations, as demonstrated by decreased slump values. This decline in slump can be traced to multiple characteristics of the waste materials. The coarser grain structure of nickel slag enhances the mixture's internal friction and creates stronger bonds between particles. These properties result in a more cohesive mixture that is less likely to flow, thereby producing lower slump test measurements. Although bottom ash has grains similar to sand, it exhibits a higher absorption rate than typical river sand. This increased capacity for absorption further enhances the mixture's cohesiveness, effectively diminishing its ability to flow [51]–[53].

The combined effect of these waste materials on concrete workability is consistent across various levels of fly ash addition. This suggests that the influence of nickel slag and bottom ash on slump values is dominant and persistent, regardless of the fly ash content in the mixture. The observed reduction in workability highlights the need for careful consideration when incorporating these waste materials into concrete mix designs. While their use offers potential environmental and economic benefits, adjustments in mix proportions or the inclusion of workability-enhancing admixtures may be necessary to achieve desired slump values for specific applications. Further research into optimizing these waste material-based concrete mixtures could lead to improved performance while maintaining the advantages of utilizing recycled materials in construction.

In conclusion, the incorporation of fly ash into fresh concrete mixtures significantly enhances workability, as evidenced by higher slump test results. This improvement is attributed to the lubricating effect of fly ash particles, which increase plasticity and cohesiveness. The enhanced workability offers numerous benefits, including easier pumping, placement, and finishing of concrete, reduced water demand, and extended setting time. However, when waste materials such as nickel slag and bottom ash are introduced alongside fly ash, the concrete's workability decreases, as indicated by lower slump values. This reduction is due to the coarser grains of nickel slag and the higher absorption rates of bottom ash, which increase internal friction and cohesiveness. These findings underscore the complex interplay between various concrete components and highlight the need for careful consideration when designing mixtures that incorporate waste materials. Future research should focus on optimizing these mixtures to balance the environmental and economic benefits of using recycled materials with the desired workability and performance characteristics of the concrete.

4.2. Effect of Adding Fly ash on Compressive Strength of Concrete

Incorporating fly ash into concrete mixtures has a notable effect on the concrete's compressive strength, though this effect has certain constraints. Studies indicate that as the proportion of fly ash in the concrete mix increases, the compressive strength also rises, reaching its peak at 20% fly ash content by cement weight. Beyond this point, however, the compressive strength begins to decline. At 50% fly ash content, the strength nearly matches that of concrete without any fly ash addition. This pattern emerges because fly ash serves a dual purpose: it acts as a filler in concrete voids and possesses pozzolanic properties that can decelerate cement hydration [54]–[56]. When fly ash is present in excessive amounts, the concrete contains an overabundance of fine particles. This surplus can negatively impact the concrete's strength by interfering with the hydration process. The surplus of fine particles can disrupt the formation of calcium silicate hydrate (C-S-H) gel, the primary binding agent in concrete, leading to a reduction in overall strength. Therefore, while fly ash can significantly improve concrete strength when used in appropriate quantities, careful consideration must be given to the optimal proportion to achieve the desired balance between strength enhancement and potential negative effects [57], [58].

The impact of incorporating fly ash into concrete on its strength:

- Concrete strength can be enhanced by the addition of fly ash.
- Strength improvements occur as fly ash content increases, but only to a certain extent.
- Optimal strength is reached when fly ash constitutes 20% of the cement's mass.
- Exceeding 20% fly ash content leads to a decline in strength.
- At 50% fly ash content, the strength becomes comparable to that of concrete without fly ash.

This phenomenon is attributed to two effects of fly ash:

- It occupies minute voids within the concrete.
- Its chemical characteristics decelerate the cement hardening process.

Nevertheless, excessive fly ash can be detrimental:

- An overabundance of fine particles accumulates in concrete.
- This surplus can disrupt the concrete's solidification.
- Consequently, the concrete's strength is diminished.

It can be concluded that the addition of fly ash in concrete mixtures can increase the compressive strength of concrete up to a certain limit (about 20-30%), but after that, excess fly ash can slow down the hydration of cement and reduce the compressive strength of concrete, especially at very high levels.

The utilization of nickel slag waste and bottom ash in standard concrete mixtures exhibits superior compressive strength compared to natural aggregate with identical fly ash additions. This enhanced performance may be attributed to the higher quality of these waste materials relative to conventional aggregates. For instance, nickel slag aggregate demonstrates a lower wear value (21.53%) than crushed stone coarse aggregate (natural) with a wear value of 26.36%. The reduced wear value suggests that the waste material, particularly the coarse aggregate (nickel slag), offers greater resistance to abrasion and improved capacity to withstand compressive loads. Consequently, concrete produced using these waste materials tends to achieve higher compressive strength than concrete using natural materials. Furthermore, the incorporation of bottom ash as fine aggregate contributes to the increased compressive strength. Although bottom ash grains visually resemble river sand, they possess a noticeably rougher surface texture when handled. This surface roughness likely plays a role in enhancing the compressive strength by promoting a stronger bond between the fine aggregate (bottom ash) and coarse aggregate (nickel slag).

5. Conclusion.

Nickel slag waste materials and bottom ash generally possess suitable properties for use in concrete production. Although the fine aggregate (bottom ash) has a relatively high absorption rate of 4.80%, exceeding the maximum requirement of 3%, this may still be acceptable. The results of this study demonstrate that the concrete produced with these materials meets the necessary standards for slump test values and compressive strength, suggesting that the elevated water absorption of bottom ash does not significantly impair the performance of concrete.

Adding fly ash to concrete enhances the workability of fresh mixtures, as evidenced by the increased slump test values observed with higher fly ash percentages in both natural aggregate and waste material concrete. The compressive strength of concrete improves with fly ash addition up to 20%, reaching 32.35 MPa, which surpasses the strength of natural aggregate concrete (28.88 MPa) at the same fly ash content. However, increasing the fly ash content beyond 20% and up to 50% by cement weight led to a decline in compressive strength, dropping to 25.12 MPa. Nevertheless, this value remains higher than the 24.35 MPa compressive strength of concrete without fly ash.

Conflict of interest

The authors declare no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Authors 1 proposed the research problem, developed the theory, and performed computations.

Both authors discussed the results and contributed to the final manuscript.

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