Jurnal
Teknologi

Full Paper

STEEL SLAG'S PHYSICAL AND CHEMICAL IMPACT ON CONCRETE WORKABILITY AND STRENGTH AS FINE AGGREGATE

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Article history
Received
20 May 2023
Received in revised form
7 August 2023
Accepted
14 August 2023
Published Online
20 December 2023

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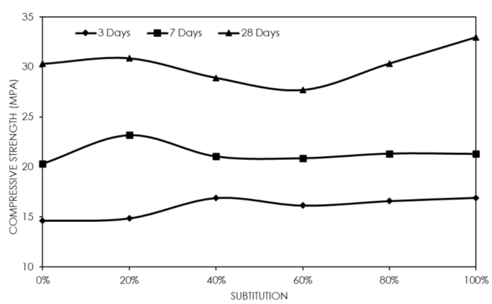
Graphical abstract



Abstract

This research aims to uncover how the properties of steel slag affect concrete strength and workability. To gain insight into the behavior of concrete over time in different circumstances, we assessed its performance with varying levels of steel slag included as fine aggregate. This examination covered periods spanning from formation to 3, 7 and 28 days for a comprehensive analysis. Concrete mixes were prepared by substituting fine aggregates with varying proportions of steel slag. The use of advanced techniques such as Scanning Electron Microscopy (SEM)and Energy Dispersive X-ray Spectroscopy (EDX) revealed that an abundant amount of calcium (Ca), and oxygen (O), exist in the composition of steel slags. According to the findings, incorporating more steel slag into concrete had an adverse impact on its workability. This manifested as a decrease in the material's flowability. The mixture that produced the optimal results had a slump value of 76 mm and a compressive strength of 30.88 MPa when 20% of the fine aggregate was replaced with steel slag. This mixture also displayed a more fluid consistency, facilitating its application.

Keywords: Compressive strength, concrete, fine aggregate, steel slag, workability

1.0 INTRODUCTION

Cilegon, located in the province of Banten, is renowned as the "kota baja" due to its numerous prominent steel-producing industries. Notable companies such as PT Krakatau Posco and PT Krakatau Steel contribute to Cilegon's reputation as a major hub for steel production. Steel slag can be used for infrastructure work. If it is not utilized, this waste is included in the category of toxic and hazardous waste. The utilization of steel slag remains relatively limited in certain Southeast Asian countries, such as Vietnam and Thailand, particularly in underdeveloped regions, with adoption rates below 10%. SS in large quantities can only be piled up and buried as waste, which causes soil pollution [1]. Concrete incorporating steel-slag aggregate has the potential to exhibit greater density compared to conventional cement-based concrete. This characteristic contributes to improved mechanical strength performance [2]–[7]. Poulikakos *et al.* [8] suggested the use of steel slag in road construction. Compared to typical cement-based concrete, concrete made with steel-slag aggregate has the potential to have a higher density. This characteristic contributes to improved mechanical strength performance [9], [10].

Bian *et al.* [11] noted that the compressive strength of FSSAC (Full-Steel Slag Aggregate Concrete) declines as the sand ratio, fine steel slag content, or coarse steel slag content increases. However, an improvement in the compressive strength of FSSAC can be achieved by reducing the water-cement ratio. Additionally, the compressive strength of FSSAC follows a pattern of initially decreasing and then increasing as the particle size of the steel slag used as a replacement for fine or coarse aggregate increases. The compressive strength decreases significantly when steel slag replaces more than 40% of the aggregates. The study adhered to the guidelines of IS 10262 for water-cement mix design, targeting strengths of 30 MPa and 40 MPa. Concrete cubes of 150x150x150 mm were tested at various ages ranging from 3 to 28 days. The results demonstrate that for a target strength of 30 MPa, a 40% substitution of steel slag results in a compressive strength of 40.8 MPa. Additionally, for a target strength of 40 MPa, a 40% substitution of steel slag accomplished the greatest compressive strength of 46.3 MPa [12].

