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RESEARCH

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Influence of Steel Slag as a Partial Replacement of Aggregate on Performance of Reinforced Concrete Beam

Tadese Birlie Mekonen[1], Temesgen Ejigu Alene[2], Yared Aklilu Alem[2*] and Wallelign Mulugeta Nebiyu[2]

Abstract

Amidst the global pursuit of sustainable alternatives in concrete production, this study explores the viability of incorporating by-products or waste materials as aggregates to support the concrete construction industry, with a specific emphasis on steel slag. The objective of this study is to evaluate the effectiveness of steel slag as a partial replacement for fine and coarse aggregates in concrete production. The experiment involved casting 30 cubes and 10 beams, replacing fine aggregate from 0 to 60%. Flexural and compressive strength tests at 7 and 28 days followed the ACI method. Results revealed that a 30% replacement of fine aggregate with steel slag led to higher compressive strength at both 7 and 28 days, while a 45% replacement showed superior flexural strength at 28 days. Further chemical analysis and optimization are recommended for deeper insights. The study concludes with marginal improvements in compressive and flexural strength with steel slag partial replacement, identifying 30% for fine aggregate and 45% for coarse aggregate as optimal replacements. In addition, the mineral composition of steel slag exhibits significant variability, with compounds, including silicon dioxide (SiO_2), iron oxide (Fe_2O_3), manganese oxide (MnO), aluminum oxide (Al_2O_3), and calcium oxide (CaO). Chemical analysis indicates high silicate content and minimal alkali content, contributing to enhanced strength during concreting. Higher steel slag replacement reduces workability, confirmed by slump tests. However, all mixes maintain a true slump, and unit weight increases with steel slag aggregate replacement. Compressive strength improves incrementally with higher steel slag content, echoing prior research. In addition, flexural strength rises with steel slag replacing both coarse and fine aggregates, suggesting enhanced performance in reinforced concrete structures. These findings highlight steel slag's potential as a sustainable alternative in concrete production, aiming to advance its application in the construction industry, promoting environmental sustainability and economic viability.

Keywords Steel slag, Reinforced concrete, Compressive strength, Flexural strength, Beam

1 Introduction

In recent times, there has been increasing attention on integrating waste materials and by-products into alternative construction materials. This approach represents a partial solution to environmental and ecological challenges. The utilization of these materials not only contributes to their effective integration into cement, concrete, and various construction products, but it also plays a role in lowering the overall cost of cement and concrete manufacturing. In addition, it brings about several indirect benefits, including a reduction in landfill costs, energy

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*Correspondence:
Yared Aklilu Alem
yareda7@gmail.com
[1] Department of Civil Engineering, College of Engineering and Technology, Bule Hora University, P.O. Box 144, Bule Hora, Ethiopia
[2] Faculty of Civil and Water Resources Engineering, Bahir Dar Institute of Technology, Bahir Dar University, P.O. Box 26, Bahir Dar, Ethiopia

savings, and the safeguarding of the environment against potential pollution effects (Shi, 2004).

Furthermore, integrating these waste materials not only facilitates their effective use in construction but also helps in cutting down the overall cost of cement and concrete manufacturing. This approach not only benefits the construction industry economically but also brings about indirect advantages such as reducing landfill costs, conserving energy, and mitigating potential pollution effects on the environment. By substituting natural aggregates with recycled concrete aggregate (RCA), for instance, the demand for virgin materials is reduced, contributing to a more sustainable construction sector (Ibrahim et al., 2022; Kurniati et al., 2023; Padmapriya et al., 2015; Siddique et al., 2019).

Despite significant advancements in construction over the past decades, addressing the global demand for reinforced concrete poses increasing challenges due to the finite nature of Earth's resources. Despite these limitations, it remains noteworthy that up to three-quarters of newly mixed concrete continues to rely on natural aggregates (Padmapriya et al., 2015). Recent studies have offered valuable insights into the application of steel slag across various construction contexts, highlighting its considerable potential.

For instance, Zhong et al., (2024) proposed an innovative method of using steel slag as coarse aggregate and filler in stone mastic asphalt mixture, demonstrating superior engineering performance, reduced environmental impact, and enhanced economic benefits. Similarly, Ali and Abdul-Hameed, (2024) reviewed the suitability of steel slag as an aggregate substitute in concrete columns, highlighting its potential to enhance strength and durability properties. In addition, studies such as Mudgal et al., (2024) investigated the utilization of steel slag as fine aggregate in geopolymer mortar, showing promising mechanical properties and durability. Furthermore, research by Ho et al., (2024) and Saravan and Annadurai, (2024) explored the mechanical properties and fire resistance of high-performance concrete with steel slag replacement, providing valuable insights into its potential applications. Baalamurugan et al., (2019) demonstrated its efficacy in gamma radiation shielding, whereas Gencel et al., (2021) elucidated its varied applications in cement and concrete technology. Furthermore, Baalamurugan et al., (2021) conducted a study on high-density concrete utilizing steel slag aggregates, indicating its superior radiation shielding properties compared to conventional concrete formulations. This emphasis on recent research highlights the growing interest in steel slag as a sustainable construction material.

Steel slag, produced as a by-product in steelmaking furnaces, is formed during the extraction of molten steel from impurities. The annual growth of steel manufacturing, driven by industrialization and urbanization, results in the substantial generation of industrial by-products, particularly slag (Netinger Grubeša et al., 2016). Annually, the global steel industry produces 1600 million tons of steel slag, with around 70% relying on blast furnaces. Currently, each ton of steel produced yields between 200 and 250 kg of slag (Davey, 2022). With the global steel industry producing approximately 1600 tons of steel slag annually, its substantial utilization has primarily been observed in the construction sector (Baalamurugan et al., 2023). This highlights the need for efficient management of industrial by-products.

Steel slag's potential in concrete production is particularly noteworthy due to its ability to address resource depletion concerns associated with unregulated concrete production (Ren & Li, 2023). Concrete slag cement reduces emissions, cuts energy use by 90%, lessens material extraction, and mitigates the "urban heat island" effect (Hoque & Hosse, 2019). However, drawbacks such as water absorption and high alkali content exist. With appropriate treatments, steel slag can be effectively utilized as either coarse or fine aggregate in concrete (Mallick, 2010). This highlights the importance of ongoing research aimed at optimizing the use of steel slag in concrete production.

