Evaluation of Flexural Behaviour of Steel Slag Fine Aggregates in Concrete

Krishnamoorthy Alagu[1*], *Jeyakumar* RKC[1], *Nandhini* J[1], and *Debiso* Bedaso Gemada[2]

[1]Department of Civil Engineering, Thiagarajar College of Engineering, Madurai, Tamil Nadu, India
[2]Department of Civil Engineering, College of Engineering and Technology, Bule Hora University, Ethiopia

Abstract. This paper examines the flexural behavior of reinforced and plain concrete beams with steel slag as a partial substitute for natural fine aggregate. Four concrete mixes were made using 0, 20, 40, and 60 percent replacement of steel slag. The beam specimens were subjected to two-point loading as per IS 516:1959. The findings indicated that the 60% replacement mix had the best flexural strength with an increase of about 1822% over the control mix. Enhanced performance is attributed to the improvement of mechanical interlocking and surface roughness of slag particles. In the current study, performance was not assessed beyond this level. The results indicate that steel slag may be used as a sustainable substitute for natural fine aggregates in structural concrete.

1 Introduction

Concrete is the most popular construction material because of its strength, durability, and flexibility for various structural uses. Nevertheless, the high rate of urbanization and industrialization has caused an unprecedented demand for natural construction materials, especially river sand, which has caused degradation of riverbeds, ecological imbalance, and depletion of natural resources [1]. At the same time, the growth of the steel industry has produced huge amounts of steel slag as an industrial by-product, which presents significant challenges to waste wastes in concrete production provides a feasible solution to resource conservation and environmental protection. Growing environmental concerns about traditional building materials have drawn a lot of attention to the production of sustainable concrete. While retaining adequate mechanical performance, the use of recycled and industrial waste materials in concrete can lessen its negative environmental effects. By minimizing waste disposal and lowering the use of natural resources, these methods support sustainable construction. [2-6].

Steel slag is dense, angular, rough-surfaced, and has good mechanical strength, which increases interfacial bonding and mechanical interlocking in cementitious matrices. Several studies have indicated that steel slag may be successfully utilized as a partial substitute for natural aggregates without affecting the performance of concrete. The flexural strength of

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[*] Corresponding author: abhaiakil@gmail.com

reinforced concrete beams was enhanced by the addition of steel slag and GGBS, which reached the maximum strength at moderate replacement levels [7]. Compressive and flexural strength improvement of 1516 percent at 28 days with the incorporation of steel slag [8].

The steel slag aggregates demonstrated strengths of up to 86 percent of the conventional dolomite aggregates [9], and strength improvements of up to 11.5 percent at replacement levels of 25 percent to 50 percent [10 -11]. All these studies point to the fact that steel slag can be used as an alternative aggregate material that is technically feasible.

Besides mechanical advantages, steel slag use is also sustainable in that it helps to decrease landfill disposal, save natural sand resources, decrease environmental degradation caused by mining activities, and promote the idea of the circular economy in the construction industry. Nevertheless, in spite of these benefits, the majority of the current research has been mainly on compressive strength and durability, whereas systematic research on the flexural behavior of reinforced and plain concrete beams with the use of steel slag as a fine aggregate replacement is still scarce. In addition, there is a lack of agreement on the optimal replacement level that can balance between structural performance and sustainability goals.

Thus, the current research will experimentally compare the flexural behavior of reinforced cement concrete (RCC) and plain cement concrete (PCC) beams with steel slag as a substitute for natural fine aggregate in 20, 40, and 60 percent weight proportions. The objective of the study is to determine the optimum replacement level and to establish the mechanistic understanding of stiffness response, crack propagation and load carrying capacity in order to support the sustainable and structural utilization of steel slag in concrete construction.

1 Materialsand methods

1.1 Materials and sample collection

The steel slag was obtained at a local steel manufacturing plant and processed, crushed, and sieved to meet the grading requirements of fine aggregates as per IS 383:1970 (Figure 1). In this experiment, the natural river sand and crushed stone aggregates were used as fine and coarse aggregates, respectively. The binding material was ordinary Portland Cement (OPC) of 53 grade that met the requirements of IS 12269:2013. All the physical and mechanical characterization tests of the cement and aggregates were performed as per the applicable Indian Standard codes. Coarse aggregates were subjected to test according to IS 2386 (Parts I-IV) and found to be in compliance with the requirements of IS 383:1970. Table 1 shows the compound composition of the OPC.

