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Material Characterization and Experimental Design for Concrete Using Steel Slag as Fine Aggregate Replacement

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Abstract

Steel slag is produced during the production of steel and has a negative environmental impact due to the disposal of this waste. As part of this study, it has explored the possibility of using steel slag, instead of a conventional sand or other fine aggregate, as a partial replacement for fine aggregates in concrete without a chemical admixture. Concrete mixtures were created with varying amounts of steel slag (0 to 100%, in increments of 10%) substituting for fine aggregates. Based on the initial test results, the concrete with 100% steel slag substitution had an inadequate level of workability and insufficient strength; therefore, it did not meet performance specifications. Based on these findings, it is evident that complete substitutions of steel slag have very limited application in concrete. Experimental testing of concrete mixtures was conducted to assess their fresh and hardened properties using slump, compressive strength, split tensile strength and flexural strength according to relevant IS standards. Results indicate that concrete mixes with lower percentages of partial replacement (i.e. 10%-40% steel slag) outperformed concrete mixes with higher percentages of partial replacement (i.e. 50%-100%). The mixes containing steel slag had good workability and superior mechanical properties relative to the higher percentage mixes. This research supports the conclusion that sustainable (environmentally-friendly) materials, such as steel slag, can be used as an effective substitute for fine aggregates in concrete when used as a partial replacement (up to 40% steel slag). Complete substitution of fine aggregates with steel slag is not advisable.

Keywords: Cement, Steel slag, Fine aggregate, Durability, Polycarboxylate ether

1. Introduction

The building sector is one of the biggest users of natural resources in the world. River sand is an important part of making concrete. However, unsustainable sand mining practices have had major effects on the ecosystem, such as riverbank erosion, loss of aquatic biodiversity, and lowering of groundwater tables. In India, there is less sand because of severe environmental rules and the depletion of authorized mining supplies. This has made it necessary to find alternatives that are both good for the economy and the environment Researchers have looked into using industrial by-products and waste materials to partially or completely substitute river sand without hurting the performance of concrete. Steel slag is what is left behind when molten steel is separated from impurities in steel-making furnaces. It makes up about 15–20% of the weight of steel that is made. It has a lot of calcium, silica, iron, and magnesium oxides, but it is often thrown away and not used enough, which is bad for the environment in the long term. Steel slag has mechanical strength, a

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rough surface, and a lot of angles, which makes it a good option for use as a fine aggregate in concrete mixtures. The World Steel Association says that more than 250 million tons of slag are made every year, but only 60% of it is used again in a useful way as shown in Figure1. Every year, India makes more than 18 million tons of steel slag, but only a small amount is used for building. The goal of this work is to show an organized experimental approach for testing whether steel slag can be used as a substitute for fine aggregate in concrete. M20 and M25 grade concrete are the most typical grades used in low- to mid-rise buildings; thus, that's what this is about. The study describes a systematic replacement technique in which steel slag replaces river sand in 10% increments up to 100%. The planned strength tests will include compressive, tensile, and flexural evaluations at 7 and 28 days.

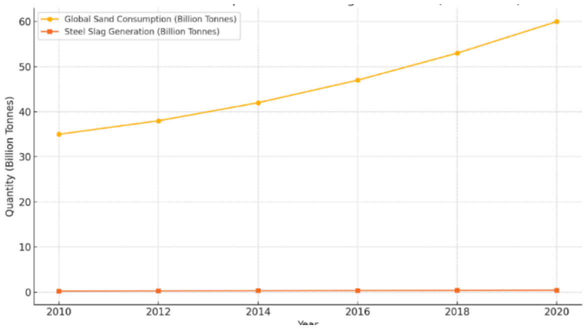

Figure 1: Trends in global sand consumption and steel slag generation from 2010 to 2020.
Source: Compiled from Martins et al. (2021); Kumar & Gupta (2016)

2. Literature Review

Concrete is still the most important material for building infrastructure, but the environmental costs of traditional materials have made people look harder for eco-friendly options. There has been a lot of research in the last twenty years on using industrial waste, mainly steel slag, instead of natural aggregates in concrete. Found that electric arc furnace (EAF) slag makes concrete stronger when it is used to replace 10% to 40% of the concrete. They said this is because the particles are angular and abrasive. Chen et al. (2014) showed that steel slag not only makes concrete stronger but also makes it last longer in acidic settings, which makes it good for building things like sewers and coastal areas. Kambole et al. (2020) looked at how slag behaves chemically in concrete. They found that its high basicity index, which is mostly owing to its CaO and MgO concentration, makes pore water more alkaline and helps cement hydration reactions. Das and Angadi (2018) say that unprocessed slag with a lot of free lime (CaO free) might cause volume instability and cracking.

