"Experimental Investigation on the Utilization of Steel Slag as Partial Replacement of Fine Aggregate in Concrete"

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Abstract

The rising need for environmentally friendly building materials has led to interest in using industrial by-products like steel slag in concrete. This study looks at how the mechanical and workability qualities of concrete change when some of the natural fine particles are replaced with steel slag in different amounts (0%, 10%, 20%, and 30%). We did experiments on standardised concrete samples to see how they held up under different conditions, such as slump, compressive strength, split tensile strength, and flexural strength. The results show that replacing 20% of the fine aggregate with steel slag gives the best performance. It increases strength while keeping workability at an appropriate level. Sieve examination showed that the grading of steel slag is good for use in concrete. During the mixing, casting, and curing procedures, both visual and laboratory investigations confirmed that the concrete mix was consistent and strong. The results suggest the use of steel slag as a good substitute for natural sand, which helps conserve the environment and save resources. This study adds to the growing number of studies that support using circular economy methods in the building industry. It is suggested that more research be done to look at how well it lasts and how well it works in different climates and under different loads.

Keywords: Steel Slag, Sustainable Concrete, Fine Aggregate Replacement, Compressive Strength, Flexural Strength, Workability, Green Construction, Sieve Analysis.

1. Introduction

The construction industry around the world is seeing an unprecedented demand for concrete because cities are growing quickly, populations are growing, and infrastructure is expanding. Concrete is a very useful and long-lasting material that uses a lot of natural aggregates like river sand and broken stones. However, the uncontrolled extraction of these natural resources has caused major environmental problems, such as ecological imbalances and rules that limit sand mining (IS 383:2016). As natural sand deposits run out and construction needs grow, both academic and industrial research are starting to look into alternative and sustainable materials. Steel slag and other industrial by-products have become promising substitutes for fine aggregates. Steel slag is a by-product of making steel, and it is made in huge amounts around the world about 0.39 billion tonnes by 2020 alone. This makes it very hard to get rid of and safe for the environment (Martins et al., 2021). At the same time, the world's use of sand is still going up, reaching more than 60 billion tonnes in the same year (Kumar & Gupta, 2016). This is a great chance to use steel slag in regular building procedures. The growing gap shows that we need long-lasting alternatives to aggregates right away. Steel slag has a granular structure that is high in calcium, magnesium, silicon, and iron oxides. This makes it chemically compatible with cementitious systems (You et al., 2019).Using steel slag in concrete has huge environmental benefits in addition to its technical ones. Wu et al. (2021) showed that porous mortar made from steel slag can hold a lot of phosphorous, which means it may be used as both a building material and a cleaning agent. Steel slag can also be used in chemical stabilisation and to improve the performance of binders. The study looks at seven levels of replacement (0% to 30%) and measures the resulting mechanical properties, including as compressive, split tensile, and flexural strengths. We also look at physical properties like particle size distribution (using sieve analysis) and specific gravity to see if they meet BIS criteria.The study not only shows that steel slag may be used as a fine aggregate replacement, but it also supports national goals for sustainability and the concepts of a circular economy.

2. Literature Review

In the last ten years, more and more people have started using steel slag as a partial or whole replacement for fine aggregate in concrete. This is because it might make the concrete stronger, last longer, and have less of an impact on the environment. This review puts the results of previous research into four main themes: (1) mechanical qualities, (2) durability and environmental performance, (3) surface treatment and chemical modification, and (4) sustainability and waste utilisation.

2.1 Mechanical Properties of Steel Slag Concrete

Adding steel slag to cementitious systems has been shown to greatly increase their strength-related performance. You et al. (2019) looked at how alkali-activated mortars with steel slag and ferronickel slag behaved when they were put under pressure and bent. Their results showed that bonding and matrix densification improved, and the best compressive strength was found at 30% slag substitution. Araújo Júnior et al. (2021) also came up with a new way to build mixes for high-strength alkali-activated slag concrete (HSAASC). They said that under the best curing conditions, the compressive strengths were over 100 MPa. This means that steel slag not only helps with structure but also helps with strength when it is chemically activated. Shanmugam et al. (2020) used microstructural instruments like SEM and XRD to link the way materials behave mechanically to the growth of their crystalline matrix. Their investigation showed that replacing up to 25% of the fine aggregate with steel slag increased the compressive and split tensile strength because it improved the transition zones between the two materials.

