

The Effect of Utilizing Steel Slag as A Partial Replacement for Cement and Aggregate On the Mechanical Properties of Concrete

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Abstract: This research evaluated the mechanical properties of concrete utilizing steel slag (SS), an industrial by-product, as a partial replacement for cement, sand, and gravel. A water-cement ratio of 0.45 was used to produce concrete mixtures with varying replacement levels of 0-20% for cement, 0-100% for sand, and 0-100% for gravel. The workability of fresh concrete was measured, while compressive strength was measured at 28, 56, 90, and 180 days, and flexural and splitting tensile strengths were recorded at 28 days. The results showed that the angularity, rough texture, and increased water absorption of steel slag decreased workability. The use of steel slag as a replacement for cement resulted in decreased compressive, splitting tensile, and flexural strengths, with optimal performance noted at a 20% replacement level. However, a 25% sand replacement increased compressive, splitting tensile, and flexural strengths, whereas higher percentages reduced performance. The optimal gravel replacement was 50%, which surpassed the control mix in both compressive and flexural strength. Durability results showed that 10% cement replacement lowered early strength but improved with curing time, remaining lower than the control. Early-age strength and long-term performance were equivalent to conventional concrete with 25% sand replacement. The mixture with 25% gravel replacement exhibited better long-term compressive strength relative to the control mixture. Steel slag is more effective as a partial aggregate replacement than as a cement replacement. Concrete strength and durability are enhanced with 25% sand replacement and 50% gravel replacement, facilitating sustainable concrete production.

Keywords: *Steel Slag; Concrete; Cement Replacement; Aggregate Replacement; Mechanical Properties.*

1. Introduction

Concrete is a fundamental material often used in construction. Many materials have been used in concrete to enhance its properties and strength. The utilization of environmentally harmful materials has emerged as a worldwide concern. Further research is being conducted to explore ways to invest in these areas so that they don't accumulate in nature. Such materials can be used instead of cement, fine aggregate, and coarse aggregate for building projects because they are both durable and helpful. In other words, making concrete, especially Portland cement, has a major effect on the environment, even though it is used a lot. It produces up to 8% of all CO₂ emissions in the world and uses up natural materials like sand and gravel [1]. In response, researchers and engineers are using more and more environmentally friendly options, such as mixing industrial waste materials into concrete.

Steel slag (SS) is a substantial industrial byproduct generated during the steel production process, produced by the removal of undesirable components from molten steel. The efficient utilization of steel slag can reduce environmental pollution while offering economic benefits to steel manufacturers. The primary chemical constituents of steel slag include CaO, SiO₂, Fe₂O₃, MgO, and Al₂O₃, with CaO, SiO₂, and Al₂O₃ being the active components; an increased concentration of these enhances the

reactivity of steel slag [2]. Steel slag shows clear pozzolanic activity attributed to the presence of reactive silica and free lime. This composition improves mechanical interlock and enhances the interfacial transition zone because of its angular surface texture, which subsequently contributes to the performance of concrete containing Slag [3].

It has been successfully employed to use instead of cement, sand, and gravel, with studies demonstrating improvements in compressive, tensile, and flexural strengths, as well as enhanced durability.

2. Literature review

2.1 Partially replacing cement with steel slag

Numerous studies have demonstrated that utilizing steel slag as a partial replacement for cement can yield equivalent or enhanced strength properties. For instance, Abdalkader [4] observed that replacing 10% of cement with steel slag resulted in strength gains of approximately 2.5%, 7%, and 13% in mortar specimens at curing ages of 28, 56, and 90 days, respectively. Incorporating a greater proportion of steel slag may lead to a lowering of concrete's strength; however, utilizing finer steel slag and glassier slag can mitigate this reduction by enhancing pozzolanic activity. Chen [5] demonstrated that replacing steel slag by 10-30% can do so without compromising strength loss. The study showed that combining steel slag with GBFS up to 50% can achieve strength comparable to or greater than that of the control mix. Roslan [6] showed that replacing 20% of cement with steel slag enhances late-age strength relative to plain cement. Replacing cement with steel slag at a ratio of 10-30% can enhance strength and improve long-term durability.

2.2 Partially replacing fine aggregate with steel slag

Numerous studies have explored the feasibility of utilizing steel slag as a replacement material for fine aggregate. Research indicated that a low percentage of steel slag as sand may enhance the strengths (mechanical properties), while a larger amount can affect durability and workability. Kothai and Malathy [7] found that using 30% steel slag as fine aggregate improved the strength of 20M concrete. But using more than 30% made the concrete lose strength. Similarly, Guo [8] indicated that replacing up to 40% of fine aggregate with steel slag enhanced strength when used 20%; however, beyond this proportion resulted in a decline in strength. The higher density, rough surface, and ability to fill small gaps of steel slag helped improve strength by creating a stronger bond between the paste and aggregate in both studies. Biskri [9] found that steel slag as a fine aggregate enhanced both strength and bonding due to its rough surface in high-performance concrete. The optimal percentage of steel slag as fine aggregate was about 15-30%; steel slag stiffens the mix and accelerates hydration without excessive water demand. Replacing 100% of the steel slag with sand resulted in good strength; however, using a higher percentage of sand generally negatively affects workability.

2.3 Partially replacing coarse aggregate with steel slag

Many studies have found that reporting natural aggregate with a higher steel slag percentage improves concrete strength (mechanical properties). For example, Awoyera [10] found that both the ability to withstand pushing (compressive strength) and pulling (tensile strength) improved as more steel slag was used and as the concrete aged, even when steel slag completely replaced granite aggregate. Tran [11] discovered that replacing steel slag with basalt coarse aggregate enhanced compressive strength by 5-17% relative to the strength recorded after 28 days. Researchers attributed the strength gain to internal curing. Steel slag is denser and more porous, which absorbs water and releases it slowly to improve hydration. Also, steel slag's rough, angular shape improves its bond with cement paste. Chinnaraju [12] determined that the ideal replacement of gravel with steel slag was 60%. This led to increased strength, while any increase beyond this amount led to decreased strength. Researchers generally agree that the replacement of 50–60% of coarse aggregate with steel slag enhances strength (mechanical characteristics), but greater proportions may diminish strength due to increased porosity.

Moreover, replacing both fine and coarse aggregates with steel slag has been shown to increase concrete density and mechanical strength [13]. Steel slag as coarse aggregate improves concrete density and strength, with ideal replacement levels at 50%-60%.

3. Materials

3.1 Cement

The ordinary Portland cement employed in the design of the normal concrete batches was obtained from the Kar company. Its physical and chemical characteristics were examined and validated according to the requirements of ASTM C150 [14] specifications. Tables 1 and 2 include full information.