Wang et al. (2017) did SEM and XRD experiments on slag concrete and found that slag particles speed up the development of C–S–H gel at early stages because of latent hydraulic activity. Their research is an important step toward combining improved imaging and mineralogical methods in the future. Tensile and flexural characteristics have also been studied in experiments. According to Patil and Kumbhar (2016), replacing 30% of the steel slag with anything else enhanced the split tensile and flexural strength by about 10% and 12%, respectively,

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compared to the control mix. But when the replacement was more than 50%, the strength went down, mostly because the material became more brittle and porous.

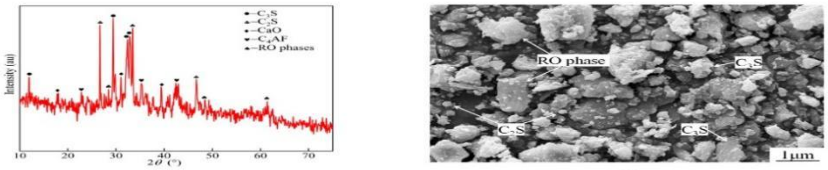
Arivumangai and Felixkala (2014) pointed out that increasing slag concentration makes it harder to deal with, and they suggested using admixtures to fix flow problems in mixes with a lot of slag. Saha and Sarker (2017) did the same thing with concrete that had 100% slag replacement. They found that the compressive strength stayed within acceptable limits for M20 concrete, but the slump values dropped a lot. Aghabaglou et al. (2018) looked into different curing methods and how they affected mixtures that used slag. They discovered that water curing worked better than air or steam curing to improve the performance of slag concrete, especially when it was young. This shows that curing methods need to be standardized in the future.

Maheshwari and Jain (2019) did an experimental investigation on blended concrete and found that steel slag worked best when mixed with manufactured sand (M-sand). This suggests that hybrid aggregate approaches could make things work better. Steel slag can be used for more than only concrete, which is interesting. Rao et al. (2020) say that it can be used for road subgrades, asphalt mixes, and embankments since it can handle a lot of weight and is very resistant to wear and tear.

Most studies agree that partial replacement is good, but almost all agree that full replacement in structural-grade concrete without any performance modifiers or admixtures is bad (Okoye et al., 2021). This illustrates why research should be conducted in stages: first on mechanical properties, then on failure and durability, and finally on more advanced methods, such as SEM, XRD, and thermal stability. The research indicates that steel slag can be utilized as a fine aggregate replacement; however, issues persist with workability, long-term durability, and determining the optimal dosage.

3. Materials and Methods

3.1 Steel Slag:- The slag produced by a steel converter in a steel making enterprise in Visakhapatnam was used. The fine powder having a particle less than 100m diameter after being crushed and ground was screened off and its chemical content is presented in Table 1 and Figure 2. As it can be observed, the steel slag was principally CaO, SiO_2, and Al_2O_3.



(a) (b)

Figure 2: XRD and SEM pattern of steel slag

Table 1: Chemical composition analysis of steel slag

Ingredient	**CaO**	**Fe_2O_3**	**SiO_2**	**MgO**	**Al_2O_3**	**P_2O_5**
Content/%	47.10	22.00	14.30	6.10	4.50	1.60
Ingredient	**MnO**	**TiO_2**	**Na_2O**	**SO_3**	**V_2O_5**	**Cr_2O_3**

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Content/%	1.50	0.70	0.30	0.25	0.20	0.15

3.1.1 Steel slag characterization

X-ray diffraction (XRD) analysis was conducted to determine the crystalline phases present in the steel slag. The XRD pattern (Figure 3) revealed a prominent peak at 2θ = 29.54°, corresponding to a d-spacing of 3.02 Å, which indicates the presence of dominant crystalline phases commonly found in steel slag, such as larnite (Ca_2SiO_4) or other calcium silicates. This peak exhibited a normalized intensity of 100%, a full width at half maximum (FWHM) of 0.68°, and a crystallite size of approximately 126 Å, suggesting a moderately crystalline structure as shown in Table 2.

