Strength and Durability Properties of Steel Slag Incorporated Self-curing Concrete

Karthika Balakrishnan and Lalith Prakash Elavazhagan

Abstract There is a growing global interest in SAP-treated cement-based materials due to their excellent durability, fracture resistance, wide availability, and cost-effectiveness. However, a drawback of SAP usage is the development of macropores when the polymer releases water, weakening the material's mechanical characteristics. To address this concern, steel slag, a byproduct of steelmaking, is used as a partial replacement for fine aggregate to compensate for the loss of strength. Steel slag emerges as a viable alternative as a partial replacement for natural aggregates when the natural aggregate usage in concrete fails to meet the required quantity and quality standards. This study aims to investigate the mechanical and durability properties of self-curing concrete incorporating steel slag and sodium polyacrylate, a super-absorbing polymer (SAP). The research compares the results of these properties with conventional concrete. In M30 grade concrete, the fine aggregate was substituted with steel slag in 30 and 40% proportions. The percentage of superabsorbent polymer (SAP) by weight of cement was also varied to 0.1, 0.2, and 0.3%. Concrete mix with 0.1% SAP and 40% steel slag dosage exhibited superior mechanical properties. Durability tests conducted on this mix combination revealed a better performance compared to control concrete mix.

Keywords Super absorbing polymer · Sodium polyacrylate · Steel slag · Durability · Self-curing concrete

1 Introduction

Steel slag (SS) is a residual bi-product obtained from steel production. Significant volumes of this waste are produced, posing issues and hazards for the factories and the environment. The disposal of steel slag creates environmental issues like land, air, water pollution, and soil contamination because it contains various heavy metals

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M. Nehdi et al. (eds.), *Proceedings of SECON'23*, Lecture Notes in Civil Engineering 381, https://doi.org/10.1007/978-3-031-39663-2_22

and other contaminants that can reach into the soil if not properly handled [1]. One of the methods for addressing the issues that this solid waste causes is recycling. Solid waste management is of particular significance due to the escalating quantities of industrial by-products [2]. Steel slag may be used in concrete as both coarse and fine aggregate, as a component of asphalt highway pavement, as clinker-making raw materials, as ballast for roadways, and as filler for a variety of excavations. Using waste materials as aggregate materials are becoming more popular, and wide-ranging research is currently underway on the utilization of a diverse range of resources as aggregate substitutes, like steel slag, coal ash, and blast furnace slag, and to lower the cost of producing concrete by using fine aggregate made from discarded steel slag. The utilization of stainless steel as a building material is becoming more popular.

Recent studies show that introducing local unprocessed steel slag in concrete has a positive impact on both compressive and tensile strength [3]. The mechanical characteristics of the concrete are enhanced when SS is used as the FA. The SS can recompense for the loss of strength that causes due to the polymer which releases the water and macropores are developed. The mechanical strength of the sample enhanced greatly, because the hydration reaction produces CSH gel due to the comparatively high CaO concentration in steel slag. These gels fill the macropores, increasing the density of the structure. When the number of mesopores increases, the number of macropores decreases noticeably. The structure becomes more compact and homogenous, giving it the appearance of a sponge. The fine particles of steel slag having sizes 1–2 mm can also act as micro fillers, occupying interstitial spaces within the concrete matrix. This micro filler effect further enhances the overall densification of the concrete and reduces the presence of macro pores.

Based on studies and research, the best results are usually obtained for substitution ratios between 30 and 50%. Using a 30–50% replacement ratio of steel slag as fine aggregate has been shown to improve the mechanical properties. It can also improve the resistance to chloride ion penetration, which can help to prevent corrosion in reinforcing cement concrete [3]. The workability of concrete is negatively affected when steel slag is substitute for fine aggregate at a ratio of 50% or higher. However, when steel slag is used as a replacement for fine aggregate, it is important to consider that the slag aggregates possess an angular structure and vary in size distribution. This characteristic results in a significant improvement in compressive strength [4].

Curing is crucial, yet in places where water availability is scarce, improper curing happens. In the process of self-curing concrete, additional internal water helps the cement to hydrate, even during the mixing process, until the required final strength is achieved, and the leftover water is retained in the concrete by the small voids. Construction activities are increasing every day in remote and desert areas. Due to the shortage of water, the construction industry is finding alternative curing methods. Self-curing concrete is a curing method that capable to meet present and future requirements for curing concrete and that can enhance strength and durability. A crucial approach to enhance the durability characteristics of concrete involves reducing its permeability through effective compaction [5].