Table 1: Physical Characteristics of cement

Tests	Result	ASTM C150-10
Initial setting time	160 mins.	At least 45 minutes.
Final setting time	245 mins.	Not exceeding 600 min.
Compressive strength at 7 days	20.67	14.7 MPa, a lower limit
Compressive strength at 28 days	29.53	22.5 MPa, a lower limit
Specific gravity	3.15	
Density	1400 kg/m ³	

Table 2: Cement chemical analysis was conducted at the Directorate of Erbil Construction Laboratory.

Chemical tests	Results %	Specification
Lost in ignition	2.70	4% Max.
Insoluble material	0.98	1.5 Max.
Al ₂ O ₃	4.90	
SiO ₂	19.82	
CaO	63.02	
Fe ₂ O ₃	3.51	
MgO	2.69	5% Max.
SO ₃	2.38	28% Max.

3.2 Steel slag (SS) as an SCM (Supplementary Cementitious Materials)

The slag is ground by a crushing rock crusher and sieved to pass through a No. 200 sieve (75 μ m) as shown in Fig. 1. Its physical and chemical characteristics were examined and validated according to the requirements of ASTM C150 specifications. As shown in Tables 3 and 4. The prepared steel slag had a Blaine fineness value of **250 m²/kg** and a specific gravity of **3.30**. It was used with different replacement percentages (**10%,15%, and 20%**) by weight of cement.



Figure 1: (a) Steel Slag before crushing, (b) Steel Slag after crushing

Table 3: Steel slag chemical analysis was conducted at the Directorate of Erbil Construction Laboratory.

Oxides composition	Content Wt. %
CaO	31.24
SiO ₂	25.06
Fe ₂ O ₃	33.79
Al ₂ O ₃	2.33
MgO	1.22
P ₂ O ₅	0.5
Mn ₂ O ₃	2.5
SO ₃	0.91
TiO ₂	0.36
Na ₂ O +K ₂ O	0.15

Table 4: Physical Properties of the steel slag as cement

Requirement	Pozzolan	
	Class N, ASTM C618 [15]	Steel Slag
Physical requirements		
Amount retained on 45µm sieve	Max,34%	25%
Strength activity index, at 7 days, percent of control	Min,75%	84%
Strength activity index, at 7 days, percent of control	Min,75%	94%
Properties		
Specific gravity	3.30	
Blaine fineness value	250 m ² /kg	

3.3 Sand (fine aggregate)

Natural sand that was screened using a 4.75 mm sieve was utilized, as shown in Figure 2(b). This experimental work utilized sand sourced locally from Aski-Kalak. Fine aggregate had a 4.75-mm particle size. Figure 3 illustrates the fine aggregate grading curve, and Table 6 demonstrates that the tests were within ASTM C33's upper and lower limits [16]. The fine aggregate's specific gravity was 2.73, bulk density of 1780-1870 kg/m³, and water absorption capacity of 1.88%, as shown in Table 5.

3.4 Gravel (Coarse aggregate)

The coarse aggregate used in this investigation was rounded river gravel from the locality, with a maximum size of 19.5 mm (D max = 19.5 mm). The results of the sieve analysis, presented in Figure

4, conformed to the limits established by ASTM C33 [16] (Table 7). The gravel exhibited a specific gravity of 2.71, a bulk density ranging from 1635 to 1775 kg/m³, and water absorption (0.5%). Table 5 provides a summary of these properties.

3.5 Steel slag as Sand (fine aggregate)

The steel slag was crushed and screened to get it to the desired size so that it could be mixed as the natural fine aggregate grade of 4.75 mm, as presented in Figure 2(c). The grading curve for the fine aggregate made from steel slag is shown in Figure 3 and Table 6. ASTM C128 [17] was used to determine the steel slag's physical properties. Steel slag exhibits a greater specific gravity and a more angular shape compared to river sand. These things change the density and strength of the concrete mix. Table 5 gives a summary of the physical properties.

3.6 Steel slag as Gravel (Coarse aggregate)

Steel slag with a maximal particulate size of 19.5 mm was produced as a replacement for river coarse aggregate, as illustrated in Figure 2(a). After drying, the slag was mechanically crushed to minimize particle size. The necessary gradation was achieved by sieving after crushing. The aggregate was graded to mirror the natural river aggregate's particle size distribution for equivalent mix design and application performance. Figure 4 and Table 7 exhibit steel slag gradation as a gravel replacement. Specific gravity, loose bulk density, compacted bulk density, and water absorption are determined according to ASTM C128 [17]. Steel slag coarse aggregate exhibits a lower bulk density in comparison to natural river coarse aggregate, while demonstrating a higher specific gravity. Table 5 summarizes these physical properties.



Figure 2: (a) Steel Slag as Gravel (max. size 19.5mm), (b) Natural Sand, and (c) Steel Slag as Sand.

Table 5: Physical attributes of the Aggregates.

Items	Water Absorption%	loose density kg/m ³	compacted density kg/m ³	Specific Gravity	Fineness modulus
Natural Fine Aggregate (FA)	1.88%	1780	1870	2.73	2.82
Natural Coarse Aggregate (CA)	0.50%	1635	1775	2.71	---
SS as Fine Aggregate (SSFA)	5%	2200	2425	3.54	2.8
SS as Coarse Aggregate (SSCA)	1.50%	1500	1680	3.05	---

Table 6: Grading of the Fine Aggregates (sand) and steel slag as Fine aggregate

Size of the sieve (mm)	(FA) Passing %	(SSFA) Passing %	ASTM Limits	
			Lower	Upper
9.5	100.00	100	100	100
4.75	99.13	100	95	100
2.36	80.90	80	80	100
1.18	68.10	68	50	85
0.6	49.00	48	25	60
0.3	17.67	18	5	30
0.15	5.07	5	0	10

Table 7: Grading of the Coarse Aggregates, maximum size (D max = 19.5 mm) and Steel slag as coarse aggregate

Size of the sieve (mm)	(CA) Passing %	(SSCA) Passing %	ASTM Limits	
			Lower	Upper
37.5	100.00	100.00	100.00	100.00
25	100.00	100.00	100.00	100.00
19	100.00	100.00	90.00	100.00
12.5	41.05	40.00	35.00	80.00
9.5	21.55	20.50	20.00	55.00
4.75	0.00	0.00	0.00	10.00
2.36	0.00	0.00	0.00	5.00