According to a study by Bai *et al*. [13] adding 25% slag and 1.5% steel fiber to 40% steel slag resulted in a substantial improvement in compressive strength during both the 7-day and 28-day curing periods. The improvements observed were 48.77% and 17.89% respectively, indicating the positive effect of this combination on concrete strength. Properly compacted concrete mixtures exhibited reduced water absorption after 56 days of curing, indicating improved quality and reduced permeability. Cylinder tests conducted in the study subjected Steel Slag Concrete (SSC) to monotonic compression and impact loading, incorporating various volumes of steel slag (0%, 10%, 20%, 30%, and 40%) which replaced the fine aggregate in the composition. The findings demonstrated that adding steel slag as a fine aggregate improved the concrete's static and dynamic compressive strength. Like the pattern seen under monotonic compression, under impact loading, the compressive strength of SSC initially increased and then dropped with larger steel slag content. The study suggested that a steel slag percentage of 20% was the ideal range for replacing fine aggregate in SSC exposed to monotonic compression and impact. [14].

The purpose of this study is to determine how the physical and chemical characteristics of steel slag, used to replace fine aggregate, affect the workability and strength of concrete. Cylindrical specimens with dimensions of 150mm x 300mm were prepared, and various levels of substitution ranging from 0% to 100% by volume were employed. The main purpose of this study was to assess the viability of using steel slag as a substitute material in concrete mixing, to achieve the ultimate objective of minimizing steel waste generated during steel casting processes. The physical and chemical characteristics of steel slag were investigated, and their impact on the workability and strength of concrete was assessed.

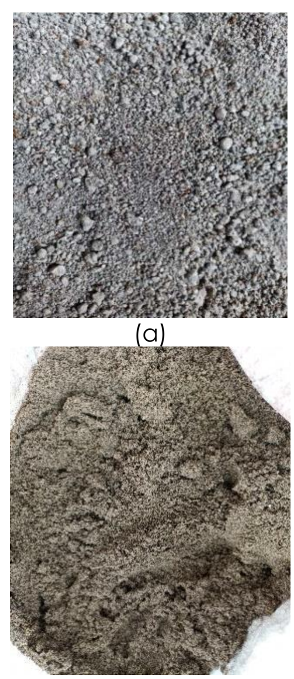
The growing accumulation of steel waste presents a notable environmental concern, particularly in terms of soil contamination. To address this issue, this study focused on the integration of steel slag as a substitute for fine aggregate, to provide valuable insights into the realm of civil engineering. The research findings contribute to the existing body of knowledge on the reduction and efficient utilization of steel slag, offering potential solutions for sustainable waste management within the construction industry.

2.0 METHODOLOGY

This study's steel slag was acquired from PT. Krakatau Posco. The cement used is Portland cement type 1 or OPC (Ordinary Portland Cement), coarse and fine aggregates used respectively came from Cilegon, Banten-Indonesia. The types of inspections carried out are listed in Table 1. Sand, gravel, and steel slag used in this study are shown in Figure 1.

Table 1 Aggregate testing standards

No.	Standard Inspection Type	Standard
1	Moisture content	ASTM C566-97, SNI 1971-2011
2	Sludge content	ASTM C123, SNI 4142-1996
3	Grain size distribution	ASTM C136, SNI 1968-1990
4	Density	ASTM C29, SNI 1973-2008
5	Specific gravity and water absorption	ASTM C127, SNI 1969-2008, SNI 1970-2008
6	Los Angeles Abrasion Test	AASHTO T96-02, SNI 2417-2008



(a)

(b)

(c)