Super absorbent polymer (SAP), which was introduced in the 1980s, is primarily intending to convenience products, food packaging, and the sanitary and medical industries. It is a polyacrylic acid that can absorb, expand, and hold onto liquid without dissolving into a solution in the area between polymer chains and crosslinks. SAPs are inherently hydrophilic. The polymer chains in SAPs contain functional groups, such as carboxyl groups (–COOH), that attract and interact with water molecules. When SAPs come into contact with water, the hydrophilic groups on the polymer chains attract and bind with water molecules through hydrogen bonding. This interaction causes the polymer chains to undergo a process called swelling, where they absorb water and expand in size. The swelling of SAPs is facilitated by capillary action. The interconnected network of polymer chains and crosslinks creates small capillary spaces or voids within the material. These capillaries draw water into the SAPs, allowing them to absorb water from their surroundings. SAPs have a high absorption capacity due to the presence of void spaces that can accommodate water molecules. Once water is absorbed by SAPs, it is retained within the spaces between the polymer chains and crosslinks. The polymer matrix traps the water, preventing it from easily escaping. SAP can absorb and store water, releasing it gradually over time as needed.

SAP acquires strength early in the life of the concrete and inhibits self-desiccation due to its capacity for retaining an increased amount of water equivalent to its weight. Additionally, it acts as an internal curing agent in concrete, enhancing its strength and durability. When SAP is incorporated into the concrete mix, it can absorb a certain amount of water, reducing the loss of moisture during the curing process. This leads to more complete hydration of the cement particles, resulting in a denser and stronger concrete matrix [6]. Additionally, SAP can also reduce shrinkage and cracking of the concrete, resulting in a more durable and long-lasting structure. The use of SAP at various percentages (0.1, 0.2, 0.3%) is more advantageous than normal concrete in terms of compressive strength, durability and reduced shrinkage and cracking, and reduced need for external curing methods [7]. As time progresses, the internal curing effect becomes increasingly noticeable, resulting in a continuous enhancement of strength [8].

The comprehensive study presented in this research offers a profound comprehension of the diverse attributes exhibited by self-curing concrete incorporating steel slag, allowing for a comparison between the recorded outcomes and the experimental observations of the control mixture. The optimum replacement level refers to the ideal proportion of steel slag and SAP. It is determined through mechanical testing results. Self-curing has emerged as a viable alternative technique to minimize water usage during the curing process.

Table 1 Physical properties of cement

S. No.	Characteristics	Value obtained experimentally
1	Fineness	3%
2	Specific gravity	3.15
3	Normal consistency	34%

2 Materials

2.1 Cement

Standard OPC 53 grade cement was utilized, and its physical properties were tested in accordance with the standard procedure specified by IS 12269:1989 requirements (Table 1).

2.2 Fine Aggregate

Manufactured sand is a replacement for river sand in buildings. It is produced by crushing granite stones that are known for their hardness. The size of manufactured sand (M-SAND) is smaller than 4.75 mm. The tests were carried out under IS 383-2016.

2.3 Coarse Aggregate

Following the recommendations of IS 383-1970, locally available materials coarse aggregate with a maximum size of 20 mm was used (Table 2).

Table 2 Physical properties of fine aggregate and coarse aggregate

S. No.	Characteristics	Value for fine aggregate	Value for coarse aggregate
1	Bulk density (kg/m^3)	1696.30	1696.58
2	Water absorption (%)	2.05	0.51
3	Specific gravity	2.67	2.8

Table 3 Physical properties of steel slag

S. No.	Characteristics	Value obtained experimentally
1	Specific gravity	3.25
2	Fineness modulus	3.34

Fig. 1 SAP particle

2.4 Steel Slag

Steel slag (SS) is a residual by-product that is obtained during the production of steel. Stainless steel slag of size 1–2 mm is used. The grade of steel slag is in accordance with IS 455: 1989 (Table 3).

2.5 Super Absorbing Polymer

SAPs, which stands for sodium polyacrylate particles, have the unique ability to react with water, causing the polymer chains to expand and form a structure capable of absorbing water up to 200–300 times its own weight, subsequently transforming it into a hydrogel (Figs. 1 and 2).

2.6 Water

According to the Indian Standard Code, portable water is used to prepare the concrete mix. It is the basic requirement for the hydration of cement. It helps to maintain workability.