Fig.1. Steel slag for fine aggregate replacement

Table 1. Chemical composition of OPC (53 grade)

Property	**Values obtained**	**Requirement as per IS 12269 (1987)**
Lime saturation factor	0.90	0.80–1.02
Alumina modulus	1.23	≥ 0.66
Insoluble residue (%)	0.25	≤ 4.0
Magnesia (%)	1.10	≤ 6.0
Sulphuric anhydride SO_3 (%)	1.50	≤ 3.0
Loss on ignition (%)	0.80	≤ 4.0
Alkalis	–	–
Chloride (%)	0.002	≤ 0.10
C_3A content (%)	7	–
Temperature during testing (°C)	27 ± 2	27 2

1.2 Experimentation

Three reinforced concrete (RCC) beams of 1600 mm length and three plain cement concrete (PCC) beams of 450 mm length were cast and tested at each mix proportion. The Structural Engineering Laboratory cast concrete specimens in manually batched and mixed material. The steel molds were well cleaned and oiled and then cast to be easily demolded. The reinforced beams were elaborated with Fe500 grade steel, which comprised of two longitudinal tension bars of 10 mm diameter and 6 mm diameter stirrups at 150 mm spacing, bound together with binding wire to maintain the correct positioning and cover (Figure 2). The constituent materials were measured based on the intended mixing ratios. The cement and aggregates were mixed dry until homogenous, and then about three-quarters of the mixing water was added slowly. The rest of the water was then added to obtain the required workability. The concrete was combined until a homogenous and workable consistency was attained. The fresh concrete was poured into the molds in three layers of equal amount and each layer was compacted by mechanical vibration to remove any trapped air and to achieve proper consolidation and uniformity of the specimens.

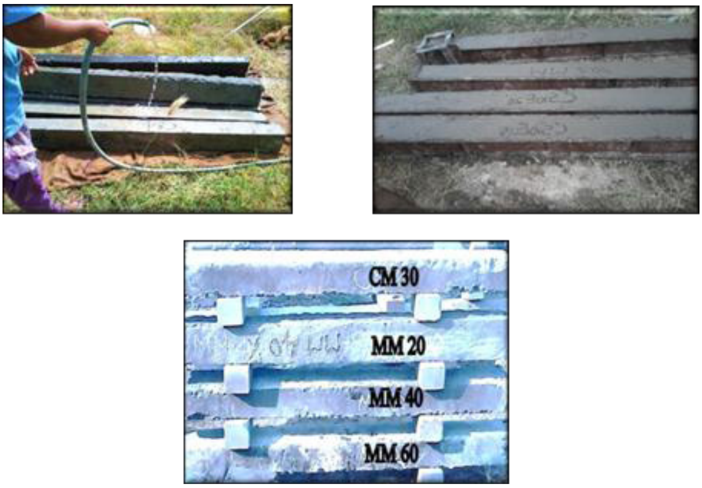

Fig.2. Reinforcement detailing of RCC beams

The specimens were demolded after 24 h and cured in a water tank at room temperature for over 28 days. After curing, the beams were air-dried for 24 h, and their surfaces were slightly cleaned. A thin layer of whitewash was applied to all faces to increase the visibility of crack initiation and propagation during the testing (Figure 3).