Moreover, this by-product can serve as an aggregate in concrete (Kumar & Shukla, 2023; Li et al., 2023). Steel slag aggregate typically has a tendency to expand due to the presence of free lime and magnesium oxides that have not reacted with the silicate structure and may hydrate and expand in humid environments.

Aggregates are categorized as natural or artificial based on their sources. Natural aggregates are sourced from quarries through the processing of crushed rocks or from riverbeds, while artificial aggregates are derived from industrial by-products like blast furnace slag. The supply condition of natural aggregates varies with regional and seasonal conditions, highlighting the importance of optional aggregate selection based on specific project requirements. This involves choosing between replacing only coarse aggregates, only fine aggregates, or both with steelmaking slag. The test cases explore different aggregate combinations, studying mixing ratios that meet the required concrete quality, considering both fresh and hardened concrete properties.

The hardening properties of concrete are intricately influenced by factors such as cement type, aggregate characteristics, water content, and mixing ratios (Ren & Li, 2023). Understanding key aggregate properties, including shape, gradation, moisture content, unit weight, specific gravity, void ratio, and chemical properties, is crucial in concrete mixture design. In the realm of high-strength concrete, the distinctive angular shape of crushed aggregates significantly enhances tensile strength by facilitating increased bonding surface with cement paste and reducing internal stress concentrations (Dinku, 2002). Recent studies exploring the incorporation of steel slag as a concrete aggregate reveal a density increase and reduced workability, yet superior mechanical properties and durability compared to natural aggregate concrete (Ren & Li, 2023).

Croatian research further supports steel slag's use, demonstrating comparable hardened state properties in concrete mixtures with coarse slag fractions relative to conventional natural aggregate materials (Netinger et al., 2011). The shape and texture of aggregates play a pivotal role in fresh concrete properties, affecting workability and, consequently, the water-to-cement mass ratio (w/cm). Notably, concrete with angular crushed stone aggregate tends to exhibit higher flexural strength at the same w/cm compared to concrete with rounded gravel aggregate (Dehghan et al., 2023). These collective findings highlight the potential of steel slag as a promising alternative to traditional aggregates, offering mechanical strength and durability benefits.

Since most of the volume of reinforced concrete is comprised of aggregates, the advantages of using slag in a concrete mix include enhancing compressive strength (Karolina & Putra, 2018). The high specific gravity and abrasion value of steel slag compared to naturally available aggregates make it an environmentally beneficial substitute. The decision to use steel slag instead of natural aggregates in concrete is based on considerations of resource availability and the favorable characteristics of steel slag.

Various studies have explored the incorporation of steel slag in concrete, investigating full and partial substitutions for both fine and coarse aggregates. For instance, Liu Chunlin's, 2011 study demonstrated that steel slag concrete (SSAC) exhibited comparable strength to conventional concrete, with higher compressive strength and slightly reduced flexural strength. Subsequent research by Emad Abdelazzzim et al., in 2014 found optimal performance with a 66.67% replacement of coarse aggregate while Devi & Gnanavel's work in the same year showcased improved strength properties in M20 grade concrete with partial steel slag substitutions. Following this line of inquiry, in 2015, (Ravikumar et al., 2015) observed enhanced strength with up to 60% coarse aggregate replacement, though full replacement led to a substantial strength decrease. Similarly, Shailja Bawa et al.,'s 2018 investigation focused on replacing fine aggregate with 20, 30, and 40% steel slag, maintaining a constant w/c ratio of 0.42 and incorporating a 1.55% high-range water-reducing admixture. Results indicated that specimens with 30% steel slag, 20% fly ash, and 10% metakaolin displayed optimal mechanical properties, contributing valuable insights to the positive influence of steel slag on concrete performance (Bawa et al., 2018; Chunlin et al., 2011; Devi & Gnanavel, 2014; Emad Abdelazzzim et al., 2014). Overall, these studies suggest that steel slag can enhance the mechanical properties of concrete.

Recognizing the limitations of existing research and the growing emphasis on sustainable construction practices, this study seeks to address the gap by evaluating the multifaceted impact of steel slag aggregate on reinforced concrete beams. By comprehensively examining physical, and chemical aspects, this research aims to offer a more holistic understanding of the potential benefits and challenges associated with incorporating steel slag as an aggregate in civil engineering construction. The overarching objective is to evaluate the impact of steel slag aggregate on reinforced concrete beams, considering physical and chemical properties, as well as economic and environmental aspects. Specific objectives encompass studying steel slag properties, exploring gradation of steel slag aggregate, and assessing its influence on compressive strength and flexural behavior in reinforced concrete beams. The research aims to contribute valuable insights into sustainable construction practices, offering alternatives near construction sites and addressing industrial waste disposal challenges while enhancing the understanding of steel slag's effects on various structural elements.

2 Methodology

2.1 Data and Sampling

This research necessitates the acquisition of relevant data related to the materials used, strength characteristics, loading conditions, and cross-sectional details. To achieve this, ten data samples are cast and subjected to testing until failure using a symmetrical three-point static loading system for flexural strength. Simultaneously, 30 data samples are cast and tested until failure to determine compressive strength, with a replacement of fine aggregate by steel slag.

Among the ten flexural strength test beams, two beams serve as control specimens without steel slag aggregate, providing a baseline for comparison, while the remaining eight beams incorporate substitute steel slag aggregate. Similarly, in the case of compressive strength tests, six out of thirty samples act as control specimens without steel slag aggregate, serving as a reference, while the remaining 24 samples include substitute steel slag aggregate. The specimen size for the compressive strength tests is in the form of cubes.