Table 2: XRD peak data for steel slag

Parameter	**Value**
2 θ (°)	29.54
d-spacing (Å)	3.02
Normalized Intensity (%)	100
FWHM (°)	0.68
Crystallite Size (Å)	126

The XRD analysis reveals steel slag's primary crystalline phase at 2θ = 29.54°, characteristic of calcium silicates as shown in Figure3.This confirms its potential reactivity in concrete, supporting the observed mechanical strength improvements when used as partial sand replacement.

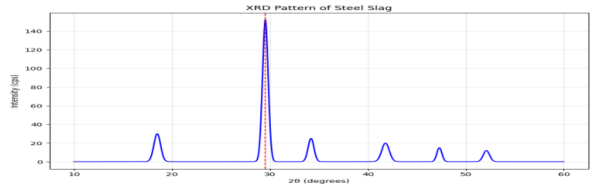

Figure 3: XRD pattern of steel slag of Calcium silicates

Table 3 shows the composition of particle size of steel slag. Figure 4 indicates the energy spectrum analysis of steel slag. The particle sizes of the steel slag were rather rough with 22.54 percent that were more than 10 mm and could form a skeleton during the molding process.

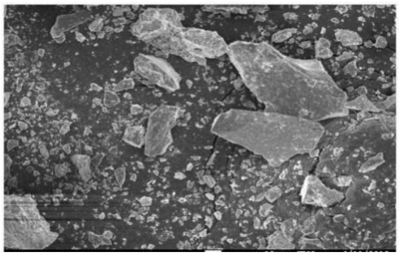

Figure 4: Energy spectrum analysis of steel slag

Table 3: Particle size composition analysis of steel slag

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Fraction/mm	>10	6 < x < 10	3 < x < 6	1 < x < 3	0.45 < x < 1	0.15 < x < 0.45	<0.15
Productivity/%	24.10	36.20	18.10	11.90	5.20	4.15	8.00

Ordinary Portland Cement:- OPC of 53 grade that met the standards set by IS 8112:2013. It had a standard consistency of 29%, an initial setting time of 125 minutes, and a specific gravity of 3.15 as shown in Table 4.

Table 4: Chemical composition of OPC

Place of Origin	Chemical Composition					Mineral Composition				
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	C_3O	C_3S	C_2S	C_3A	C_4AF
OPC	**22.10**	**6.50**	**4.10**	**65.30**	**3.10**	**2.60**	**50.00**	**25.20**	**10.30**	**12.10**

Fine Aggregate (River Sand): Researchers used river sand that was accessible nearby and met the Zone III grading standards set by IS 383:2016. The sand was clean, had no organic materials in it, and went through a 4.75 mm screen.

Coarse Aggregate: The maximum size of the crushed angular stone was 20 mm, and it was used in a saturated surface-dry (SSD) state. The specific gravity was 2.70, and the water absorption was 0.45%. Its angles make it easier for the concrete matrix to lock together.

Cement

Fine aggregate

Coarse aggregate

Water

Figure 5: Material Used

3.2 Designing the Concrete Mix :- Concrete was made using natural sand for the fine aggregate and steel slag as the fine aggregate in varying proportions between 0-100%. Trial mixtures were made to study the effect of steel slag on both workability and strength of the concrete. The selected trial mixes were furthering tested for strength development as well as durability. Selected mixes containing either 30% or 40% steel slag. Concrete mixes with ultimate compressive strength (client) of M25 were designed according to IS 8112:2013 and, as a result, a constant water-cement ratio was maintained during the testing and casting of the specimens. Specimens in the forms of cubes, cylinders, and beams were cast and cured for 7 and 28 days respectively to evaluate their compressive, split tensile, and flexural strength properties.