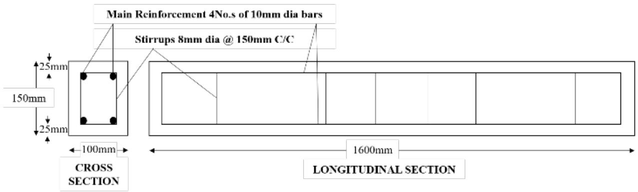

Fig. 3. Reinforced concrete beam specimens

1.3 Loading arrangement and test set-up

The beam specimens were subjected to supported conditions with a loading frame made of steel I-sections with hinged end supports to enable free rotation. A two-point loading configuration was used, and the loads were placed symmetrically at one-third span points, and the distance between the loading points was kept at 300 mm. A manually operated hydraulic jack with a capacity of 250 kN was used to apply the load. A proving ring with a capacity of 100 kN was used to measure the applied load accurately. Before testing, the correct positioning of the specimen, loading points, and instrumentation was done to prevent eccentric loading effects. In the case of RCC beams, flexural strength was determined by the following expression:

Flexural Strength, $(Ft) = PL / bd^2$, where P is the ultimate load at failure, L is the effective span, b is the specimen width, and d is the effective depth.

1.4 Procedure for testing and measurements

The experimental setup was checked before testing to make sure that the instrumentation was correctly aligned and calibrated. A hydraulic jack was used to load the beams in small steps, and the load readings were taken with a proving ring. Dial gauges were used to measure midspan deflections, and a mechanical strain gauge of 150 mm was used to measure surface strains. The measurements were recorded at constant load intervals until failure. The loading process was observed and recorded visually in terms of crack initiation, propagation, and failure modes. The loading was maintained until total structural failure was reached. The load-deflection and load-strain data were collected, and response curves were developed, and the beam stiffness was determined as the ratio of the applied load to the respective mid-span displacement (kN/mm) in the elastic range of loading.

Fig.4. Flexural testing of reinforced concrete (RCC) beams

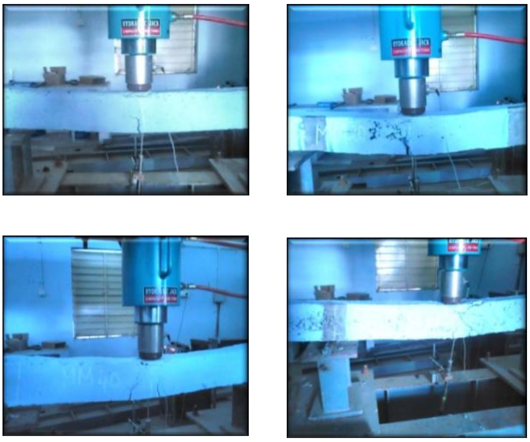

Fig.5. Flexural testing of reinforced concrete (RCC) beams

3 Results and discussion

3.1 Physical Properties

The physical and chemical properties of the constituent materials were established using the respective Indian Standards to establish their suitability in the manufacture of concrete. The cement was of standard consistency of 32 percent and specific gravity of 3.15 with the initial and final setting times of 30 and 300 min respectively, which is in line with IS 12269:2013. The coarse aggregate specific gravity was 2.75, and the fineness modulus was 3.05, which was in compliance with the IS 2386:1963 and IS 383:1970. The fine aggregate was natural river sand of specific gravity 2.64 and fineness modulus 2.78, which is Zone II as per IS 383:1970. The steel slag used as a partial fine aggregate replacement had a specific gravity of 2.63 (measured by the pycnometer method) and a fineness modulus of 3.06, which showed that it was suitable in structural concrete. Steel slag is mainly composed of CaO, Fe_2O_3, and SiO_2 phases, which proves its applicability as a reactive and mechanically stable fine aggregate in cementitious composites. Table 2 shows the compound composition of the steel slag.

Table 2. Steel slag Oxide composition

Name of the oxides	Contents (wt.%)
CaO	38–45
SiO_2	12–18
Fe_2O_3	18–25
MgO	5–10
Al_2O_3	2–6
MnO	2–5
TiO_2	0.5–2
P_2O_5	0.5–1.5
SO_3	<1.0
Loss on ignition	<2.0

The concrete mix design of M30 grade concrete was prepared based on IS 10262:2009. Steel slag was used as a partial substitute for natural fine aggregates in different proportions. Slump tests were used to determine the workability of the fresh concrete as per IS 7320:1974. Table 3 gives the slump values.