In the context of materials, Ordinary Portland cement (OPC) from the Dangote cement brand 42.5R was

Table 1 Specimen details for compression and flexure tests with coarse and fine aggregate replacement

Name of specimen	Test type	Size of specimen (mm)	Number of specimens	
			Coarse replacement	Fine replacement
Cube	Compression	150*150*150	30	30
RC beam	Flexure	150*150*750	10	10

Table 2 Physical properties of natural coarse aggregate and natural fine aggregate

Property	Coarse aggregate	Natural fine aggregate
Specific Gravity	2.78	2.71
Water Absorption	1.27%	1.01%
Loose Bulk Density	1605 KN/m^3	1685 KN/m^3

utilized in the production of concrete. As for natural aggregate, the coarse aggregate comprises crushed stone particles with a size equal to or greater than 4.75 mm. The source of this aggregate for the thesis work is a quarry, and the material features a normal maximum size of 25 mm. In the tables below, Table 1 provides details of specimens for compression and flexure tests, highlighting the replacement of both coarse and fine aggregates, while Table 2 presents the physical properties of natural coarse and fine aggregates for reference.

The steel slag aggregate originates as an industrial by-product obtained from the Ethiopian steel and iron factory, featuring a normal maximum size of 25 mm. Characterized by its black and gray color, rough texture, angular shape, and porosity, the steel slag's porosity can influence absorption, strength, permeability, and aggregate durability. The steel slag aggregate is solid material resulting from condensation in water during production. Notably, the properties of steel slag can vary significantly based on the grade of steel produced, with classifications including uniform, well-graded, and poor-graded. Uniform-grade steel slag possesses consistent particle sizes, well-grade exhibits proportioned particle sizes, while poor-grade steel slag contains both lower and higher particle sizes. The determination of the required size is influenced by selecting the maximum aggregate size and subsequent screening after crushing by a hammer.

Fine aggregate is characterized as material capable of passing through a 4.75 mm sieve while predominantly being retained on a 75 µm sieve. The primary role of fine aggregate is to fill the voids within the coarse aggregate and serve as a workability agent in the concrete mix.

Fig. 1 depicts fine steel slag that has undergone screening and washing, alongside Natural Sand.

For steel reinforcement, deformed high-grade steel bars were employed in the study. The longitudinal reinforcement consisted of bars with a yield strength of approximately 500 MPa and a diameter of 8 mm. In addition, stirrups with a diameter of 6 mm and a yield strength of 300 MPa were used, positioned at a center-to-center spacing of 85 mm.

Potable water is employed for mixing in concrete production. Serving as a universal solvent, water plays a crucial role in increasing the workability of the concrete mix.

2.2 The Mix Procedure in the ACI Method

Mix design is the systematic process of proportioning concrete mixtures, providing a reliable method to determine the appropriate ingredients for concrete. In this research, materials are meticulously proportioned, and their weights are determined. The primary variables throughout the entire experiment are the fine and coarse aggregates. The specific substitution of these aggregates is contingent on the density of the aggregate to be replaced. This substitution is guided by a mathematical equation, ensuring a systematic and precise approach in achieving the desired concrete mix.

The formula provided

a. Fine steel slag after screening and washing

b. Natural sand

Fig. 1 Fine steel slag after screening and washing and natural sand

$$V(\alpha x + \beta y) = \text{massoftheaggregate(control)} \quad (1)$$

outlines the relationship between the known volume of the aggregate (V), the percentage of steel slag aggregate (x), the fixed percentage of crushed coarse aggregate (y), the unit weight of steel slag aggregate (α), and the unit weight of aggregate (β).

To express x in terms of y, Eq. 1, is rearranged, resulting in the equation:

$$x = \frac{\beta}{\alpha}(100 - y) \quad (2)$$

This equation allows for the calculation of the percentage of steel slag aggregate (x) based on the given values of y, α, and β, providing a systematic approach to determine the desired mix proportions.

The replacement of coarse aggregate using Eq. 3 is tabulated in Table 3, where V represents the known volume of coarse aggregate (0.67 m^3), x is the percentage of steel slag aggregate, y is the fixed percentage of crushed coarse aggregate, α is the unit weight of steel slag aggregate (1510 kg/m^3), and β is the unit weight of crushed coarse aggregate (1605 kg/m^3). The replacement equation is given by

$$\boldsymbol{x} = \frac{1605}{1510} \times (100 - y) \quad (3)$$

Similarly, for the replacement of fine aggregate, expressing x in terms of y and substituting the value of y gives:

$$\boldsymbol{x} = \frac{1685}{1651} \times (100 - y) \quad (4)$$

Here, V is the known volume of fine aggregate (0.43 m^3), x is the percentage of steel slag aggregate, y is the fixed percentage of crushed fine aggregate, α is the unit weight of steel slag aggregate (1651 kg/m^3), and β is the unit weight of crushed fine aggregate (1685 kg/m^3).

According to the values in Table 4, the mixing process was conducted as illustrated in Fig. 2 for each percentage replacement of course and fine aggregates.

2.3 Research Approach

The research is dedicated to investigating the influence of steel slag aggregate on the behavior of reinforced concrete beams, specifically focusing on their compression and flexural characteristics. The experimental study commences by progressively substituting a percentage of the weight of natural aggregates, commonly used in concrete production, with steel slag. This replacement, ranging from 15 to 25%, incrementally increases until reaching a complete substitution of natural aggregates with steel slag. The primary goal is to pinpoint the optimal replacement level for steel slag in concrete. Various concrete properties are thoroughly examined throughout the experiment.

The workability of freshly mixed concrete or mortar, crucial for assessing its ease of mixing, placement, consolidation, and finishing, is a key consideration. While there isn't a direct test to measure workability, the slump

Table 3 Replacement of fine aggregate

% Crushed fine aggregate	% Fine steel slag aggregate	Mass of crushed fine aggregate (g)	Mass of fine steel slag aggregate (g)	Check (g) $V(\alpha x + \beta y)$	Total mass of fine aggregate replacement (g)
100	0	717.77	0	717.81	717.81
85	15.31	610.10	109.88	717.81	719.99
70	30.62	502.44	219.77	717.81	722.20
55	45.93	394.77	329.65	717.81	724.42
40	61.24	287.11	439.53	717.81	726.64

Table 4 Mass of each ingredient for fine replacement

Percentage replacement	Cement (Kg)	Fine aggregate (Kg)	Natural coarse aggregate (Kg)	Steel slag aggregate (Kg)	Water (Kg)
0	26.00	70.12	46.80	0	12.71
15	26.00	70.12	39.78	7.46	12.78
30	26.00	70.12	32.76	14.92	12.84
45	26.00	70.12	25.74	22.39	12.91
60	26.00	70.12	18.72	29.85	12.98

Fig. 2 Mixing of material using mixer

test is extensively employed on-site to detect variations in concrete mix uniformity.