2.2 Durability and Environmental Performance

Long-term durability is an important part of sustainable concrete. Several studies have shown that steel slag makes things last longer by making them less permeable, less likely to get carbonated, and less likely to be attacked by sulphate. Wu et al. (2021) took this a step further by adding miscanthus and steel slag to porous adsorptive mortar. Their research showed that the mortar not only kept the structure strong, but it also served as an adsorbent medium to remove phosphorous, which is good for the environment. Martins et al. (2021) did a thorough review and discovered that the thick microstructure of electric arc furnace (EAF) slag makes it more resistant to chloride and better at absorbing water. Luo et al. (2021) also looked at how compacted steel slag carbonates at different curing temperatures. When slag was thermally stabilised, their results indicated that it was better able to keep CO_2 out, which suggests that it will last a long time.Manso et al. (2004) added to this by testing the freeze-thaw resistance of concrete made using slag and aggregate. They said that the durability performance was better after 90 days of exposure, mostly because of the angularity and pore-filling properties of slag.

2.3 Surface Treatment and Chemical Behavior of Steel Slag

Untreated steel slag may have problems with free lime and periclase hydration, which can make it unstable in volume. Because of these problems, research has concentrated on changing slag to get around them. Gan et al. (2022) looked at a number of physical and chemical approaches for treating surfaces to make steel slag aggregates more stable. looked into how steel slag-based binders can help stabilise soft clay soils. Their binder compound did a great job of reducing swelling and making the soil more compact, showing that slag may be used in more ways than just making concrete.Luo et al. (2021) said again that the temperature at which slag is cured is very important for its chemical stability. Higher curing temperatures (60–80°C) were discovered to make slag more reactive and resistant to carbonation. These results show how important processing methods are for making slag a useful part of concrete.

3. Materials and Methods

3.1 Selection of Materials

- Cement: IS 12269:2013 says that Ordinary Portland Cement (OPC) of 53 Grade (KCP brand) was used.
- Coarse Aggregate: Crushed angular stone aggregates with a nominal size of 20 mm that were accessible in the area were used as coarse aggregate.
- Steel Slag: The main experimental material was air-cooled steel slag that came from a neighbouring steel mill.
- Water: Throughout the project, we used drinking water that was pH-balanced, devoid of salts, organics.Figure 3.1 shows the steps of the experiment, from gathering materials to analysing the data.

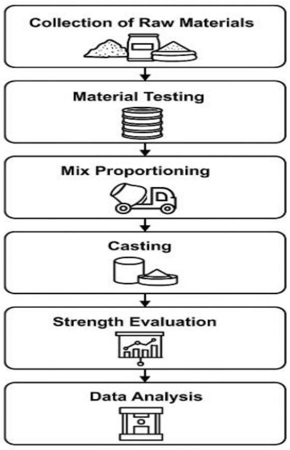


Figure 3.1: Block Diagram of Experimental Methodology

This figure illustrates the sequential flow of the experimental study, beginning with the collection of raw materials and proceeding through material testing, mix proportioning, casting, curing, and strength evaluation.

3.2 Characterization of Materials

All chosen materials were first characterised to make sure they met quality and compliance standards. Vicat equipment to test the cement according to IS 4031. The average specific gravity was 3.15. The initial and final setting times showed that it was good for use in structures. Studied coarse aggregates (20 mm) to see how much water they could hold, their specific gravity (around 2.7), and their bulk density. Shape and texture observations verified that the angular and rough features helped with bonding. A sieve to look at samples of steel slag that were 10 to 20 mm long. They had a greater specific gravity (around 3.2 to 3.5) than regular aggregates.

3.3 Concrete Mix Proportioning

This study used IS 10262:2019 to make the mix design, with the goal of making concrete with a strength of M25 grade. The mix was made using a consistent amount of binder and a water-cement ratio of 0.45. The most interesting thing about this study was that it used steel slag aggregates (10–20 mm) to partially replace natural coarse aggregates (20 mm) at different rates. Five different mixes were made:

Mix ID	%SteelSlag Replacement (Coarse Aggregate)	Cement (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Steel Slag (kg/m³)	Water (liters)
M0	0%	400	650	1200	0	180
M10	10%	400	650	1080	120	180
M20	20%	400	650	960	240	180
M30	30%	400	650	840	360	180
M40	40%	400	650	720	480	180

All of the mixes employed 53 Grade KCP OPC cement, Zone III river sand, and 20 mm angular coarse aggregate that was accessible in the area. Steel slag was added as a 10–20 mm fraction. We weighed the ingredients and stirred the dry ones well before adding the water.

3.4: Casting and Curing of Specimens

In the lab, we used a tilting drum mixer to make all of the concrete mixes. According to IS 516:1959, the concrete was poured into standard moulds once the mix was made even.