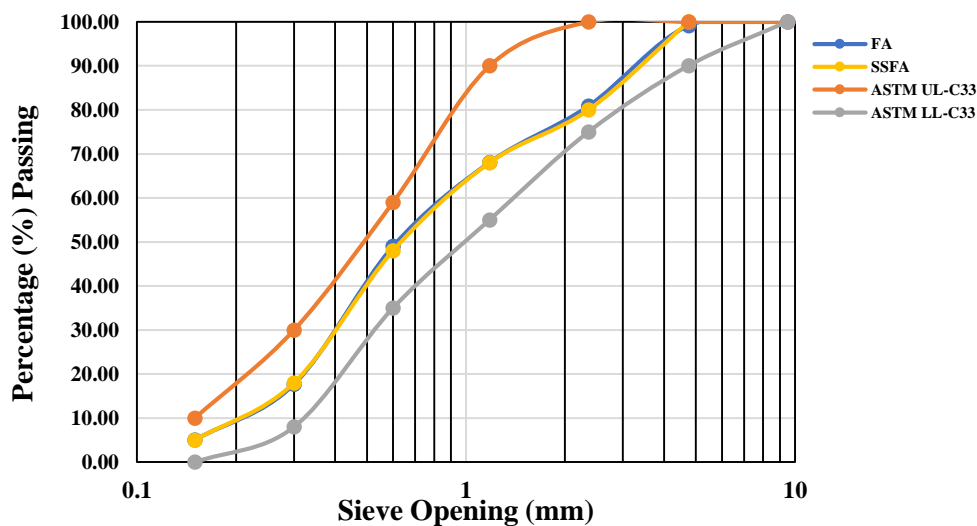


Figure 3: Gradation curve of Fine aggregate and Steel slag as Fine aggregate with ASTM limits

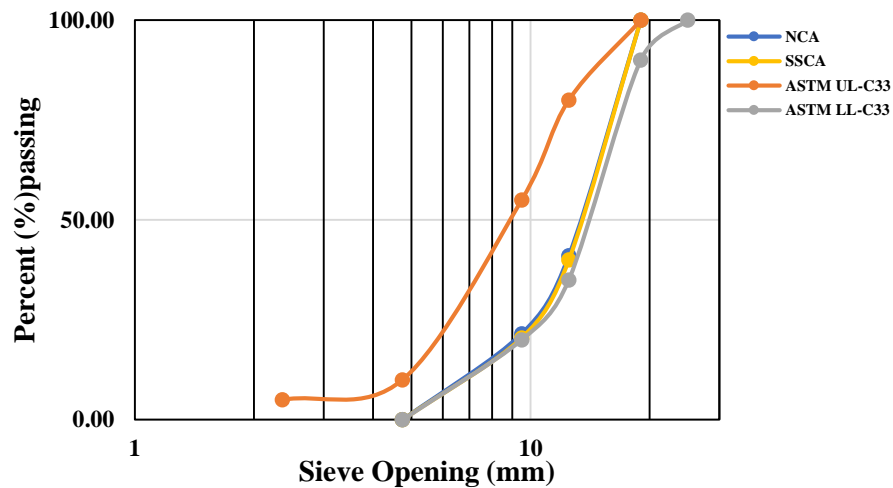


Figure 4: Gradation curves for natural coarse aggregate and steel slag as coarse aggregate in accordance with ASTM limits.

3.7 Experimental work and mix design

Several trial mixes were prepared using locally obtained materials in Erbil, aiming for a control mix compressive strength of 35 MPa. The final mix proportions (1:1.5:2) from these trials were used to cast 1 m³ of concrete, as shown in Table 8. The concrete materials and specimen casting equipment used in the experimental program are shown in Figure 5. These mixtures were designed to account for local cement and aggregate qualities, including steel slag (SS) used to replace cement, sand, and gravel partially. All concrete batches were mixed utilizing a mechanized mixer to ensure uniformity, and the workability of fresh concrete was evaluated using the slump test, as illustrated in Figure 6. Ten concrete mixtures were formulated and evaluated to assess the influence of partially replacing cement, sand, and gravel with steel slag on mechanical properties. The replacement ratios were adjusted systematically. Fresh concrete was then placed into cylindrical and prismatic molds, and the cast specimens are shown in Figure 7. Each combination was systematically placed into cylindrical and prism molds and cured under controlled conditions. The mechanical properties were analyzed after (28, 56, 90, and 180 days) curing. Cylinders measuring 100×200 mm were utilized to assess compressive strength and tensile strength. Cylinder specimens were prepared following ASTM C31/C31M [18], and prismatic molds dimension 100×100×500 mm were utilized to assess flexural strength in accordance with the ASTM C78 [19] standard, as illustrated in Figure 8. Three cylinders were evaluated for compression strength after 28 days of curing, and three cylinders were used to test splitting tensile strength after 28 days of age. Three prisms were employed to assess flexural strength following 28 days of cure. This procedure is executed for each mixture. The long-term strength and durability were evaluated for both the control mix and the selected modified mixes. Three specimens were produced and evaluated at 56 days, three at 90 days, and the last three at 180 days. This process is used for control mix and selected mixes.



Figure 5: Concrete Materials and Specimen Casting Equipment.



Figure 6: Slump test.

Table 8: Mix proportion of concrete mixes(kg/m3)

Mix label	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Steel Slag as					
				Cement		Fine aggregate		Coarse aggregate	
				kg	%	kg	%	kg	%
M-01	485	725	970						
M-02	436	725	970	49	10				
M-03	413	725	970	72	15				
M-04	388	725	970	97	20				
M-05	485	544	970			181	25		
M-06	485	363	970			363	50		
M-07	485	-	970			725	100		
M-08	485	725	728					242	25
M-09	485	725	485					485	50
M-10	485	725	-					970	100



Figure 7: Casted specimen (Cylinder and Prism).



Figure 8: Specimens with mechanical properties tests.

5. Results and Discussion

5.1 Workability of fresh concrete

5.1.1 Workability using partially replaced cement with steel slag

Table 9 indicates the impacts of steel slag SS% on the slump test workability. Concrete mixes with 0%, 10%, 15%, and 20% steel slag were made, after mixing with 0.45 water-cement. Fig. 9 shows that increasing steel slag decreased fresh concrete workability. With lower percentages of 10%, the reduction was minimal, 97.5% with the control mix, but with higher percentages of 15% and 20%, the workability decreased to 90% and 85% of the control mix, respectively. Since the steel slag was coarser than cement (75 μm), it reduced workability because its rough shape increased friction, it absorbed more water, which lowered the free water, and there was less paste to lubricate the mix. This shows that shape, texture, and absorption affect workability more than size alone [6], [12].