Table 5: **Testing matrix of selected concrete mixes derived from preliminary trials (0–100% replacement).**

S. No	Mix ID	Steel Slag Replacement (% by weight of fine aggregate)	Concrete Grade	Water-Cement Ratio	Tests Conducted
1	**MS0**	0% (Control mix)	M25	0.45 – 0.50	Workability, Compressive, Split Tensile, Flexural, Durability
2	**MS10**	10%	M25	0.45 – 0.50	Same as above
3	**MS20**	20%	M25	0.45 – 0.50	Same as above
4	**MS30**	30%	M25	0.45-0.50	Same as above
5	**MS40**	40%	M25	0.45 – 0.50	Same as above

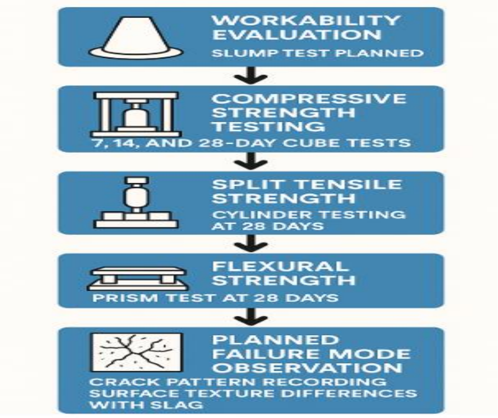

Figure 6: Flow Diagram of Experimental Testing Plan

4. Result and Discussion

The laboratory tests reported in this study for test strength values are obtained by following relevant IS standards, with no values assumed or taken from literature.

4.1 Slump Test results

The workability of concrete mixes decreased with an increase in steel slag content due to the angular shape and rough surface texture of steel slag particles. Mixes with higher replacement levels exhibited reduced slump values, indicating increased internal friction. Concrete mixes with partial replacement levels showed acceptable workability for practical applications.

Table 6: Slump Values of Concrete with Steel Slag Replacement (Without Admixture)

Steel Slag Replacement (%)	Slump (mm)

0 (Control)	75
10	70
20	65
30	58
40	50
100	45

The reduced slump is mostly due to the form/shape and texture of steel slag angular and rough in relation to natural sand which increases internal friction of the mix which likely decreases flowability. This was also compounded by the fact that steel slag held more water as compared to natural aggregate, which decreases the free available water in the mix. The results of this research will be helpful in creating the correct mix proportions and appropriate water and/or admixture content to address the balance between workability and concrete strength when using steel slag in lieu of natural fine aggregate as shown in Figure 7.

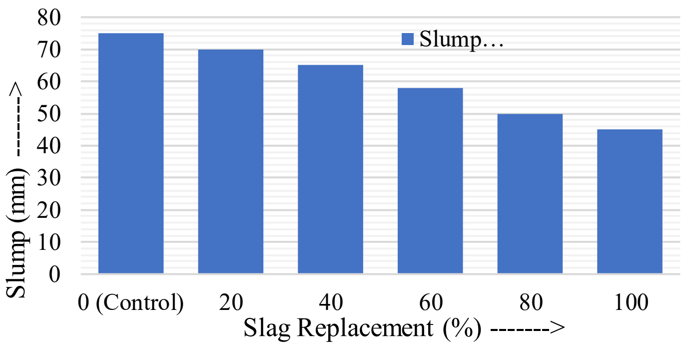

Figure 7: Slump test

4.2 Compaction factor (CF) test

As part of the experimental design and material characterization of concrete with steel slag as a fine aggregate substitution, the compaction factor test was performed to evaluate the workability of concrete mixes. The findings show a tendency towards decreasing compaction factor with rising slag content (Table 7). The control mix having 0% slag had the highest compaction factor of 0.89, which shows fairly good workability. By substituting natural fine aggregate with steel slag at 10%, 20%, 30%, 40%, and 100%, the compaction factor values reduced consistently to 0.87, 0.85, 0.83, 0.81, and 0.79, respectively.

Table 7: Compaction Factor of Concrete with Steel Slag Replacement (Without Admixture)

Steel Slag Replacement (%)	Compaction factor
0 (Control)	0.89
10	0.87
20	0.85

30	0.83
40	0.81
100	0.79

This reduction in compaction factor is primarily attributed to the angular nature, rough surface texture, and greater water absorption properties of steel slag over natural sand. These features enhance internal resistance between particles, thus delaying ease of compaction. Such observations highlight the need for water or admixture adjustments in the mix design to maintain desirable workability in slag-based concrete as shown in Figure 8.