Figure 1 Raw material: (a) steel slag; (b) sand; (c) gravel

The SEM-EDX test was used in this work to investigate the properties of steel slag, looking at its chemical composition and particle surface shape. The physical attributes of steel slag, sand, and gravel materials were assessed through tests including water content, silt content, grain size analysis, specific gravity, density, grain fineness modulus, and LAA (Los Angeles Abrasion). The mechanical properties of steel slag concrete were assessed specifically through compressive strength testing. A total of 54 samples were used in this study, all of which were cylinders with 15 cm in diameter and 30 cm in height. Three specimens were constructed for each variation of the compressive strength test, with immersion times of 3 days, 7 days, and 28 days. The concrete mixture design followed the SNI 7656-2012 method [15] which is based on the normal concrete design with a target strength of 30 MPa. The study included variations in the substitution of steel slag for sand at 0%, 20%, 40%, 60%, 80%, and 100%. The detailed composition of the concrete mixture can be found in Table 2.

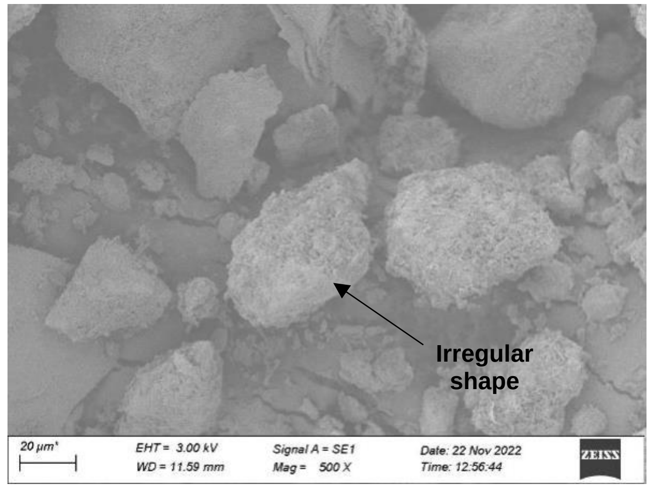
Table 2 Composition of the mixture

Material	0%	20%	40%	60%	80%	100%
Water (kg)	3.77	3.77	3.77	3.77	3.77	3.772
Cement (kg)	7.70	7.70	7.70	7.70	7.70	7.70
Sand (kg)	11.02	8.82	6.61	4.41	2.20	-
Gravel (kg)	20.01	20.01	20.01	20.01	20.01	20.01
Steel slag (kg)	-	3.32	6.64	9.96	13.28	16.06

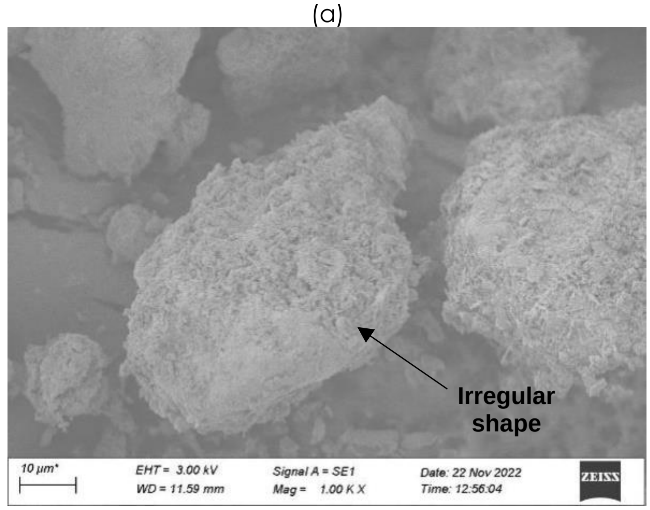
3.0 RESULTS AND DISCUSSION

3.1 Steel Slag Characteristics

The SEM observations at 500X, 1000X, and 5000X magnifications showed the irregular surface morphology in the steel slag particles (Figure 2), while the EDX test findings showed that the chemical composition in the steel slag was predominantly composed of O and Ca elements (Figure 3).