Table 9: Slump test- slag replacement as cement

Mix ID	Steel slag %	Slump (mm)
M-01	0%	200
M-02	10%	195
M-03	15%	180
M-04	20%	170

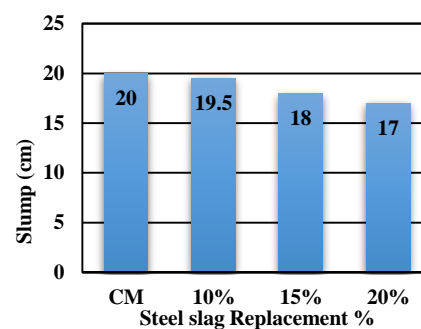


Figure 9: Effect of steel slag as a partial cement replacement on slump

5.1.2 Workability using partially replaced fine (sand) aggregate with steel slag

The workability of concrete using slag instead of sand was assessed using the slump test. Table 10 illustrates the results, while Fig. 10 demonstrates a decline in workability with increasing percentages of fine steel slag. The findings show that using 25% steel slag as sand lowers the slump from 20 cm to 16 cm compared to a control mix with 0% steel slag. Using 50% and 100% steel slag lowers the slump to 15 cm and 14 cm, respectively. This drop might be because the slag has an angular and rough texture. Porous steel slag absorbs more water than natural sand, making the mix stiffer and reducing its Slump value [7]. These data indicate that slag diminishes the workability of the fresh mixture.

Table 10: Slump test- slag replacement as sand

Mix ID	Steel slag %	Slump (mm)
M-01	0%	200
M-05	25%	160
M-06	50%	150
M-07	100%	140

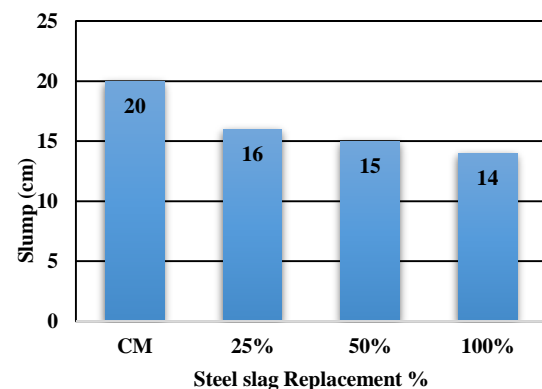


Figure 10: Effect of steel slag as a sand replacement on slump

5.1.3 Workability using partially replaced coarse aggregate (gravel) with steel slag

In comparison to the control mix at 0%, Fig. 11 and Table 11 show how the slump test was used to see how easy it was to work with concrete mixes that included 25%, 50%, and 100% steel slag gravel replacement. It was noted that the workability diminishes when steel slag is utilized as coarse aggregate. Workability drops from 20 cm to 15 cm with 25% replacement compared to 0%. The slump values were recorded at 14 cm and 15 cm for 50% and 100%, respectively. This aligns with previous research [21]. The flowability of fresh concrete is greatly affected by the angularity of steel slag particles. Coarse steel slag demonstrates a superior water absorption capacity relative to rounded gravel, due to its elevated porosity. Comparable patterns were noted by Qasrawi [22], suggesting that the workability of fresh concrete diminishes as the percentage of steel slag aggregate increases.

Table 11: Slump test- slag replacement as gravel

Mix ID	Steel slag %	Slump (mm)
M-01	0%	200
M-08	25%	150
M-09	50%	140
M-10	100%	130

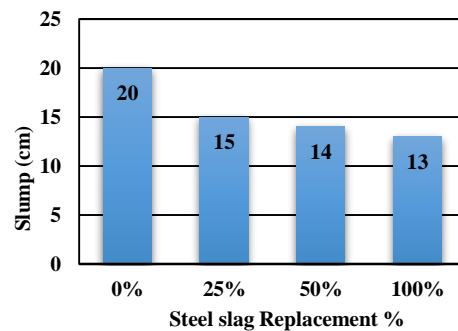


Figure 11: Effect of steel slag as a gravel replacement on slump

5.2 Compressive strength

5.2.1 Compressive strength using partially replaced cement with steel slag

Table 12 presents the compressive strength of concrete using 10%, 15%, and 20% steel slag as a partial replacement of cement at a water–cement ratio of 0.45. The findings demonstrate that replacing cement with steel slag influences compressive strength, as illustrated in Figure 12. At 28 days, all mixtures modified with steel slag demonstrated reduced compressive strength relative to the control mixture, with decreases of approximately 21% and 24% for the 10% and 15% replacement levels, respectively. At 20% replacement, steel slag showed the highest strength compared to the slag-modified mixes. However, it was around 6% lower than the control mix. The reported reduction in compressive strength in this study primarily results from the lower fineness of the steel slag (250 m²/kg Blaine), which diminishes its hydration rate and pozzolanic reactivity. Conversely, previous studies indicate that strength enhancement used finer steel slag, which increased the reactive surface area and encouraged secondary hydration [4] and [5]. The improved performance at the 20% replacement level is mainly attributed to the filler effect and better particle packing provided by the angular and dense steel slag; however, this effect was insufficient to offset the reduced cement content, and compressive strength remained lower than that of the control [23].

Table 11: Compressive Strength-Slag Replacement as cement

Mix ID	Steel slag %	Compressive strength at 28 days (MPa)
M-01	0%	35.41
M-02	10%	28.02
M-03	15%	30.60
M-04	20%	33.20

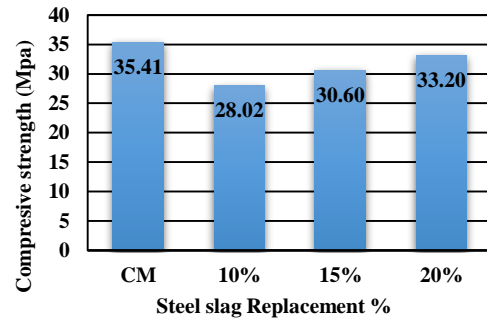


Figure 12: Effect of steel slag as partial cement replacement on compressive strength at 28 days

5.2.2 Compressive strength using partially replaced sand with steel slag

Sand was replaced with steel slag at ratios of 25%, 50%, and 100% to assess the compressive strength after 28 days, relative to the reference mixture, as shown in Table 13. Figure 13 illustrates that a 25% replacement results in enhanced compressive strength after 28 days in comparison to the reference mixture and other replacement levels. The enhancement may be attributed to Steel slag at a moderate replacement level, demonstrating superior interlock relative to natural sand, owing to its angular morphology and improved particle packing, or due to Steel slag's cementitious characteristics, which might improve hydration products. The use of 50% and 100% steel slag as a sand replacement negatively impacts the compressive strength of concrete. The elevated slag percentage may result in insufficient cohesion between steel slag and cement paste due to low hydration of the cementitious material, since angular steel slag requires a greater amount of cement for coating. The optimal percentage of steel slag for reaching optimum concrete compressive strength is 25%. This aligns with the experimental findings indicating that optimal compressive strength enhancement occurs with steel slag fine aggregate replacement rates of 20% to 40% [8].