- Compressive strength samples: cubes that are 150 mm × 150 mm × 150 mm
- Split tensile strength samples: cylinders that are 150 mm wide and 300 mm tall
- Flexural strength samples: beams that are 100 mm × 100 mm × 500 mm

After 24 hours, all of the samples were taken out of their moulds and put in a water tank with a pH level that was just right for 7, 14, and 28 days.

4. Results and Analysis

4.1 Introduction

The primary focus is to analyze the effects of various percentages of steel slag replacement namely 0%, 10%, 20%, and 30% on the fresh and hardened properties of concrete. The evaluation involves a systematic interpretation of data obtained from workability tests, compressive strength assessments at 7, 14, and 28 days, as well as tensile and flexural strength tests.

4.2 Visual Examination of Specimens and Materials

Figure 4.1 shows that the cured concrete cube samples, which were designated MS0 (0% slag), MS1 (10%), MS2 (20%), and MS3 (30%), had surfaces that were mostly smooth and well-compacted. This shows that the material may become less cohesive, which could be because the slag is angular and has a coarser texture as coarse aggregate.

Figure 4.1: Concrete Cube Specimens after Demoulding and Curing

The steel slag material in Figure 4.2 was mechanically sieved and had a rough, porous, and angular shape that was very different from the rounded natural coarse aggregates. This angularity may make it easier for things to stick together at the interface, but it could also make it harder to deal with because it makes friction harder.

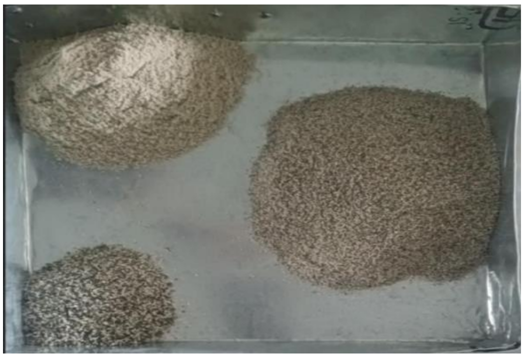


Figure 4.2: Sieved Steel Slag Samples Classified by Particle Size

Also, Figure 4.3 illustrates the stack of IS sieves that were used to do gradation tests on both natural aggregates and steel slag. These sieves, which ranged in size from 4.75 mm to 150 µm, were very helpful in checking the particle size distribution according to IS 383:2016 and backing up the mix design that was described earlier. In Section 4.6, you may see the results of this sieve analysis.

Figure 4.3: Standard IS Sieves Used for Aggregate Gradation

In short, these data support the idea that the physical structure of steel slag helps with mechanical performance but needs to be mixed differently to make it easier to work with and get a good finish. Notably, replacing up to 20% of the slag exhibited good look and compaction, but replacing more than that may cause problems with the surface.

4.3 Workability Test Results (Slump Test)

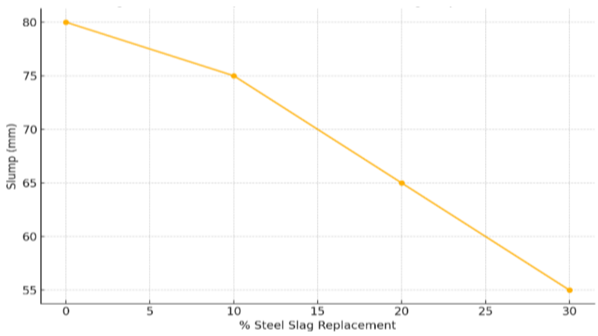
The slump cone test, which is based on IS 1199:1959, was used to check how well new concrete mixes worked. The goal was to see how adding more steel slag (which was used to partially substitute coarse material) affected the consistency and convenience of placing concrete. Table 4.1 shows the slump values for concrete mixes MS0 to MS3, which had 0%, 10%, 20%, and 30% of the coarse aggregate replaced with steel slag. The data show a clear downward trend:

the slump value went from 80 mm (MS0) to 55 mm (MS3). The slump is getting lower with time because the steel slag particles have more angular shapes, rough surfaces, and higher absorption rates. These factors increase internal friction and make it harder for free water to get into the mix. Figure 4.4 displays these patterns in a way that makes it evident that the slump goes down in a straight line as the percentage of steel slag goes up. especially when more than 20% is used as a replacement.