Concrete properties, evolving over time and under different humidity conditions, are scrutinized using the compressive strength test, a common measure for hardened concrete. In this research, the initial experiment involves determining the optimum replacement level by conducting compressive tests on cube specimens for both 7 and 28 days.

The compressive strength test, a widely used performance measure in concrete structures, involves casting cubes (150 × 150 × 150 mm) for C25/30 grade concrete. The results from this test provide valuable insights for quality control, concrete acceptance, and estimating concrete strength for construction operations. In Fig. 3, the slump measurements, compression tests on cubes, and flexural tests on beams are presented.

Concurrently, the study employs the flexural strength test to evaluate the indirect tensile strength of concrete. This test is crucial for understanding the maximum stress on the tension face of a concrete structure, commonly referred to as the modulus of rupture (MOR). It plays a significant role in determining deflection, identifying minimum flexural reinforcement, and signaling the onset of visible cracks under flexure. The study focuses on a simple beam loaded at the center and supported at the ends, with beams of dimensions 150 × 150 × 750 mm cast for C25/30 grade concrete.

As the loaded beam experiences tension on the bottom fibers and compression on the upper fibers, the introduction of steel bars in the lower part enhances load-bearing capacity. Known as reinforced concrete, this material can support significantly greater loads due to the high tensile strength of the reinforcing steel.

The flexural strength of the specimen is determined using the formula (Padmapriya et al., 2015):

$$\sigma = \frac{3Pl}{2bd^2} \tag{5}$$

where:

σ is the flexural strength in N/mm^2,

P is the maximum load in N,

l is the distance between central lines of supporting rollers in mm,

b is the average width of the block measured from both faces of the specimen in mm,

d is the average thickness measured from both ends of the fracture line in mm.

2.4 Instrumentation and Loading Procedures

The experimental investigation into beam specimens, meticulously designed to explore the mechanical implications arising from different degrees of coarse steel slag substitution. The experimental procedures outlined in (Qiu et al., 2020) provide a robust framework for investigating the mechanical properties of beam specimens. Commencing with a control beam, the experimental setup subjected it to loading, withstanding a maximum concentrated load of 55.63 KN at a 750 mm span, while meticulously recording mid-span deflection and load–displacement curves. Subsequent testing involved beams replaced with 25, 50, 75, and 100% coarse steel slag, replicating loading conditions and

a. Slump measurement b. Compression test of tube c. Flexural test of beam

Fig. 3 Slump measurement, compression test of cube, and flexural test of beam precisely documenting load increments alongside corresponding deflections. This systematic approach facilitated the observation of each specimen's load response, elucidating any behavioural deviations and pinpointing critical parameters such as yield loading, ultimate loading, and displacement characteristics.

3 Results and Discussion

In this section, the discussion and analysis of laboratory test results for steel slag as a potential aggregate replacement material are presented. Various properties of the steel slag under investigation include:

- Physical properties of steel slag
- Chemical properties of steel slag
- Workability and strength, encompassing both compressive and flexural aspects

3.1 Experimental Results

3.1.1 Gradation of Aggregate

Following the sieve analysis, a particle size distribution curve for the aggregate is generated. This curve serves to assess the fineness modulus, providing insights into the fineness, coarseness, and uniformity of the aggregates. The graph as shown in Fig. 4 reveals that the steel slag aggregate exhibits finer characteristics, particularly up to a sieve size of 12.5 mm. These aggregate properties significantly influence the overall properties of the concrete.

3.1.2 Physical Properties of Steel Slag

Specific gravity and absorption capacity are key indicators of the physical properties of steel slag. Specific gravity serves as a measure of aggregate density, expressing the ratio of the substance's weight to that of the same volume of water. The inclusion or exclusion of pores in this measurement affects the specific gravity, considering that aggregates inherently possess pores in their structure.

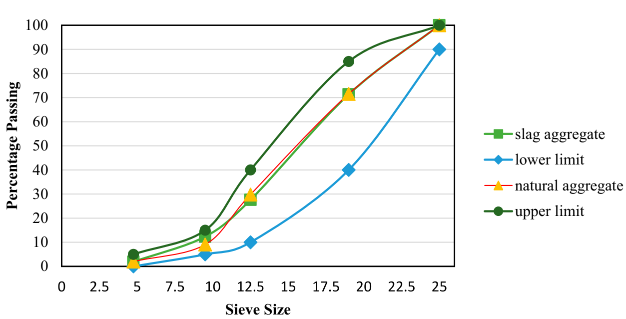

Fig. 4 Comparison of natural and slag coarse aggregate curve

Table 5 illustrates notable differences between coarse and fine steel slag and their counterparts. Steel slag exhibits a higher water absorption capacity than natural aggregate. While fine steel slag boasts a higher specific gravity compared to sand, coarse steel slag is comparable to natural aggregate. In addition, the bulk density of fine steel slag is akin to sand, but the bulk density of coarse steel slag is less than that of natural aggregate. These variations highlight the importance of considering steel slag's physical properties in concrete applications.

3.1.3 Chemical Properties

The chemical composition of steel slag exhibits significant variability due to the diverse chemical composition of steel slags (Guo et al., 2018). Chemical analysis reveals that the slag comprises both major and minor elements, with significant compounds including Silicon Dioxide (SiO_2), Iron Oxide (Fe_2O_3), Manganese Oxide (MnO), Aluminum Oxide (Al_2O_3), and Calcium Oxide (CaO). Minor compounds consist of Sodium Oxide (Na_2O), Potassium Oxide (K_2O), Phosphorus Oxide (P_2O_3), and Titanium Oxide (Ti_2O_3). It is widely acknowledged that the presence of C_3S, C_2S, C_4AF, and C_2F enhances the cementitious properties of steel slag (Roslan et al., 2016; Shi & Qian, 2000).