Table 13: Compressive strength - slag replacement as sand

Mix ID	Steel slag %	Compressive strength at 28 days (MPa)
M-01	0%	35.41
M-05	25%	36.93
M-06	50%	34.29
M-07	100%	33.90

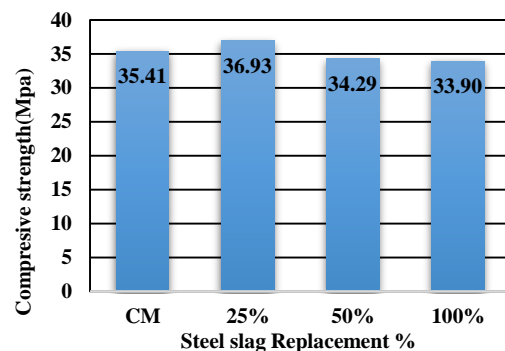


Figure 13: Effect of steel slag as a sand replacement on compressive strength at 28 days

5.2.3 Compressive strength using partially replaced gravel with steel slag

Table 14 presents the compressive strength of concrete with steel slag utilized as a partial replacement for coarse aggregate (gravel) at proportions of 0%, 25%, 50%, and 100%. Concrete results after 28 days are shown in Fig. 14. As steel slag partially replaces gravel, improved strength is achieved. The value increased from 35.41 MPa to 39.04 MPa with 25% replacement over the control mix (0%). The

ideal coarse aggregate amount of steel slag with 50% replacement yields 41.61 MPa compressive strength. This enhancement results from the increased angularity and rough texture of slag, and its higher specific gravity than natural aggregate promotes cement paste-aggregate bonding and load transmission. At 100% replacement, the strength reduced to 38.78 MPa but was still higher than the control mix. Higher amounts of steel slag diminish the bonding between cement paste and aggregate, adversely affect particle packing, and decrease workability, eventually causing a loss of strength [12].

Table 14: Compressive strength - slag replacement as gravel

Mix ID	Steel slag %	Compressive strength at 28 days (MPa)
M-01	0%	35.41
M-08	25%	39.04
M-09	50%	41.61
M-10	100%	38.78

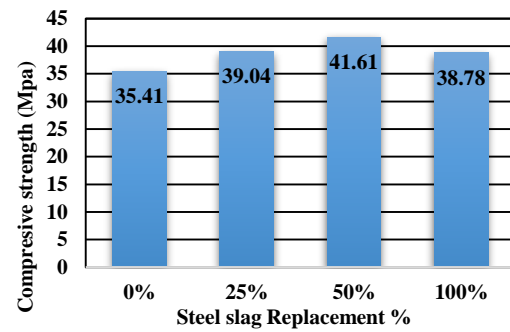


Figure 14: Effect of steel slag as gravel replacement on compressive strength at 28 days

5.3 Tensile strength

5.3.1 Splitting tensile strength using partially replaced cement with steel slag

Table 15 shows the effect of using 10%, 15%, and 20% steel slag on splitting tensile strength after 28 days. Splitting tensile strength achieved 99.75%, 99%, and 96% of the control mix after replacing 10%, 15%, and 20% of the material, respectively. Findings indicated that replacing cement with steel slag has little effect on splitting tensile strength relative to the control mix. Fig. 15 shows that 10% and 15% replacement percentages did not affect tensile strength. The reduction was apparent with a 20% replacement. With an increase in steel slag percentage, particularly at 20%, splitting tensile strength is reduced due to many reasons. Because steel slag particles are larger than cement particles, they don't bond as effectively with the surrounding paste. This weakens the interfacial transition zone (ITZ), resulting in lower splitting tensile strength [17]. Steel slag produces less calcium-silicate-hydrate (C-S-H) gel, which mostly functions as a filler in the mix rather than a binder.

Table 15: Splitting tensile strength- slag replacement as cement

Mix ID	Steel slag %	Ten. Strength at 28 days (MPa)
M-01	0%	4.06
M-02	10%	4.05
M-03	15%	4.02
M-04	20%	3.90

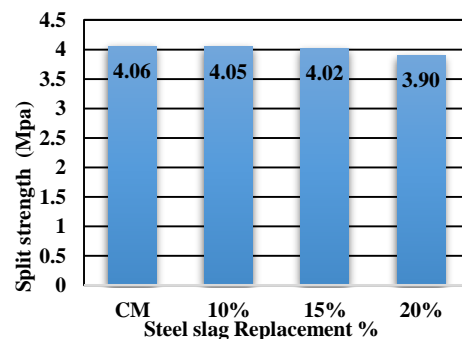


Figure 15: Effect of steel slag as a partial cement replacement on splitting tensile strength after 28 days

5.3.2 Splitting tensile strength using partially replaced sand with steel slag

Splitting tensile strength test was utilized to find the splitting test resistance of the control mix and concrete with 25%, 50%, and 100% steel slag as sand replacement at 28 days. The outcomes of the steel slag-replaced mixture and the control mixture are presented in Table 16 and Fig. 16. A concrete mix with 25% steel slag-replaced sand had a greater splitting tensile strength than the control mix. This indicates that a 25% replacement of SS with sand provides higher splitting tensile strength relative to the control mix and other SS replacement ratios. However, increasing steel slag to 50% and 100% decreased tensile strength. The full replacement of sand with steel slag decreased the splitting tensile strength more than the control combination. Reaches 94% control mix strength. This aligns with the findings of a previous research [24], which showed that the best improvement in splitting tensile strength was obtained with steel slag replacement percentages as fine aggregate between 30% and 40%.