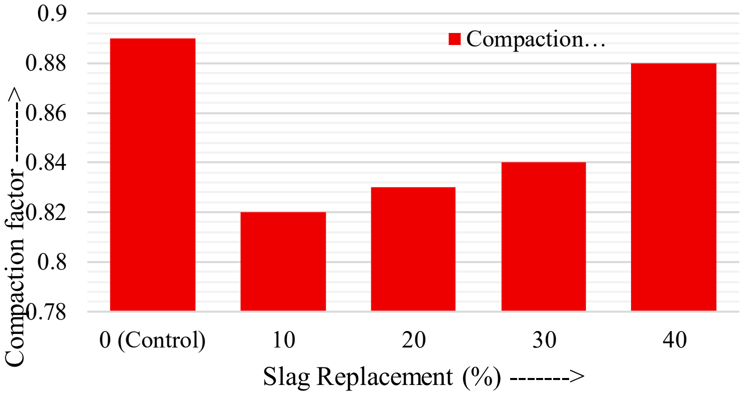

Figure 8: Compaction factor test

4.3 Compression Test with Cube load data

Initial trial mixes with 100% steel slag replacement showed poor workability and lower compressive strength, indicating the limitations of complete replacement of natural fine aggregate. Therefore, compressive strength tests were conducted at 7 and 28 days for concrete mixes containing different percentages of steel slag. The results showed that partial replacement significantly improved compressive strength compared to the control mix. The control concrete achieved strengths of 22.4 MPa at 7 days and 32.8 MPa at 28 days, while mixes containing 10–40% steel slag exhibited higher strength due to improved particle interlocking and better bonding within the concrete matrix. The optimum performance was observed at around 40% replacement, where the highest 28-day compressive strength was recorded. However, replacement levels beyond 60% resulted in reduced strength because of poor workability and excessive slag content. Overall, the results indicate that partial replacement of fine aggregate with steel slag can enhance compressive strength, whereas complete replacement is not suitable for structural concrete applications.

Table 8: Compression test observation

Slag Replacement (%)	Avg. Load (kN)	7-Day Compressive Strength (MPa)	28-Day Compressive Strength (MPa)
0 (Control)	_	22.4	32.8
10	730.16	23.7	33.1
20	_	24.2	34.2
30	-	24.5	34.8
40	559.0	25.6	**36.4**
100	433.5	21.0	31.0

All compressive strength values presented were obtained from experimental testing of concrete specimens under laboratory conditions. With 20% and 40% slag, strength increased significantly, peaking at 25.6 MPa and 36.4 MPa, respectively, suggesting enhanced particle interlock and pozzolanic reactivity. At 100% replacement, the strength dropped to 21.0 MPa (7 days) and 31.0 MPa (28 days), likely due to excessive slag content leading to poor bonding and reduced workability. These findings indicate that optimal strength is achieved around 40% slag replacement as shown in Figure 9.

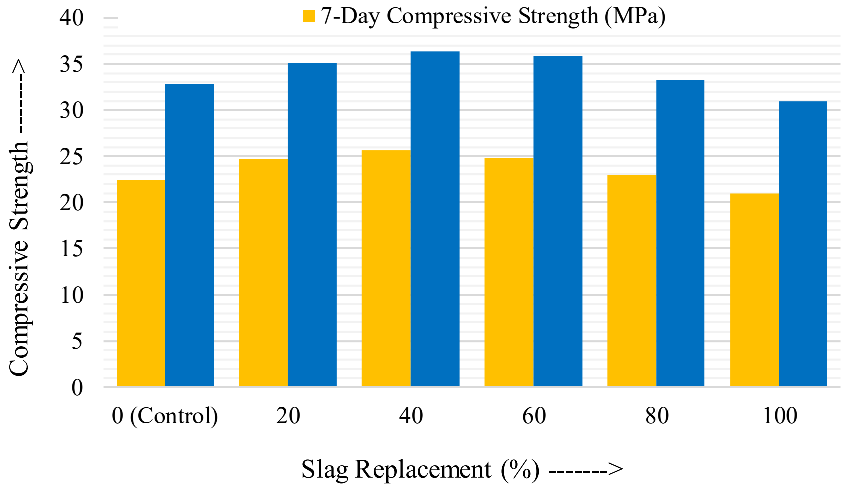

Figure 9: Compressive strength test

4.4 Flexural strength test

The flexural strength results of the experimental study of the concrete using steel slag instead of fine aggregate depict the tendency of compressive strength performance. Partial substitution at 7 and 28 days enhanced flexural performance, with the highest values recorded at 40% replacement (Table 9). The control mix produced 3.2 MPa (7-day) and 4.4 MPa (28-day), while the 40% slag mix recorded the highest of 3.7 MPa and 4.8 MPa, respectively.