(a)



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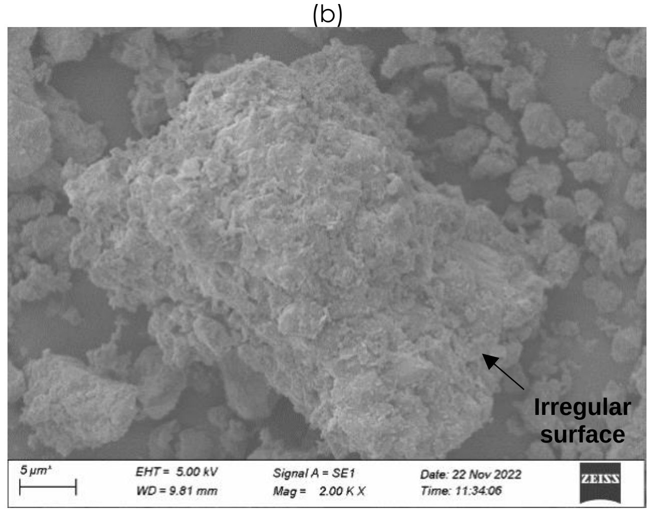

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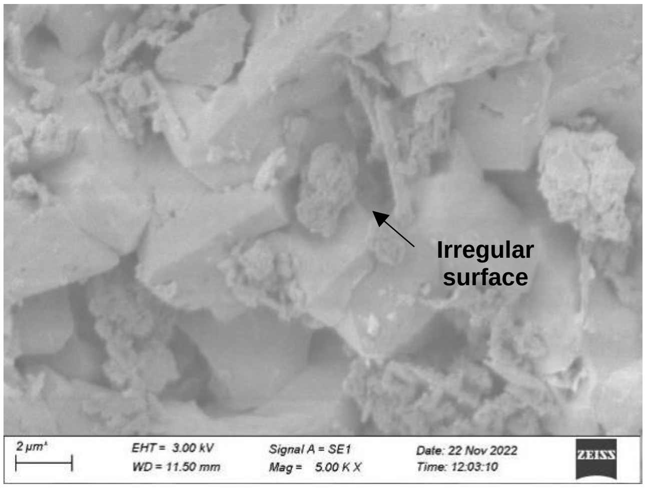

(d)

Figure 2 SEM result of steel slag: (a) Mag: 500X ; (b) Mag: 1000X; (c) Mag: 2000X ; (d) Mag: 5000X

Figure 2 shows that using steel slag as a fine aggregate substitute for concrete can have several effects:

1. Interlocking: The presence of steel slag particles that have irregular surfaces can cause interlocking or locking between concrete particles and steel slag particles. This has the potential to enhance the bond strength between the fine aggregate material and the concrete matrix, thereby augmenting the overall strength of the concrete.

2. Pore clogging: Steel slag particles that have an irregular surface can fill the pores in the concrete matrix more effectively than fine aggregates that have a smoother surface. This can enhance concrete's density and resistance to the infiltration of water and other substances while decreasing the number of pores in the concrete.

3. Filler effect: Irregular steel slag particles present in the concrete mixture can serve as filler material, contributing to the composition and structure of the concrete. The particles can fill the small gaps between the coarse and fine aggregates, increasing the density of the mix and contributing to the dimensional stability of the concrete.

4. Effect of workability: Because steel slag has an irregular surface, this can affect the workability or flow tendency of the concrete. A rough surface can increase the stickiness of the concrete mix.

Figure 3. shows how the significant amounts of calcium (Ca) and oxygen (O) in steel slag can affect the workability and strength of concrete. These components significantly influence the properties of the concrete, including its strength and workability.