Table 16: splitting tensile strength- slag replacement as sand

Mix ID	Steel slag %	Ten. Strength at 28 days (MPa)
M-01	0%	4.06
M-05	25%	4.25
M-06	50%	3.98
M-07	100%	3.85

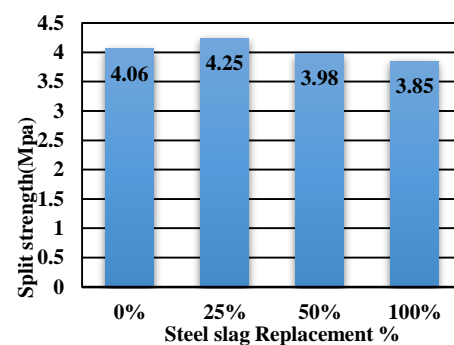


Figure 16: Effect of steel slag as a sand replacement on splitting tensile strength at 28 days

5.3.3 Splitting tensile strength using partially replaced gravel with steel slag

Table 17 demonstrates the splitting tensile strength values for coarse aggregate composed of 25%, 50%, and 100% steel slag. Figure 17 presents a comparison of the results with the 28-day control mix. The control mix exhibited a splitting tensile strength of 4.06 MPa, while the 25% replacement mix demonstrated a strength of 4.21 MPa. The irregular and rough morphology of steel slag particles enhances their adherence to cement paste, hence increasing cohesiveness. Splitting tensile strength subsequently decreased to 4.03 MPa and 3.85 MPa for 50% and 100% replacements, respectively. The elevated porosity of the concrete mixture, resulting from the higher level of steel slag aggregate, could affect aggregate compatibility and the adhesion between the aggregate and cement paste. Sabapathy [25] found that the greater amount of modified steel slag particles increases concrete porosity, reducing splitting tensile strength beyond 25% replacement.

Table 17: splitting tensile strength- slag replacement as Gravel

Mix ID	Steel slag %	Ten. Strength at 28 days (MPa)
M-01	0%	4.06
M-08	25%	4.21
M-09	50%	4.03
M-10	100%	3.85

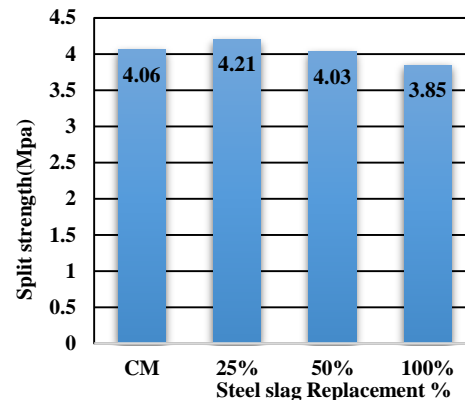


Figure 17: Effect of steel slag as a gravel replacement on splitting tensile strength at 28 Days

5.4 Flexural strength

5.4.1 Flexural strength using partially replaced cement with steel slag

Slag was employed instead of cement to assess flexural strength at 28 days. Table 18 illustrates a comparison between steel slag cement and the control mix, emphasizing the decrease in strength. The replacement mixes at 10%, 15%, and 20% achieved flexural strengths of 99.80%, 85%, and 78% of the control mix, respectively. Fig.18 shows that when the proportion of steel slag increases, the flexural strength decreases, which shows that it has a big effect on strength. Steel slag had a coarser texture than cement and exhibited less pozzolanic activity at an early age, acting mainly as a filler rather than a binder, which weakened the binder-aggregate bond. The utilization of steel slag weakens the interfacial transition zone (ITZ), critical for flexural strength. The performance progressively diminishes with steel slag replacement exceeding 10% of cement replacement [23].

Table 18: flexural strength - slag replacement as cement

Mix ID	Steel slag %	Flex. Strength at 28 days (MPa)
M-01	0%	6.59
M-02	10%	6.51
M-03	15%	5.61
M-04	20%	5.14

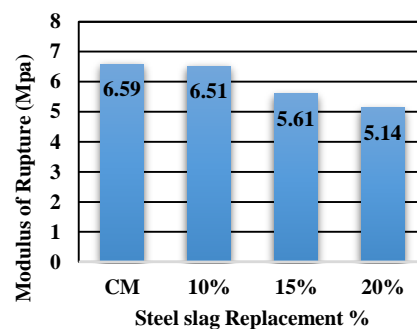


Figure 18: Effect of steel slag as a partial cement replacement on flexural strength at 28 days.

5.4.2 Flexural strength using partially replaced sand with steel slag

Table 19 shows the findings of a flexural strength test utilizing steel slag as sand. The control mix and mixes with 25%, 50%, and 100% steel slag replacing sand were assessed after a cure period of 28 days. The optimal proportion of 25% steel slag to sand improved flexural strength relative to the control mix and other steel slag replacement combinations. This enhancement may be due to its rough and angular shape, which makes steel slag adhere better to cement paste. This improves paste-aggregate adhesion. Fig.19 illustrates a 3.3% reduction in flexural strength at 50% replacement and a 15.3% reduction at 100% replacement compared to the control mix. The full replacement has the lowest flexural strength. Increasing the percentage of steel slag may result in the development of internal voids and microcracks, which weaken the bond between the paste and the aggregate. This is due to lower workability and poor compaction, which form weak zones prone to flexural failure. These results correspond with research conducted by Palanisamy [24]. The highest flexural strength was reached by replacing 36% of the sand with steel slag.

Table 19: flexural strength - slag replacement as sand

Mix ID	Steel slag %	Flex. Strength at 28 days (MPa)
M-01	0%	6.59
M-05	25%	6.94
M-06	50%	6.37
M-07	100%	5.58

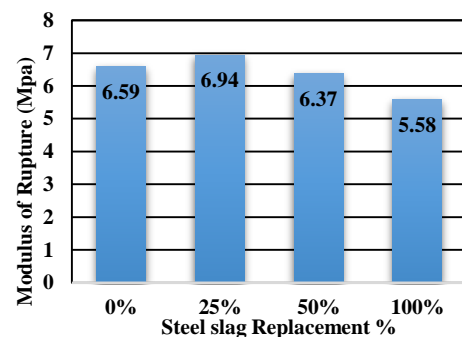


Figure 19: Effect of steel slag as a sand replacement on flexural strength at 28 days.

5.4.3 Flexural strength using partially replaced gravel with steel slag

The effect of coarse aggregate replacement with steel slag at proportions of 25%, 50%, and 100% on flexural strength was assessed after 28 days, as shown in Table 20 and Fig. 20. A 25% replacement led to a reduction in flexural strength from 6.59 MPa to 6.17 MPa relative to the control mix. When the steel slag percentage is raised to 50%, the value increases to 7.23 MPa, the highest of all mixes. Flexural strength drops to 7.05 MPa with 100% replacement, although it is still higher than the control mix. This enhancement may result from improved internal distribution, while the angularity and roughness of the steel slag contribute to paste-aggregate bonding and mechanical interlocking. This observation aligns with a previous study Saxena [26], who found that steel slag as a coarse aggregate improves flexural resistance, cracking resistance, and bending capacity at 50% replacement, but performance declines beyond this level.