The slag exhibits a variable mineralogical composition, constituting a cementitious material in the form of Silicon Dioxide (SiO_2), Iron Oxide (Fe_2O_3), and Aluminum Oxide (Al_2O_3). (Fallah & Nematzadeh, 2017). This leads to greater compactness within the concrete, thereby enhancing the bonding between the aggregate and cement.

Table 6 highlights the chemical properties, indicating high silicate content, low calcium and magnesium content, and minimal alkali content. The fine and coarse aggregate substitutions with steel slag possess a significant amount of cementitious material, contributing to enhanced strength during concreting. The lower calcium and magnesium content may impact volumetric stability.

The chemical composition analysis of steel slag, as shown in (Fallah & Nematzadeh, 2017). This leads to greater compactness within the concrete, thereby

Table 5 Physical properties of steel slag

Physical properties of steel slag	Coarse steel slag	Fine steel slag
Specific gravity	2.67	3.23
Water absorption	1.4%	1.45%
Loose bulk density	1510KN/m^3	1651.67KN/m^3

Table 6 Chemical properties of steel slag

Elements	Experimental Results (%)
Silicon Dioxide (SiO_2)	49.7
Aluminum Oxide (Al_2O_3)	13.01
Ferric Oxide (Fe_2O_3)	20.64
Calcium Oxide (CaO)	1.56
Magnesium Oxide (MgO)	1.02
Sodium Oxide (Na_2O)	< 0.01
Potassium Oxide (K_2O)	< 0.01
Manganese Oxide (MnO)	14.58
Phosphorus Oxide (P_2O_5)	0.05
Titanium Oxide (Ti_2O_3)	0.51
Water (H_2O)	0.42
(LOI)	< 0.01

enhancing the bonding between the aggregate and cement.

Table 6 highlights its potential as a valuable material for enhancing concrete properties. The high content of Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), and Ferric Oxide (Fe_2O_3) indicates a significant presence of cementitious compounds, which can contribute to the strength and durability of concrete when used as aggregate replacements. In addition, the low calcium and magnesium content, along with minimal alkali content, suggest a reduced risk of alkali–silica reactions in concrete mixes incorporating steel slag. Moreover, the presence of minor compounds such as Manganese Oxide (MnO), Phosphorus Oxide (P_2O_5), and Titanium Oxide (Ti_2O_3) further enriches the chemical composition, potentially enhancing the pozzolanic activity and overall performance of the concrete. The composition highlights the potential for steel slag to contribute to cementitious reactions in concrete, emphasizing its suitability as an aggregate replacement material.

The presence of higher SiO_2 content in steel slag aggregates significantly influences the mechanical properties and microstructure of concrete, particularly in enhancing the bond strength at the interface between aggregates and cement paste (Balapour et al., 2018; Givi et al., 2010; Nili et al., 2010; Zhuang & Chen, 2019). The presence of higher SiO2 content in steel slag aggregates improves the bond between the aggregate and cement acting as a supplementary material in concrete, filling the pores and voids between the aggregate particles (Fallah & Nematzadeh, 2017). This leads to greater compactness within the concrete, thereby enhancing the bonding between the aggregate and cement.

Table 7 Slump test results

% of Replacement	Slump for Coarse Aggregate (mm)	% of Replacement	Slump for Fine Aggregate (mm)
0	65	0	65
25	60	15	55
50	52	30	47
75	45	45	40
100	35	60	38

3.1.4 Properties of Concrete: An Investigation into Steel Slag Aggregate Replacement

I.Fresh Concrete Properties

The slump test results as Table 7 reveal that at 0% replacement, the concrete mix exhibited a true slump value of 65 mm. As the percentage of replacement increased, both for coarse and fine aggregates, the slump values decreased. This trend indicates that river sand is generally finer than steel slag. The water-absorbing property of steel slag in both fine and coarse aggregates is higher than that of river sand and crushed aggregate. Consequently, for a constant water–cement ratio of 0.49, steel slag absorbs more water, leaving less for mortar hydration. The increase in the percentage of aggregate replacement by steel slag correlates with decreased workability, as evidenced by the slump values in the table. Ren and Li (2023) support these findings, noting significant reductions in concrete slump when SSA fully replaces river sand or gravel. Sharba (2019) also observes a negative correlation between concrete slump and the ratio of replacement SS, emphasizing the need for careful mix adjustments when incorporating steel slag aggregates (Ren & Li, 2023; Sharba, 2019). Despite these variations, all mixes maintain a true slump, regardless of the replacement percentage.

II. Hardened Concrete Properties

i. Determination of Unit Weight

The dry unit weight of concrete in coarse and fine aggregate replacement was determined after 28 days of standard curing. The results are presented in Tables 8 and 9.

The unit weight values used in this research analysis were measured from the concrete cube samples after 28 days of standard curing. An increase in unit weight of up to 3.67% was observed when 50% by weight of the coarse aggregate was replaced by steel slag aggregate. A 4.16% increment was observed for 45% steel

Table 8 Dry unit weight of concrete in coarse replacement

% Replacement of coarse aggregate	Sample weight (Kg)	Average weight (Kg)	Volume of cube (m^3)	Dry unit weight of concrete (Kg/m^3)
0	8.6	8.52	8.71	8.629
25	8.9	8.73	8.92	8.883
50	9.0	8.94	8.85	8.946
75	8.4	8.39	8.53	8.459
100	8.63	8.51	8.25	8.46

Table 9 Dry unit weight of concrete in fine replacement

% Replacement of fine aggregate	Sample weight (Kg)	Average weight (Kg)	Volume of cube (m^3)	Dry unit weight of concrete (Kg/m^3)
0	8.653	8.524	8.71	8.629
15	8.94	8.866	8.917	8.907
30	8.708	9.058	9.077	8.947
45	8.964	8.749	9.251	8.988
60	8.86	8.893	9.022	8.925

slag aggregate replacement of fine aggregate. The finer particle size of steel slag resulted in a denser concrete matrix with lower porosity, attributed to the fact that the density of SSA is 10–50% higher than that of natural aggregate, as stated by Ren and Li (2023).

ii. Compressive Strength Test

Table 10 presents the compressive strength results for concrete mixes with varying percentages of coarse aggregate replacement at both 7 and 28 days.