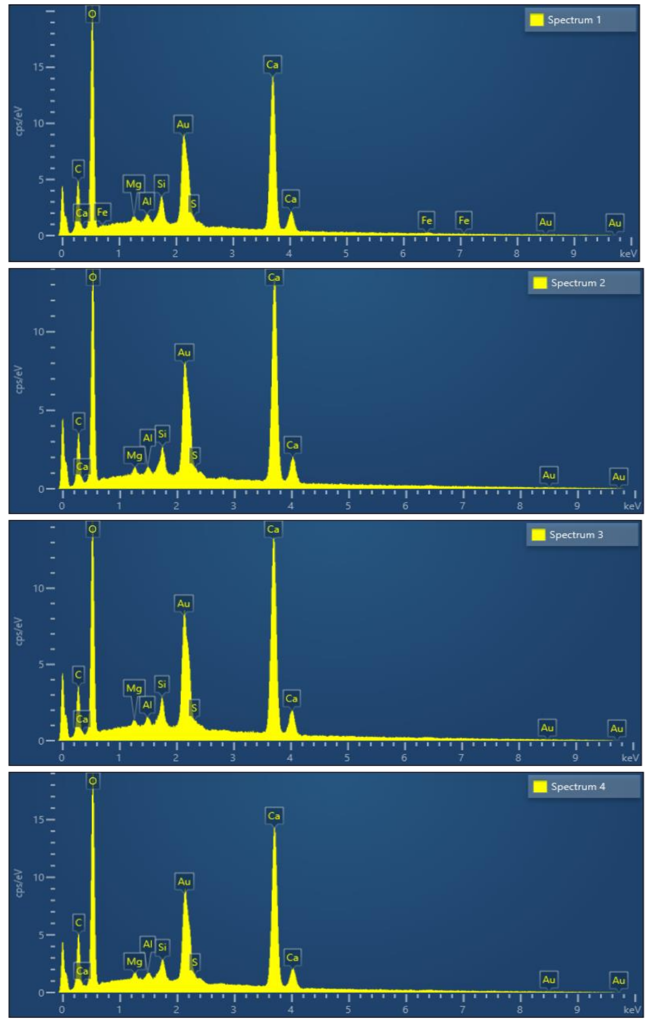

Figure 3 Results of EDX analysis of steel slag

1. Content of Calcium (Ca):
The calcium content in steel slag can contribute to the pozzolanic reaction in concrete. A pozzolanic reaction occurs when a pozzolanic material, such as steel slag, reacts with calcium hydroxide ($Ca(OH)_2$) formed during the hydration process of cement. Concrete strength may be increased by the binder compounds produced by this process. Concrete can be made stronger by adding steel slag with a high calcium concentration. The pozzolanic reaction that occurs helps in forming binder compounds that fill the pore spaces and increase the bond between the particles of aggregate and the cement paste.

2. Oxygen content (O):
The oxygen content in steel slag can affect the concrete hydration process. Oxygen can interact with elements in concrete, such as calcium and silicon, during cement hydration, forming hydration compounds that are important for concrete hardening and strength. Concrete's ability to be worked can also be impacted by the amount of oxygen in steel slag. Changes in the concentration of oxygen in the

concrete mix can affect the viscosity and flow properties of the concrete. The flow characteristics of the concrete can change if steel slag with a varied oxygen content is added.

3.2 Physical Material

Characteristics testing produces data used in mixing concrete. The results of these tests are presented in Table 3, Table 4, and Table 5.

Table 3 Results of fine aggregate characteristics test

No	Type of Inspection	Result	Standard Specifications
1	Sludge content (%)	7,6	< 5
2	Specific gravity (gr/cm3)		
a	Apparent Specific Gravity	2,49	1,60 – 3,20
b	Bulk Specific Gravity on Dry	2,26	1,60 – 3,20
c	Bulk Specific Gravity on SSD	2,35	1,60 – 3,20
d	Absorption (%)	3,81	< 2
3	Water content (%)	15,43	< 5
4	Fineness modulus of grains	2,175	1,5 – 3,8