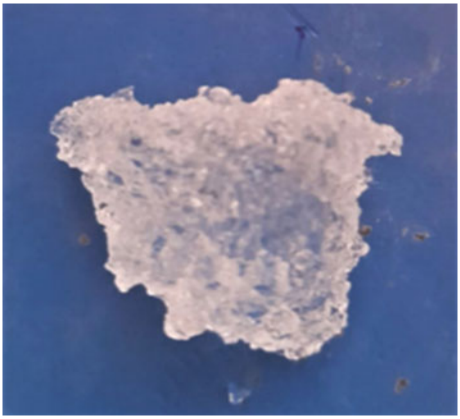

Fig. 2 SAP particle after absorption

3 Methodology

3.1 Mix Design

The mix design specifications for achieving M30 grade concrete has been prepared following IS 10262:2009, the mix design is 1:1.64:3.04 and the w/c ratio is 0.45 for maintaining workability for the control mix. The substitution ratios of steel slag were 30 and 40%, and the SAP dosages were 0.1, 0.2, and 0.3% by cement mass (Table 4).

Table 4 Mix for M30 concrete grade (kg/m^3)

Mix	Cement	CA	FA	SS	SAP	w/c
M1[a]	448	1366.12	735.59	0	0	0.45
M2	448	1366.12	545.13	220.76	1.36	0.45
M3	448	1366.12	441.54	294.35	1.36	0.45
M4	448	1366.12	545.13	220.76	2.73	0.45
M5	448	1366.12	441.54	294.35	2.73	0.45
M6	448	1366.12	545.13	220.76	4.09	0.45
M7	448	1366.12	441.54	294.35	4.09	0.45

[a] Control mix

Table 5 Mix percentage and combinations

Mix	Cement	CA	FA	SS	SAP
M1[a]	100	100	100	0	0
M2	100	100	70	30	0.1
M3	100	100	60	40	0.1
M4	100	100	70	30	0.2
M5	100	100	60	40	0.2
M6	100	100	70	30	0.3
M7	100	100	60	40	0.3

[a] Control mix

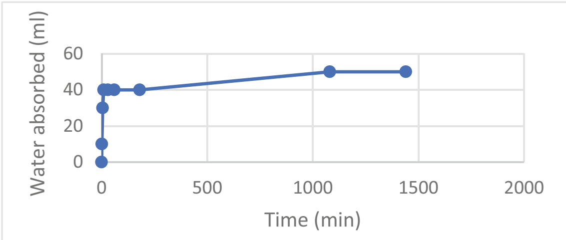

Fig. 3 Water absorbed for 1 g of SAP

4 Tests, Results and Discussions

4.1 Tea Bag Method

As per the Recommendation of RILEM TC 260-RSC, the tea bag method is a method used for measuring the absorption behavior of SAP. The dry tea bag containing 1 g of SAP was placed in a measuring jar containing 200 ml of water and covered with a lid to minimize carbonation and evaporation. The wet tea bag with an enlarged SAP was removed from the measuring jar after 1, 5, 10, 30, 60 min, 3 h, 18 h, and 24 h. Now, observing how much water is absorbed in each period, each SAP sample was measured by three individual tea bags. The water absorption becomes constant from 18 h so the average water absorption value is taken at the end of 24 h, which was conducted on 3 samples. The average water absorption is 50 ml per gram of SAP (Fig. 3).

4.2 Flow Table Test

To assess the workability of the concrete, a flow table test was conducted in accordance with the specifications outlined in IS 1199:1959. Flow percent is calculated for

Table 6 Mechanical proper test results at 28 days

S. No.	Mix combination	Flow percent (%)	Compressive strength (N/mm^2)	Split tensile strength (N/mm^2)	Flexural strength (N/mm^2)
1	M1[a]	34.67	31.21	2.46	3.53
2	M2	34.33	37.2	2.67	3.61
3	M3	40.67	41.33	2.88	4.1
4	M4	42.33	35.5	2.35	3.71
5	M5	51	30.41	2.45	3.8
6	M6	43.67	25.57	2.14	3.05
7	M7	47	2.61	2.38	3.7

[a] Control mix

each combination, and the results obtained are shown in Table 6. The flow table test results indicate that the flow table values of the concrete produced were between 34 and 51%. The M5 mix combination has better workability compared to the control mix (M1).