The compressive strengths of concrete specimens were determined after 7 and 28 days of standard curing. The addition of steel slag aggregate showed an increment in concrete compressive strength compared to the control concrete, increasing with the percentage of steel slag aggregate up to 100%. The observed increment of compressive strength at 7 day test when 25, 50, 75, and 100% of the coarse aggregate was replaced by steel slag aggregate were 9.55, 30.30, 15.99, and 0.56%, respectively. Concrete containing 50% steel slag aggregate showed the maximum percentage increment. The percentage increment in compressive strength at 28 days from the control concrete cube at 25, 50, 75, and 100% coarse aggregate replaced by steel slag was 6.19%, 26.26, 9.51, and 6.24%, respectively, indicating a slightly higher increment at the early stage than at 28 day compressive strength. This result is also supported by Lai et al. (2021), which states that steel slag aggregate can enhance the compressive strength of ordinary concrete up to 50%. However, the highest dosage of steel slag aggregate is usually limited to 50% due to increased loss of working performance, and negative results may arise from poor workability and cracking caused by volume expansion (Lai et al., 2021).

Table 11 illustrates the compressive strength results for concrete mixes with varying percentages of fine aggregate replacement at both 7 and 28 days.

When the sand is replaced by steel slag, the compressive strength increases with an increasing percentage of steel slag aggregate up to 45%. The observed increment of compressive strength at 7 day test when 15%, 30%, and 45% of the fine aggregate were replaced by steel slag aggregate were 9.72, 12.19, and 5.31%, respectively. Concrete containing 30% steel slag aggregate showed the maximum percentage increment. The percentage increment in compressive strength at 28 days from the control concrete cube at 15, 30, and 45% fine aggregate replaced by steel slag was 7.70, 15.80, and 10.69%, respectively, showing comparable percentage increments in compressive strength at the early stage and at 28 days. These findings align with the research conducted by Lai et al. (2021), which asserts that steel slag aggregate can improve the compressive strength of ordinary concrete by up to 50%. Nevertheless, the common practice is to limit the maximum dosage of steel slag aggregate to 50% due to an associated increase in the loss of working performance. Negative outcomes are primarily attributed to issues such as poor workability and cracking induced by volume expansion.

iii. Flexural Strength

Concrete beams, measuring 150 × 150 × 750 mm, were meticulously prepared to assess the flexural strength of slag aggregate concrete. The results, summarized in Table 12 present the performance of beams with varying percentages of coarse aggregate replacement by steel slag.

The flexural strengths of reinforced concrete specimens were examined after 28 days of standard curing. The table indicates that incorporating steel slag aggregate led to an overall increase in flexural strength compared to the control beams. This increase was observed with an ascending percentage of steel slag aggregate replacement, reaching a peak at 75% and declining at 100% replacement. The

Table 10 Compressive strength of coarse aggregate replacement at 7 and 28 days

Compressive strength	Coarse aggregate in percentage (%)	7-Day compressive test results (Cubical)	28-Day compressive test results (Cubical)
C25/30	100	23.39	34.76
C25/30	75	25.63	36.92
C25/30	50	30.49	43.89
C25/30	25	27.14	38.07
C25/30	0	23.55	37.14

Table 11 Compressive strength of fine aggregate replacement at 7 days and 28 days

Compressive strength	Fine aggregate in percentage (%)	7-Day compressive test results (Cubical)	28-Day compressive test results (Cubical)
C25/30	100	23.39	34.76
C25/30	85	25.67	37.44
C25/30	70	26.25	40.26
C25/30	55	24.64	38.48
C25/30	40	22.62	33.09

Table 12 Flexure strength results for coarse aggregate replacement

% Replacement of coarse aggregate	Beam name	Ultimate load (KN)	Ultimate stress (MPa)	Deflection at ultimate load (mm)
0	CB-1	54.32	18.106	6.977
	CB-2	56.94	18.98	7.217
Average	CB	55.63	18.543	7.097
25	B25-1	55.98	18.66	7.587
	B25-2	57.2	19.062	6.326
Average	B25	56.59	18.8635	6.957
50	B50-1	62.03	22.00	7.347
	B50-2	63.8	22.74	9.325
Average	B50	62.92	22.37	8.356
75	B75-1	58.62	19.56	8.448
	B75-2	61.9	20.634	5.406
Average	B75	60.26	20.087	6.927
100	B100-1	51.18	17.060	11.642
	B100-2	56.5	18.834	7.88
Average	B100	53.84	17.94	9.761

enhanced strength is attributed to the favorable characteristics of steel slag aggregates, including their shape, size, and surface texture, fostering improved adhesion within the cement matrix. Table 13 provides further insights into these attributes.

The observed percentage increment in flexural strength at the 28 day test for 25, 50, and 75% coarse aggregate replacement by steel slag was 1.73, 13.1, and 8.22%, respectively. Notably, beams containing 50% steel slag aggregate exhibited the maximum percentage increment in flexural strength.

When the sand is replaced by steel slag, the flexural strength also increases with an increasing percentage of steel slag aggregate up to 45%. The percentage increment in flexural strength at 28 days from the control beam at

Table 13 Flexural strength of fine aggregate replacement

% Replacement of fine aggregate	Beam name	First crack load (KN)	Ultimate load (MPa)	Deflection at ultimate load (mm)
0	CB-1	54.32	18.106	6.977
	CB-2	56.94	18.98	7.217
Average	CB	55.63	18.543	7.097
15	B15-1	58.38	20.78	7.448
Average	B15	58.38	20.78	7.448
30	B30-1	65.12	21.707	7.878
	B30-2	64.8	21.6	8.679
Average	B30	64.96	21.654	8.279
45	B45-1	67.18	23.885	6.346
	B45-2	65.34	22.975	9.039
Average	B45	66.26	23.431	7.692
60	B60-1	52.105	17.36	8.368
	B60-2	54.28	18.09	10
Average	B60	53.193	17.62	9.184

15, 30, and 45% fine aggregate replaced by steel slag are 4.94, 16.77, and 19.04%, respectively.