Table 20: flexural strength - slag replacement as gravel

Mix ID	Steel slag %	Flexural Strength at 28 days (MPa)
M-01	0%	6.59
M-08	25%	6.17
M-09	50%	7.23
M-10	100%	7.05

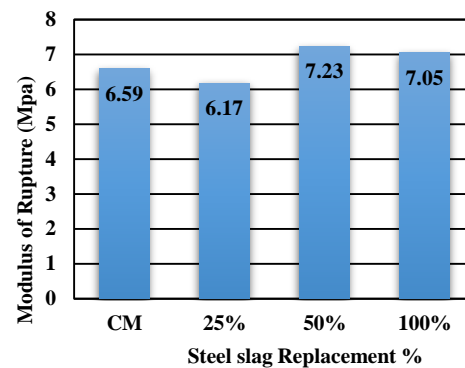


Figure 20: Effect of steel slag as a gravel replacement on flexural strength at 28 days

5.5 long-term strength (Durability)

5.5.1 Long-term strength (Durability) using partially replaced cement with steel slag

Fig. 21 demonstrates the compressive strength of the control mix (CM) and the concrete that included 10% steel slag as a cement replacement (10C) at different curing ages. The CM exhibited a linear development trend, evidenced by the regression equation $y = 0.0445x + 33.825$ and a strong correlation coefficient ($R^2=0.9908$). This indicates that strength increased steadily and consistently with age. The mixture 10C exhibited a polynomial growth trend, marked by an initial rapid increase that gradually diminished over time. The behavior is described by the equation $y = -0.0008x^2 + 0.2253x + 22.877$, exhibiting a strong coefficient of determination ($R^2 = 0.9605$). The growth rate was almost twice as high as the control mix. The mix (10C) exhibited a much lower compressive strength than the control, showing that replacing an amount of the cement with steel slag weakens the mix after 28 days. Despite its steady strength enhancement over time, ultimately nearing that of the CM mix, it consistently exhibited lower strength at all ages. At 180 days, it reached about 39 MPa, whereas the CM mix surpassed 41 MPa. The findings show that replacing 10% of the cement with steel slag lowers the strength at an early age, but improves performance over time. Due to its delayed reactivity, steel slag slows cement hydration and reduces C–S–H gel formation in concrete, reducing early-age compressive strength [23,27]. Steel slag filler enhances particle packing and pore structure, while unreacted cement and slag phases gradually hydrate, increasing matrix density. Chen [5] found that mixes containing 10–30% steel slag often had compressive strengths similar to or greater than standard concrete at later ages.

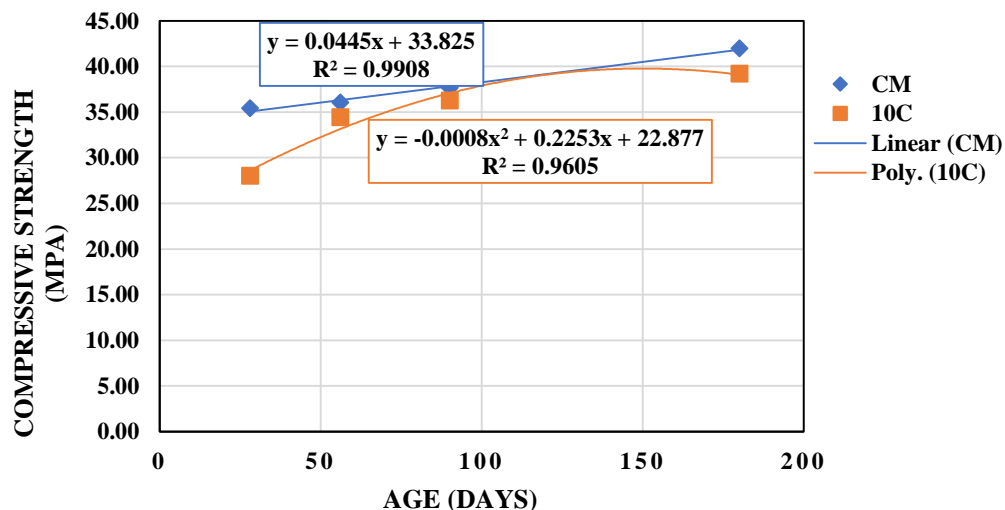


Figure 21: Long-term strength with partial cement replacement (10%) by steel slag

5.5.2 long-term strength (Durability) using partially replaced sand with steel slag

Fig. 22 illustrates the variation in compressive strength relative to curing age for both the control mix (CM) and the concrete incorporating 25% steel slag as a sand replacement (25S). The regression equation $y = 0.0445x + 33.825$ demonstrates a linear relationship between strength and age in the CM. The coefficient of determination R^2 was 0.9908, showing a consistent increase in the CM's strength over time. The 25S mix demonstrated a linear growth pattern, described by the equation $y = 0.0238x + 36.778$, with a coefficient of determination $R^2 = 0.9058$. The 25S mix exhibited better compressive strength relative to the control at 28, 56, and 90 days of age. Steel slag contributed to enhanced strength in both the short and medium term. After 180 days, the strength of the control mix was marginally greater than that of the 25S mix. This indicates that while steel slag enhanced early hydration and strength gain, its long-term impact on strength development was comparatively less significant than that of the control mix. The improvements result from the angular texture and hidden hydraulic characteristics of SSA, which enhance particle interlock, promote pozzolanic reactions, and elevate the density of the cementitious matrix [28]. However, the long-term performance remains comparable to that of traditional concrete, irrespective of the replacement ratio.

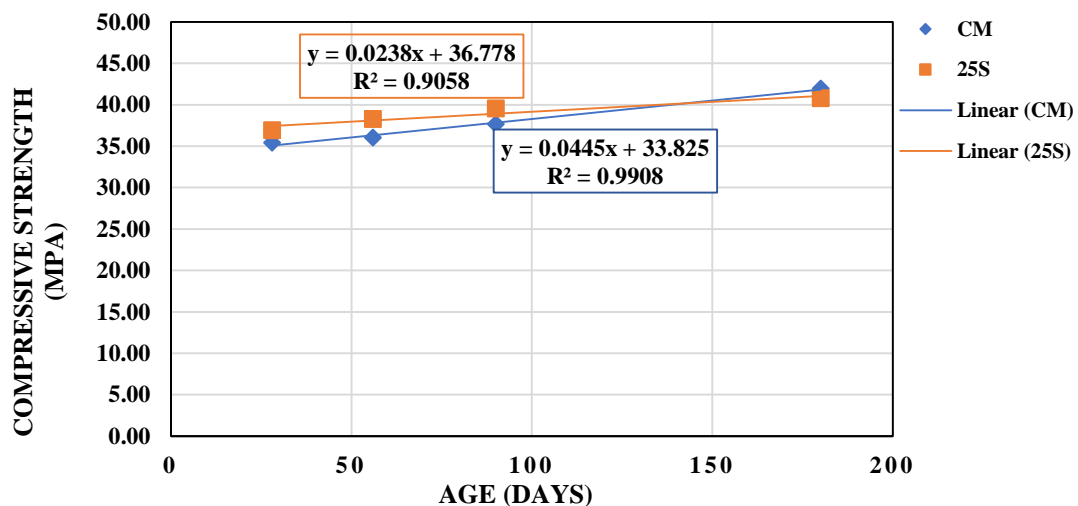


Figure 22: Long-term strength with partial sand replacement (25%) by steel slag

5.5.3 long-term strength (Durability) using partially replaced gravel with steel slag