Table 4 Results of coarse aggregate characteristics test

No	Type of Inspection	Result	Standard Specifications
1	Sludge content (%)	2.27	< 2
2	Specific gravity (gr/cm3)		
a	Apparent Specific Gravity	2.87	1.60 – 3.20
b	Bulk Specific Gravity on Dry	2.73	1.60 – 3.20
c	Bulk Specific Gravity on SSD	2.78	1.60 – 3.20
d	Absorption (%)	3.81	< 2
3	Water content (%)	2.74	< 3
4	Fineness modulus of grains	6.473	5.0 – 8.0
5	Abrasion (%)	21.96	< 40
6	Density (kg/m3)	1531	1400 - 1900

Table 5 Results of steel slag characteristics test

No	Type of Inspection	Result	Standard Specifications
1	Sludge content (%)	6,4	< 5
2	Specific gravity (gr/cm3)		
a	Apparent Specific Gravity	3,95	1,60 – 3,20
b	Bulk Specific Gravity on Dry	3,32	1,60 – 3,20
c	Bulk Specific Gravity on SSD	3,48	1,60 – 3,20
d	Absorption (%)	4,75	< 2
3	Water content (%)	2	< 5
4	Fineness modulus of grains	3,186	1,5 – 3,8

According to the test results, the amount of mud content contained in the coarse aggregate, fine aggregate, and steel slag exceed the maximum limit set by SNI, so washing must be carried out before mixing so that the sludge in the aggregate can be reduced. After washing the aggregate, the aggregate is dried to get the appropriate moisture content.

3.3 Slump Test

The workability of fresh concrete, which indicates its ability to flow and be molded, was assessed using the slump test, and the corresponding results are depicted in Figure 5. As per the research design, the targeted slump range was set between 75 mm and 100 mm. The findings revealed that as the value of steel slag substitution for fine aggregate increased, the slump value decreased. The high water absorption capacity of steel slag is responsible for this decrease in slump value.

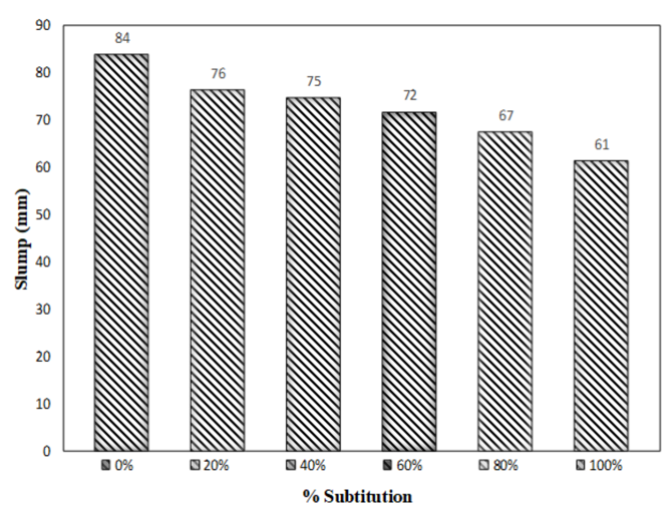

Figure 4 Slump value of steel slag concrete

3.4 Density

Concrete volume weight can also affect the compressive strength of concrete. Normal concrete has a volume weight of less than 2500 kg/m^3 [16]. As shown in Figure 5, steel slag concrete with acceptable aggregate substitutions of variations of 80% and 100% is not included in normal concrete. Table 6 displays the unit weight of concrete.

Table 6 Concrete density test results

Variation	Density (kg/m^3)
0%	2297
20%	2312
40%	2426
60%	2454
80%	2570
100%	2586

3.5 Compressive Strength Test

Figure 6 presents a graph of the relationship between compressive strength values and steel slag substitution variations.