This study significantly enhances the current understanding of flexural strength in steel slag aggregate concrete, corroborating previous research by demonstrating an increase in flexural strength with both coarse and fine aggregate replacement by steel slag. Our findings align with a study by Jagadisha, (2021), which reported a similar increase in flexural strength with a 50% replacement of coarse aggregate by steel slag (Jagadisha et al., 2021). Furthermore, our observation of increased flexural strength (up to 45% replacement of fine aggregate) is consistent with another study that found optimal flexural strength at a 33% replacement of steel slag (Rajendran et al., 2020). Notably, this study extends existing knowledge by showing that even higher replacement percentages can yield improved flexural strength, highlighting the potential of steel slag as a viable and beneficial alternative to traditional aggregates in concrete production for the construction of stronger and more durable structures. However, it is essential to interpret these findings within the specific experimental conditions and validate them through further studies.

3.2 Load–Displacement Curves

The evaluation of mechanical behaviors in simply supported RC beams involved the critical analysis of mid-span loading–displacement curves. Figs. 5 and 6 present these curves for various RC beams subjected to the same loading rates, considering both fine and coarse aggregate replacements. The observed behavior across

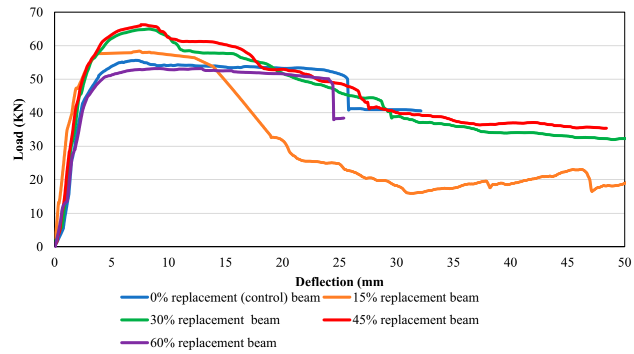

Fig. 5 Load–displacement curves of fine aggregate replacement

all beams exhibited similarities during each test under a center point concentrated load. Initial cracking at the concrete surface was a common occurrence, followed by the appearance of smaller flexural cracks in the positive moment region. Subsequent to bottom surface cracking, a significant increase in mid-span deflection occurred, and the steel reinforcement began to de-bond from the concrete as the load increased. The tests were terminated upon the yielding of the steel reinforcement, marked by a substantial decrease in load.

The loading–displacement curves revealed three main regions: the initial crack region, yielding region, and ultimate region. Initially linear, the loading–displacement curve gradually became nonlinear with increasing load due to a decrease in the RC beam's stiffness, attributed to the failure of tensile concrete. As the load continued to rise, the lower crack zone expanded, and the nonlinearity of the curve became more prominent. Upon the yielding of the bottom steel, the RC beam's stiffness decreased rapidly, resulting in a flatter loading–displacement curve. Further load increase led to the crushing of the top compressive concrete, indicating the RC beam's achievement of the ultimate state. The mid-span displacement

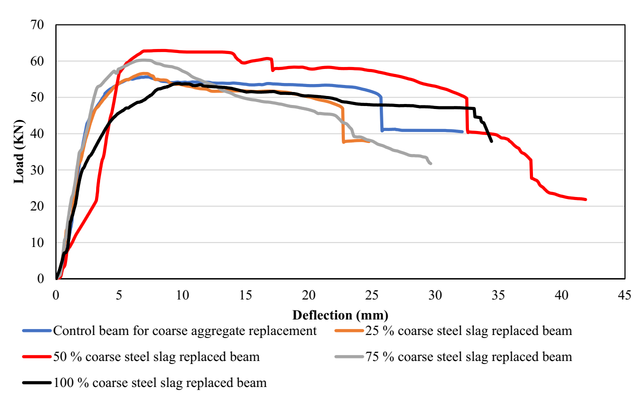

Fig. 6 Load–displacement curves of course aggregate replacement

increased rapidly, while the loading decreased slightly, ultimately resulting in the destruction of the RC beam when the bottom steel reinforcement snapped.

a. Control Beam for Fine and Coarse Aggregate Replacement

In Figs. 5 and 6, the control beam exhibited a maximum concentrated load of 55.63 KN at a 750 mm span, with a mid-span deflection of 7.097 mm. Beyond the ultimate load, the displacement increased without a load increment, causing the load–displacement curve to flatten. At the failure load of 49.93 KN, the maximum deflection reached 25.7 mm.

b. 25% Coarse Steel Slag Replaced Beam

The beam with 25% coarse steel slag replacement displayed a maximum concentrated load of 56.57 KN at a 750 mm span, with a mid-span deflection of 8.36 mm. Similar to the control beam, the load–displacement curve became flatter after reaching the ultimate load. The failure load was 49.01 KN, and the maximum deflection reached 21.29 mm.

c. 50% Coarse Steel Slag Replaced Beam

With 50% coarse steel slag replacement, the beam experienced a maximum concentrated load of 62.915 KN at a 750 mm span, accompanied by a mid-span deflection of 8.36 mm. The load–displacement curve exhibited a flatter profile after the ultimate load, reaching a failure load of 49.65 KN and a maximum deflection of 32.49 mm. Notably, this curve indicated improved ductility compared to other replacement percentages.

d. 75% Coarse Steel Slag Replaced Beam

The beam featuring 75% coarse steel slag replacement attained a maximum concentrated load of 60.26 KN at a 750 mm span, with a mid-span deflection of 6.93 mm. After reaching the ultimate load, the load–displacement curve gently decreased, leading to a failure load of 49.02 KN and a maximum deflection of 16.1 mm.

e. 100% Coarse Steel Slag Replaced Beam

For the beam with 100% coarse steel slag replacement, the maximum concentrated load was 53.84 KN at a 750 mm span, with a mid-span deflection of 9.76 mm. Similar to other replacement scenarios, the load–displacement curve became flatter after reaching the ultimate load. At the failure load of 49.02 KN, the maximum deflection reached 22.48 mm.