Table 4.1: Slump Test Results

Mix ID	**% Steel Slag Replacement**	**Slump (mm)**
M0	0%	80
M1	10%	75
M2	20%	65
M3	30%	55

As shown in **Figure 4.4**, the slump value consistently declined with the increase in steel slag content. This indicates reduced workability and higher internal friction in the mix, necessitating potential adjustments in water content or use of admixtures at higher replacement levels.



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4.4 Compressive Strength Results

The compressive strength of concrete mixes with steel slag at 7, 14, and 28 days after mixing them according to the IS 516:1959 standards to see how the mechanical strength changed over time. The test was done on standard cube samples of each mix: M0 (0% slag), M1 (10%), M2 (20%), and M3 (30%). The coarse aggregate (20 mm) was replaced by slag by volume. Table 4.2 shows the compressive strength values for different curing ages. The results show that replacing up to 20% of the slag greatly increases the compressive strength. Mix M2 (20% replacement) had the highest 28-day strength at 36.8 MPa, which was better than the control mix's strength of 33.5 MPa. Mix M3 (30%), on the other hand, showed a small drop in strength during all curing times. Figure 4.5 shows how the strength of the mixes changes over time and proves that 20% slag is the best mix since it has the right amount of packing density and mechanical performance.

Table 4.2: Compressive Strength at Different Ages

Mix ID	**% Slag**	**7-Day (MPa)**	**14-Day (MPa)**	**28-Day (MPa)**
M0	0%	22.5	28.0	33.5

Mix ID	% Slag	7-Day (MPa)	14-Day (MPa)	28-Day (MPa)
M1	10%	24.0	29.5	35.0
M2	20%	25.8	31.0	36.8
M3	30%	23.0	28.5	34.0

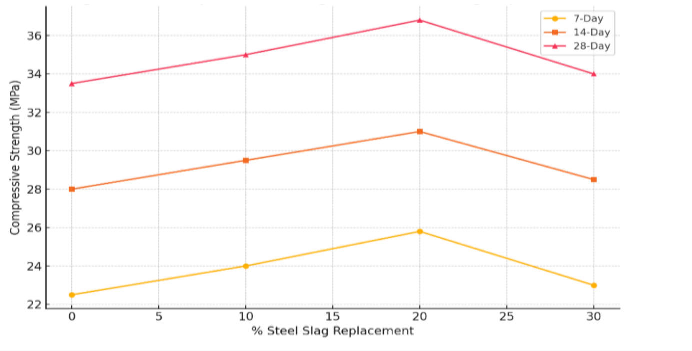

Figure 4.5 Compressive Strength vs. % Steel Slag Replacement

4.5 Split Tensile and Flexural Strength Results

At 28 days, the concrete's tensile and flexural properties were further tested to see how steel slag affected its indirect tensile behaviour and resistance to bending. The split tensile strength test on standard cylindrical samples according to IS 5816:1999. Table 4.3 shows that tensile strength went up from 2.5 MPa (MS0) to 2.9 MPa (MS2), with the highest value at 20% slag substitution. After this point, M3 showed a small drop to 2.7 MPa. Third-point loading on beam samples according to IS 516 to measure the flexural strength. Table 4.4 shows that the results went from 4.2 MPa (MS0) to 4.5 MPa (MS2), then dropped slightly to 4.3 MPa (MS3). These trends show that replacing up to 20% of coarse aggregate with steel slag can greatly increase tensile performance. This is because the angular and rough surfaces of slag particles make it easier for the aggregate to connect with the matrix. Figure 4.6 shows the trends in tensile and flexural strength, which supports the conclusion that adding 20% slag is the best option from a mechanical point of view.

Table 4.3: Split Tensile Strength at 28 Days

Mix ID	% Slag	Split Tensile Strength (MPa)
MS0	0%	2.5
MS1	10%	2.6
MS2	20%	2.9
MS3	30%	2.7

Table 4.4: Flexural Strength at 28 Days

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Mix ID	% Slag	Flexural Strength (MPa)
MS0	0%	4.2
MS1	10%	4.3
MS2	20%	4.5
MS3	30%	4.3

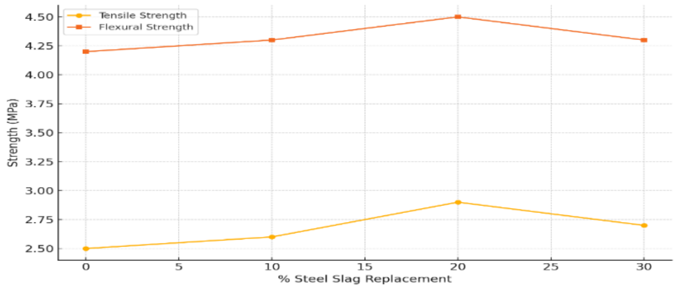

Figure 4.6: Tensile and Flexural Strength at 28 Days

4.6 Sieve Analysis and Particle Size Gradation

As per IS 2386 (Part I):1963, a complete sieve analysis was done on both river sand and steel slag to make sure that the steel slag utilised as a coarse aggregate substitute fits the gradation requirements of fine aggregates in concrete. The analysis used a conventional IS sieve stack that went from 4.75 mm to 150 µm, as shown in Figure 4.3. Table 4.5 shows a summary of the outcomes.