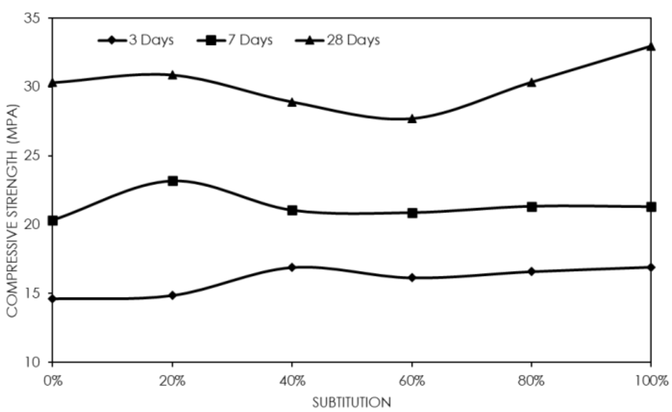

Figure 6 Graph of compressive strength relationship with steel slag concrete variations

Normal concrete has a compressive strength of 14.63 MPa after three days, whereas fine steel slag concrete has compressive strengths of 14.87 MPa, 16.90 MPa, 16.15 MPa, 16.60 MPa, and 16.92 MPa, respectively. After three days of curing, the variant of fine steel slag concrete with 100% substitution reaches its highest compressive strength. After a 7-day curing period, the compressive strength of normal concrete reaches 20.32 MPa, while fine steel slag concrete with substitutes of 20%, 40%, 60%, 80%, and 100% has compressive strengths of 23.18 MPa, 21.06 MPa, 20.88 MPa, 21.34 MPa, and 21.31 MPa, respectively. After 7 days of curing, the variation of fine steel slag concrete with a 20% substitution shows the highest compressive strength. Due to the tricalcium silicate and dicalcium silicate found in steel slag, the compressive strength has increased. When compared to the control mixture, compressive strength is significantly increased when up to 30% of the sand is replaced with steel slag [17].

The compressive strength of normal concrete after 28 days of aging is recorded as 30.32 MPa. In comparison, the compressive strength of fine steel slag concrete with a 20% substitution reaches 30.88 MPa, indicating a slight increase. However, as the substitution increases to 40% and 60%, the compressive strength decreases to 28.92 MPa and 27.70 MPa, respectively. Compressive strength increased at 80% variation with a compressive strength value of 30.35 MPa, and the maximum compressive strength was found at 100% variation with a compressive strength value of 32.99 MPa. The compressive strength of the concrete, aged 3 days and 7 days in all variations, reaches the compressive design strength. This is because the bond between cement paste and steel slag is more substantial than sand, and the high content of iron oxide in steel slag contributes to the development of initial strength [18]. The decrease was caused by a synergistic effect of differences in the fineness modulus of the sand used and steel [19].

The optimum percentage of steel slag content in the concrete mix is determined based on achieving the highest compressive strength among the tested variants while meeting other requirements such as slump value and weight unit. Compared to conventional concrete, steel slag concrete that contains the optimal amount of steel slag demonstrates improved compressive performance [20]. Up to a 30% sand usage ratio, steel slag concrete's compressive strength increases. [21]. The study determined that the ideal proportion of compressive strength in the concrete mixture was achieved by using steel slag concrete with a 20% substitution of fine aggregate. This particular mixture demonstrated the highest compressive strength while meeting additional criteria such as slump value and unit weight. Comparing it to normal concrete, it showed a 1.85% improvement in compressive strength. Conversely, the highest percentage of compressive strength was found in steel slag concrete that had 100% of the fine aggregate replaced; this concrete had an 8.8% higher compressive strength than regular concrete.

4.0 CONCLUSION

This study concludes that the SEM-EDX examination demonstrates that steel slag contains considerable amounts of calcium (Ca) and oxygen (O). The data show that as the quantity of steel slag in the concrete increases, the workability decreases, indicating decreased flowability. Slump ranges from 84 mm to 61 mm, suggesting that the addition of steel slag as a substitute for fine aggregate reduces the workability of concrete. With a 20% increase in steel slag variation, the 0.438 cement water factor showed the optimum compressive strength value of 30.88 MPa with a slump value of 76 mm, which has a more fluid consistency and is easier to apply. This result indicates that steel slag can be effectively used as a substitute for fine aggregate in concrete, provided proper mixing ratios and designs are implemented.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Acknowledgement

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