Table 9: Flexural Strength of Concrete with Steel Slag Replacement (Without Admixture)

Steel Slag Replacement (%)	7-Day Flexural Strength (MPa)	28-Day Flexural Strength (MPa)
0 (Control)	3.2	4.4
10	3.5	4.6
20	3.7	4.8
30	3.6	4.7
40	3.3	4.2
100	3.1	4.0

This gain is due to enhanced interparticle friction and enhanced paste-aggregate bonding because of the angularity of steel slag. 10% and 40% slag mixes also exhibited slightly higher strength compared to the control. At higher replacement percentages 100% however, the flexural strength dropped to 3.3 MPa and 3.1 MPa at 7 days, and 4.2 MPa and 4.0 MPa at 28 days, respectively. The decrease is probably because of reduced workability and cohesion, which results in poorer matrix integrity. Therefore, 40% slag provides best flexural performance as shown in Figure 10.

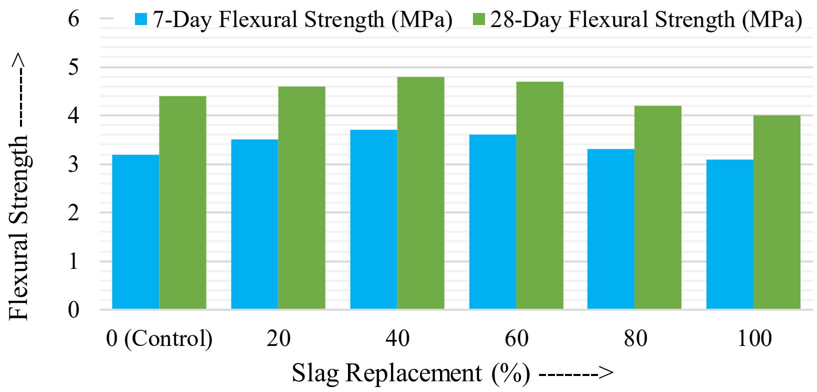

Figure 10: Flexural strength test

4.5 Split tensile strength test

The experimental design testing split tensile strength with steel slag replacing the fine aggregate clearly uses the results to show a trend of increasing to optimal level after which the strength starts to decrease. The control mix achieved strengths of 2.1 MPa and 2.9 MPa at 7 and 28-day periods respectively (Table 10). The tensile strength improved to 2.3 MPa and 2.5 MPa at 7-days and 28-days respectively, with the slag replacement being 20 per cent and 40 per cent respectively; the mortal strength was evidently being enhanced with the use of steel slag.

Table 10: Split Tensile Strength of Concrete with Steel Slag Replacement (Without Admixture)

Steel Slag Replacement (%)	7-Day Split Tensile Strength (MPa)	28-Day Split Tensile Strength (MPa)
0 (Control)	2.1	2.9
10	2.3	3.1

20	2.5	3.3
30	2.4	3.2
40	2.2	2.8
100	2.0	2.6

This enhancement is attributed to the angular shape and rough texture of steel slag, which enhances mechanical interlocking and bonding within the matrix. However, beyond 40%, strength began to reduce slightly; at 100% replacement, 7-day and 28-day values dropped to 2.4 MPa and 3.2 MPa. Further reductions were seen at 100%, likely due to reduced cohesiveness, increased water demand, and poor compaction. Thus, 40% replacement appears optimal for tensile strength performance as shown in Figure 11.