4.3 Compressive Strength Test

The compressive strength of a cube with dimension 10 cm × 10 cm × 10 cm by varying the percentage at 28 days is given in Table 6. According to IS 516-1969, compressive testing equipment, UTM was used to perform a compressive strength test on three cubes. The maximum compressive strength among the trial mixes corresponds to self-curing concrete incorporated with steel slag (M3), and it is 41.33 N/mm^2. The compressive strength reduces with SAP dosage beyond 0.1% (Fig. 4).

4.4 Split Tensile Strength Test

The split tensile strength of concrete was evaluated following the guidelines of IS 5816-1999, and the results are presented in Table 6. For each combination, three concrete cylinders measuring 100 mm in diameter and 200 mm in height were assessed. After a hydration period of 28 days, the specimens were positioned on the testing platform of a Compression Testing Machine (CTM). A uniformly distributed load was then applied until the specimens fractured. The split tensile strength is higher for self-curing concrete incorporating steel slag compared to a control mix. The maximum split tensile strength among the trial mixes corresponds to self-curing concrete incorporated with steel slag (M3), and it is 2.88 N/mm^2. The control mix (M1) has a comparable strength of 2.46 N/mm^2 (Fig. 5; Table 6).

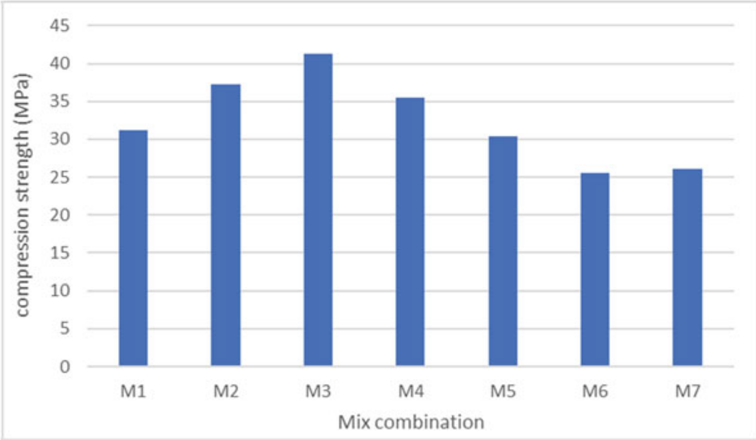

Fig. 4 Compression strength at 28 days

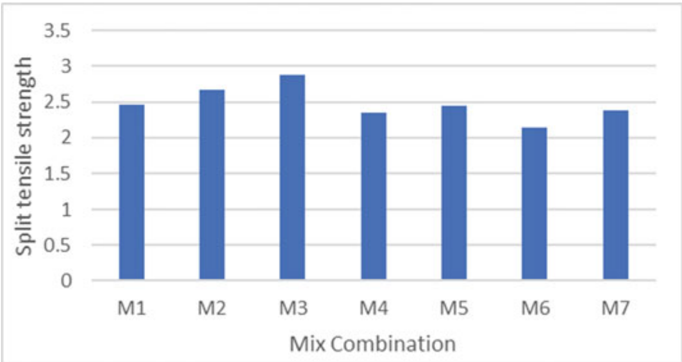

Fig. 5 Split tensile strength at 28 days

4.5 Flexural Strength Test

The flexural strength of concrete was assessed following the guidelines of IS 516-1959, and the corresponding results are displayed in Table 6. For each combination, three concrete beams measuring 100 mm × 100 mm × 500 mm were subjected to testing using a Universal Testing Machine (UTM). The maximum flexural strength among the trial mixes corresponds to self-curing concrete incorporated with steel slag (M3), and it is 4.1 N/mm^2 (Fig. 6; Table 6).

In all of the above tests the mix combination M3 (SS 40% and SAP 0.1%), performed well and it qualifies as the optimum mix among the tested combinations. Further, the basic durability properties, such as water absorption and sorptivity are

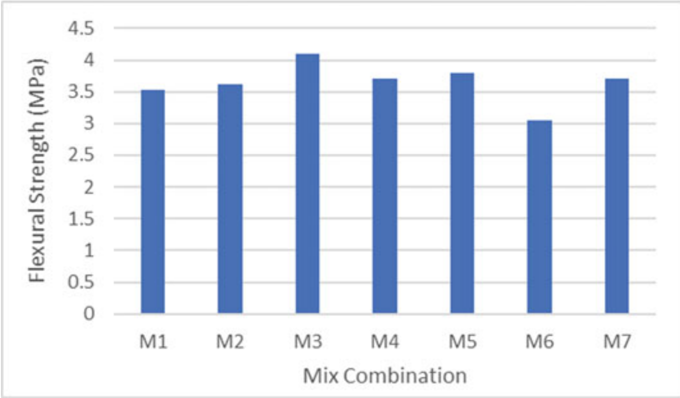

Fig. 6 Flexural strength at 28 days

Table 7 Durability performance—optimum mix versus control mix

S. No.	Mix combination	Water absorption (%)	Sorptivity (mm/s$^{0.5}$)
1	M1	4.02	0.178
2	M3	3.48	0.106

examined for this optimum mix combination (M3) and compared with the control mix.