Fig. 23 illustrates the progression of compressive strength for the control mix (CM) in comparison to the mixture with 25% steel slag as a replacement for gravel (25G) at different curing ages. The CM demonstrated a linear trend of strength enhancement, characterized by the regression equation $y = 0.0445x + 33.825$ and a strong correlation coefficient ($R^2=0.9908$), showing a steady rise in strength over time. The 25G mix exhibited a polynomial trend described by the equation $y = 0.0003x^2 - 0.0105x + 38.173$, with an R^2 value of 0.8464, exhibiting little change in compressive strength at intermediate ages but a notable enhancement at later ages. At 28 days, the 25G combination demonstrated enhanced compressive strength relative to the control, suggesting that steel slag as a partial gravel replacement improves early performance. While at 56 days, the strength value of 25G is decreased slightly and remains comparable to the control. By 90 and 180 days, the 25G mix surpassed the CM, reaching more than 45 MPa compared to about 41 MPa for the control at 180 days. The utilization of slag as gravel improves the long-term compressive strength of concrete, despite intermediate-age results indicating a temporary decline in performance. This finding aligns with a previous study [29], which reported that SS as Gravel slows lower or stable strength due to microcracks from volume stability or slow reaction, surface roughness causes weak early bonding, while in the long-term, strength increases again due to continued hydration, filling microcracks by formation of C-S-H gel from slag's free CaO and SiO₂ at later ages.

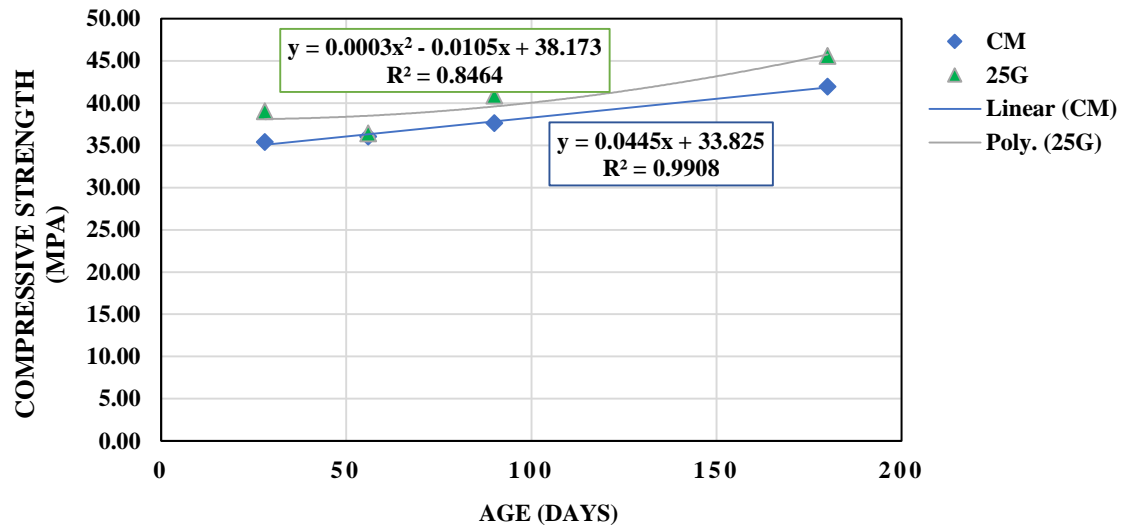


Figure 23: Long-term strength with partial gravel replacement (25%) by steel slag

6. Conclusion

This study examined the fresh, mechanical, and Long-term properties of utilizing steel slag as a partial replacement for cement, sand, and gravel in concrete. Workability consistently reduced with higher replacement levels of steel slag. At lower replacement levels (10% as cement or 25% as sand and gravel), the decrease was noticeable, whereas at the higher replacement levels, the reduction became progressively more significant. The workability is reduced because steel slag has a rougher surface, a more angular shape, and is more effective at absorbing water than cement and natural aggregates.

Replacing cement with steel slag decreased compressive strength at an early age, but the 20% replacement level gave the best results (among the modified mixes). This reduction was due to the lower pozzolanic activity and smaller Blaine fineness compared to cement. The replacement of steel slag for sand improved strength by 25% because of better particle interlocking and packing efficiency; however, increased replacement levels after 25% decreased strength. While at 50% gravel replacement, there is an improvement in compressive strength compared to the control mix. However, the 100% gravel replacement was reduced, but still exceeded the control strength.

Splitting tensile strength showed small decreases at 10% and 15% replacement as cement, but declined significantly at 20% replacement. Optimal sand splitting tensile strength was reached at 25% replacement, whereas higher percentages led to lower results. The replacement of gravel resulted in a 25% enhancement in splitting tensile strength, whereas 50% and 100% replacements exhibited a gradual decrease; however remained comparable to the control mixture.

When the proportion of cement replaced increased, the flexural strength gradually decreased. Consequently, it was demonstrated that cement had a higher binding capability than steel slag. The best results for sand occurred when 25% of it was replaced. When 50% or 100% of it was replaced, the strength decreased due to internal voids and inadequate compaction. Using 50% steel slag as gravel replacement provided the highest flexural strength of all mixtures. Even after full replacement, the results exceeded the control, showing that steel slag coarse aggregate improves flexural performance.

At 10% cement replacement, the mix exhibited reduced early strength in comparison to the control, but it progressively enhanced with curing, although it never completely reached the strength of the control even after 180 days. A 25% replacement of sand improved compressive strength during the early ages (28–90 days), but by 180 days, it matched the control. A 25% gravel replacement exhibited improved long-term performance, surpassing the control at 180 days, thus illustrating the effectiveness of steel slag coarse aggregate in improving durability.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contribution

All experiments, data analysis, interpretation, and paper writing were done by Khanda Hamid Sahreef. The manuscript was reviewed by Ayad Zaki Saber, who provided scholarly comments. The manuscript was finalized with the author's approval.

Use of AI tool Declaration

The authors declare that any AI tools used in the preparation of this manuscript were limited to language and readability improvement only, and were not used to generate scientific content, data, analyses, or conclusions, with full responsibility retained by the authors.

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