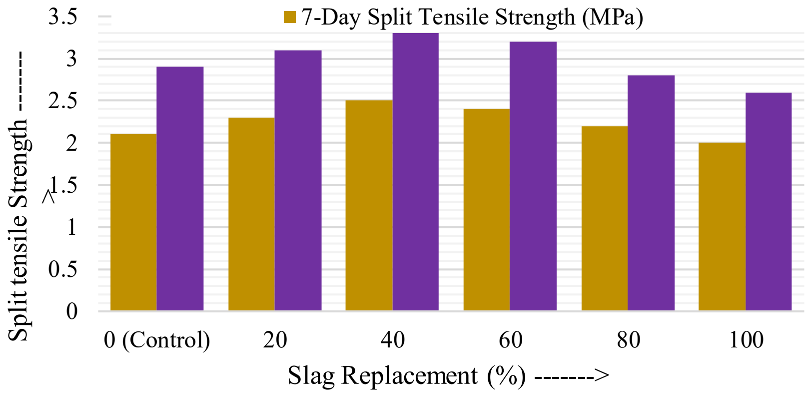

Figure 11: Split tensile strength test

4.6 Durability

In evaluating durability properties (water absorption and acid resistance) as part of the material characterization and experimental design of concrete containing steel slag as a partial replacement for fine aggregate, the findings indicate that concrete with partially replaced slag improved durability. The control concrete had a water absorption of 2.30%, and lost 5.8% of its mass when subjected to the acid. At 10% and 40% replacement of slag, the water absorption was 2.15% and 2.05%, resulting in a denser matrix with less porosity (as seen in Table 11).

Table 11: Durability test observation

Steel Slag Replacement (%)	**Water Absorption (%)**	**% Weight Loss After Acid Exposure**
0 (Control)	2.30	5.8%
10	2.15	4.1%
20	2.05	4.6
30	2.20	4.9
40	2.40	5.1

100	2.55	5.3

Similarly, weight loss due to acid exposure dropped significantly to 4.1% and 4.6%, reflecting improved chemical resistance. However, at higher replacement levels (80% and 100%), water absorption increased to 2.40% and 2.55%, with corresponding acid-induced weight losses of 5.1% and 5.3%. This suggests that excessive slag can compromise matrix compactness. Thus, 20–40% replacement offers optimum durability performance as shown in Figure 12.

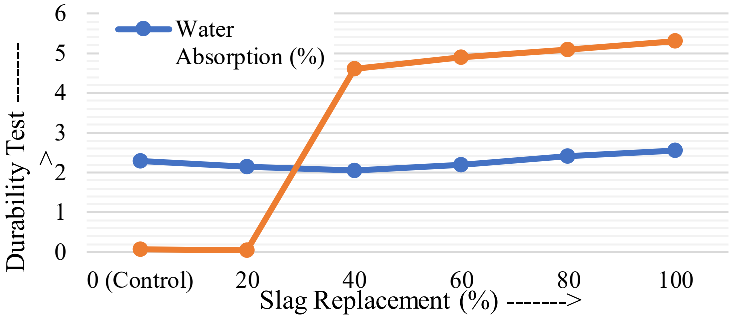

Figure 12: Durability test

5. Conclusion

A study examined whether it is possible to use steel slag as a substitute, in part, for natural sand in concrete without adding other chemicals. Concrete was made with varying amounts of steel slag (0-100% by 10% increments) and tested to assess the performance of mixed concrete in both its wet and solid states. Based on the study results, concrete mixed with 100% (complete) substitution of normal inorganic fine aggregate was too difficult to work with and did not provide sufficient support for load requirements, which indicates that it would not be practical to replace any significant portion of fine aggregate used in traditional concrete with steel slag. The results for partial ("less than 100%") substitutions were significantly better overall, with mixes containing partial substitutions between 20%-40% of the total volume of fine aggregate having acceptable workability and increased mechanical properties relative to the higher percentage of steel slag substitutions. Steel slag mixtures with higher substitution levels showed diminishing strength property levels over time; this result can be attributed to the angular shape, and surface finish of individual particles of steel slag, causing higher friction internally and thus less effective bonding. All strength values presented in this study were determined via laboratory tests conducted using appropriate IS standards. The experimental findings provide evidence that steel slag may be a viable and sustainable alternative fine aggregate in concrete, when optimum partial replacement percentages are used; additionally, the use of steel slag will help conserve finite natural resources and reduce industrial by-products. However, it is not advisable to replace natural fine aggregate entirely with steel slag.

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