Table 4.5: Particle Size Distribution of Steel Slag and River Sand

Sieve Size (mm)	% Passing (River Sand)	% Passing (Steel Slag)
4.75	100	100
2.36	91.2	86.3
1.18	72.5	64.8
0.600	54.1	48.6
0.300	35.6	28.7
0.150	16.8	11.5

The results show that steel slag has a coarser gradation than river sand, with a lesser percentage of fine particles passing through smaller sieve sizes. This roughness is due to its angular texture, which may help with mechanical bonding but makes it harder to work with, which is what the slump test results in Section 4.3 show. Even if the steel slag gradation is not very fine, it is still within the Zone II restrictions set by IS 383:2016, which means it can be used as a partial substitute in concrete mixtures.

4.7 Comparative Analysis and Discussion

This part compares the concrete mixes MS0 to MS3 based on the test results for slump, compressive strength, split tensile strength, and flexural strength. Table 4.6 is a summary of the information.

Table 4.6: Summary of All Properties at 28 Days

Mix ID	Slump (mm)	Comp.Strength (MPa)	Tensile Strength (MPa)	FlexuralStrength (MPa)
MS0	80	33.5	2.5	4.2
MS1	75	35.0	2.6	4.3
MS2	65	36.8	2.9	4.5
MS3	55	34.0	2.7	4.3

As seen, the best mechanical performance was reached with 20% steel slag substitution (M2). This blend had the best results on all mechanical testing while still being easy to work with. The angular and rough shape of the slag particles helped them fit together better and made fewer microvoids, which improved their ability to bend and compress. However, when more than 20% of the material is replaced, performance starts to drop slightly, especially in slump and compressive strength. This suggests that too much slag may make hydration less effective since it increases the surface area and water demand. If you want to employ more slag in a practical way, you will require superplasticizers or water-reducing additives. These results are in line with what Reddy et al. (2022) and Mishra et al. (2020) found before, which also said that the greatest structural outcomes come from replacing 15–25% of the slag. This study adds to the body of knowledge by providing particular benchmark values for strength metrics that may be used in real-world situations for designing sustainable concrete mixes.

4.8 Summary of Findings

Based on tests, the following conclusions may be made about using steel slag as a partial replacement for coarse aggregate in concrete:

- The slump test trends show that workability goes worse as the amount of slag goes up because the texture is more angular and there is more friction.
- Mechanical strengths, such compressive, tensile, and flexural, go up a lot up to 20% replacement with the M2 mix giving the best results.
- The sieve test shows that steel slag has bigger particles, although they are still within the Zone II limitations of IS 383:2016.
- Visual checks also show that the specimens are all the same, with only small faults seen when the slag level is higher.
- The 20% replacement level is the best balance between strength and workability, making it the optimal blend for structural-grade uses.

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The study confirms that steel slag can be used in concrete instead of natural aggregates and is both technically sound and good for the environment. Future studies can look into higher levels of replenishment by adding admixtures and check long-term durability factors including resistance to sulphate and penetration of chloride.

5. Conclusion and Future Scope

The current study did a good job of looking at whether steel slag may be used as a partial replacement for fine aggregate in concrete. Experimental results show that replacing up to 20% of river sand with steel slag makes concrete much stronger. Mix MS2 (20% slag replacement) had the highest compressive strength (36.8 MPa), tensile strength (2.9 MPa), and flexural strength (4.5 MPa) after 28 days. The angular shape and rough texture of steel slag particles help them fit together better in the cementitious matrix, which makes the bond stronger. However, performance dropped at 30% slag concentration, perhaps because there were too many voids and the material was harder to work with, as shown by the slump test and visual observations (Figures 4.1–4.4). The results also showed that steel slag meets the grading criteria of IS 383:2016 and is in Zone III, which means it can be used as a structural substitute for natural sand. Using steel slag has two benefits from both an environmental and an engineering point of view: it helps manage trash in a way that is good for the environment and it makes concrete work better.

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