4.6 Water Absorption Test

Water absorption tests for the cube were performed using 3 samples under IS 2185 (Part 1) 2005. A concrete specimen of size 10 cm × 10 cm × 10 cm was soaked in water for 24 h, and the wet mass of the block was measured. The cube was dried in an oven at 105 °C for at least 24 h, and the mass of the cubes after drying was recorded as shown in Table 7. Water absorption for self-curing concrete incorporated with steel slag is 3.48%, lower than the control mix of 4.02%.

4.7 Sorptivity Test

The samples were prepared according to IS 4031-Part 6. Water penetration through capillary holes from one side of the unsaturated concrete was measured using sorptivity. From the cylinder specimens, concrete discs with measurements of 100 mm × 50 mm were cut. A sealant was then applied to the top and curved surfaces of

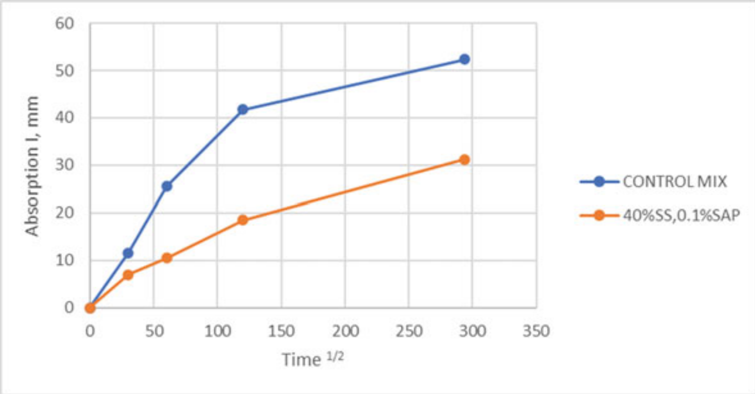

Fig. 7 Sorptivity test at 28 days

the discs, leaving the bottom surface exposed. These specimens were submerged in water, ensuring that the exposed surface made interaction with the water while maintaining a water depth of 1–3 mm. Weight was noted and shown in Table 7. Sorptivity was 0.106 mm/s$^{0.5}$ for self-curing concrete incorporated with steel slag, lower than the control mix of 0.178 mm/s$^{0.5}$. A lower sorptivity value indicates that the porosity of the concert has been reduced after the inclusion of steel slag (Fig. 7).

5 Conclusion

This paper presents the findings of an experimental investigation on the mechanical and durability properties of steel slag-incorporated self-curing concrete. Self-curing concrete is prepared by partially substituting the fine aggregate with steel slag. Based on the results, the ideal proportion of steel slag as a partial replacement in the fine aggregate is found to be 40%, while the optimal SAP dosage is 0.1%. From the research studies, the following findings were established:

- Flowability increases significantly with an increase in SAP content. Even though there is a falling trend at 0.3% SAP dosage, the values are still above the control mix.
- The optimum mix combination M3 performs better than the control mix in terms of mechanical and durability properties.
- The mixes perform better in all the test mechanical properties showing an upward trend with an increase in SAP dosage of up to 01%. Higher dosages beyond 0.1% affect the performance negatively.
- Mixes with higher Steel slag content exhibit better mechanical properties due to their micro filler effect.

- Compared to the control mix, self-curing concrete incorporating steel slag exhibits lower water absorption. This can be attributed to the porous characteristics of steel slag, which enable it to absorb and retain moisture. Consequently, the self-curing concrete containing steel slag demonstrates reduced water absorption, thereby enhancing the durability and moisture retention properties of the material.
- In contrast to the control mix, the self-curing concrete that incorporates steel slag demonstrates lower sorptivity. This indicates that the self-curing concrete, combined with steel slag, offers enhanced water resistance and reduced permeability. As a result, it becomes more durable and less susceptible to damage caused by water-related factors.

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