Comparative analysis of these curves of course replacement revealed that, during the initial loading, both reinforced steel and concrete were within their elastic stages, presenting a linear loading–displacement curve. As the load increased, the strain rate effects of concrete and steel became more pronounced, resulting in a nonlinear loading–displacement curve. Consequently, the yield loading, ultimate loading, yield displacement, and ultimate displacement increased distinctly. The variability in displacement for each replacement percentage was attributed to the chemical composition of the steel slag.

f. 15% Fine Steel Slag Replaced Beam

The beam with 15% fine steel slag replacement displayed a maximum concentrated load of 58.38 KN at a 750 mm span, with a mid-span deflection of 7.45 mm. After reaching the ultimate load, the load–displacement curve flattened, and the load decreased drastically. The failure load was 49.18 KN, and the maximum deflection reached 15.06 mm.

g. 30% Fine Steel Slag Replaced Beam

With 30% fine steel slag replacement, the beam experienced a maximum concentrated load of 64.96 KN at a 750 mm span, with a mid-span deflection of 8.28 mm. Similar to other replacement scenarios, the load–displacement curve gently decreased after reaching the ultimate load. The failure load was 49.01 KN, and the maximum deflection reached 22.48 mm.

h. 45% Fine Steel Slag Replaced Beam

In the case of the 45% fine steel slag replaced beam, a maximum concentrated load of 66.26 KN was applied over a 750 mm span. The mid-span deflection at the maximum load was 7.69 mm. After reaching the ultimate load, the displacement continued to increase without a corresponding load increment, indicating a gradual decrease in the load–displacement curve. Upon reaching the failure load of 49.01 KN, the maximum deflection was recorded at 24.44 mm.

i. 60% Fine Steel Slag Replaced Beam

For the 60% fine steel slag replaced beam, the maximum concentrated load applied at a 750 mm span was 53.19 KN. At the maximum load, the mid-span deflection was 9.18 mm. Following the ultimate load, the displacement continued to increase without a load increment, resulting in a flatter load–displacement curve. Upon reaching the failure load of 50.03 KN, the maximum deflection was noted at 24.41 mm.

Upon comparison of these five curves of fine replacement, it is concluded that at the beginning of the load, both reinforced steel and concrete were within their elastic stages, and the loading–displacement curve appeared linear. As the load increased, the strain rate effects of the concrete and steel became more pronounced, leading to a nonlinear loading–displacement curve. Consequently, the yield loading, ultimate loading, yield displacement, and ultimate displacement exhibited distinct increases.

The load–displacement curves obtained from the evaluation of simply supported reinforced concrete beams with varying degrees of steel slag aggregate replacement reveal valuable insights into the mechanical behavior of these structures. The initial cracking, flexural cracks, and subsequent stages leading to failure are well-documented across all beams, highlighting commonalities in their response to mid-span loading. The comparative analysis of course and fine steel slag replacement percentages demonstrates distinct variations in yield loading, ultimate loading, yield displacement, and ultimate displacement, attributed to the chemical composition of the steel slag. Notably, beams with 50% coarse steel slag replacement exhibit improved ductility, indicating a potential for enhanced performance. However, the fine steel slag replacement curves exhibit unique characteristics, emphasizing the importance of replacement percentage in influencing concrete behavior.

4 Conclusion and Recommendation

4.1 Conclusions

In conclusion, the study revealed that the compressive strength of normal concrete is marginally lower than that of concrete replaced with steel slag. Similarly, the flexural strength of beams without steel slag showed a slight decrease compared to beams containing steel slag aggregate. The maximum increase in compressive strength for fine aggregate replacement was approximately 15.5% after 7 days of curing and 15.8% after 28 days. Flexural strength exhibited an ascending trend with an increase in steel slag percentage, reaching a peak increment of 19.04% after 28 days for C25/30 grade reinforced concrete beams. Optimal replacement percentages for compressive and flexural strength were identified as 30 and 45%, respectively, for fine aggregate substitution with steel slag. Displacement variability was found to be contingent on the chemical composition of the steel slag, with beams featuring fine aggregate replacement exhibiting higher displacement than control beams at the ultimate load. Furthermore, the presence of higher SiO_2 content in steel slag aggregates contributed to improved bond strength at the interface, fostering a favorable aggregate–cement paste interlock.

4.2 Recommendations

The study suggests conducting an extensive field investigation on concrete structures incorporating steel slag aggregates, focusing on durability, elastic modulus, cement quantity, and mechanical properties. In addition, further exploration into the resistance of concrete with steel slag aggregates against various environmental factors and corrosive conditions is advised. Assessing its behavior under fire and enhancing its fire resistance capacity would contribute to a more comprehensive understanding, ultimately benefiting the construction industry and promoting the broader use of steel slag in concrete applications for improved properties and cost-effective solutions.

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Tadese Birlie Mekonen Lecturer, Department of Civil Engineering, College of Engineering and Technology, Bule Hora University, P.O. Box 144, Bulie Hora, Ethiopia.

Temesgen Ejigu Alene Lecturer, Faculty of Civil and Water Resources Engineering, Bahir Dar Institute of Technology, Bahir Dar University, P.O. Box 26, Bahir Dar, Ethiopia.

Yared Aklilu Alem Lecturer, Faculty of Civil and Water Resources Engineering, Bahir Dar Institute of Technology, Bahir Dar University, P.O. Box 26, Bahir Dar, Ethiopia.

Wallelign Mulugeta Nebiyu Lecturer, Faculty of Civil and Water Resources Engineering, Bahir Dar Institute of Technology, Bahir Dar University, P.O. Box 26, Bahir Dar, Ethiopia.