Table 3. Slump values

Water Cement Ratio	0.4	0.42	0.45
Slump Value (mm)	80	75	110

Though there was a slight decrease in slump at a water-cement ratio of 0.42, the general trend was that workability increased with the increase in water-cement ratio, as is expected of normal concrete behavior. The ultimate blend ratio of the M30 grade concrete obtained was Water: Cement: Fine aggregate: Coarse aggregate = 0.47:1:1.75:2.98. Table 4 shows the quantities of the mix design.

Table 4. Mix design quantities

Cement Kg/m^3	Fine Aggregates Kg/m^3	Coarse Aggregate kg/m^3	Water L/m^3
394	692.20	1176.45	197
1	1.75	2.98	0.47

3.2 Flexural Strength of RCC

The reinforced concrete beam specimens were tested under two-point loading in flexural strength tests, and the results are shown in Figure 6. The use of steel slag as a partial substitute for natural fine aggregates had a great impact on the flexural behavior of the beams. The ultimate load-carrying capacity increased with the steel slag content up to 60 percent replacement, which showed that the flexural resistance was improved over the control mix.

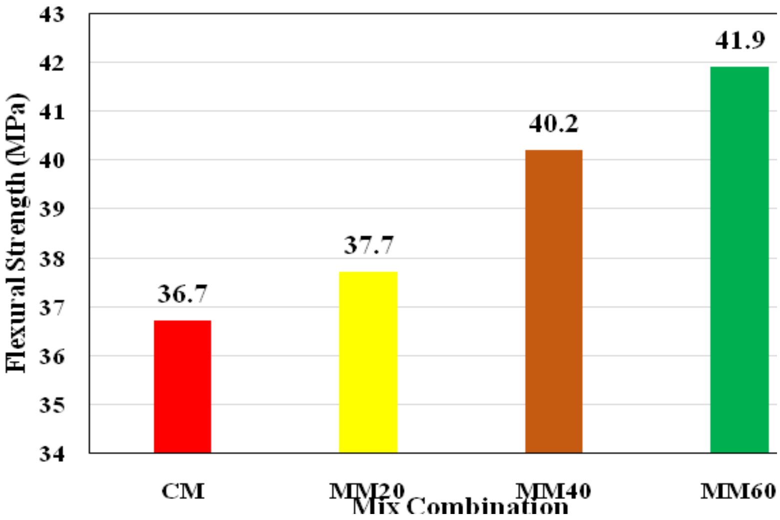

Fig.6. Flexural Strength of RCC beams

3.3 Deflection and stiffness behaviour

Table 5 summarizes the midspan deflections and the respective stiffness values of the control mix (CM), MM20, MM40, and MM60. Figure 7 shows the load-deflection characteristics of all mixes, and Figure 8 shows the load-stiffness characteristics. The ratio of the applied load to the corresponding midspan deflection (kN/mm) in the elastic loading range was used to determine stiffness. The MM40 and MM60 beams had lower deflections than the control and MM20 beams at similar load levels, which means that they had a better flexural rigidity. Specifically, the MM60 beams showed the greatest values of stiffness at the first and middle loading phases, which indicates an increased deformation resistance. This is due to the angular shape and coarse surface texture of the steel slag particles, which enhances mechanical interlocking and interfacial bonding between the aggregate and cement paste with continued loading, the stiffness of all mixes reduced gradually due to cracking and damage accumulation in the tension zone. Nevertheless, the steel slag-modified beams showed a slower crack initiation and slower stiffness degradation compared to the control mix, which showed better structural performance under flexural loading.

Table 5. Mid-span deflection and stiffness values of RCC Beams

Load (kN)	**Deflection (mm)**				**Stiffness (kN/mm)**			
	CM	MM20	MM40	MM60	CM	MM20	MM40	MM60
0	0	0	0	0	0	0	0	0
5	1.53	2.65	0.59	1.79	3.26	1.88	8.47	2.79
10	3.02	3.12	1.2	3.42	3.31	3.2	8.33	2.92
15	5.6	5.43	3.68	6.62	2.67	2.76	4.07	2.26
20	6.88	7.01	5.76	7.42	2.9	2.85	3.47	2.69
25	9.52	8.62	8.31	9.03	2.62	2.9	3	2.77
30	11.76	9.89	10.62	12.2	2.55	3.03	2.82	2.45

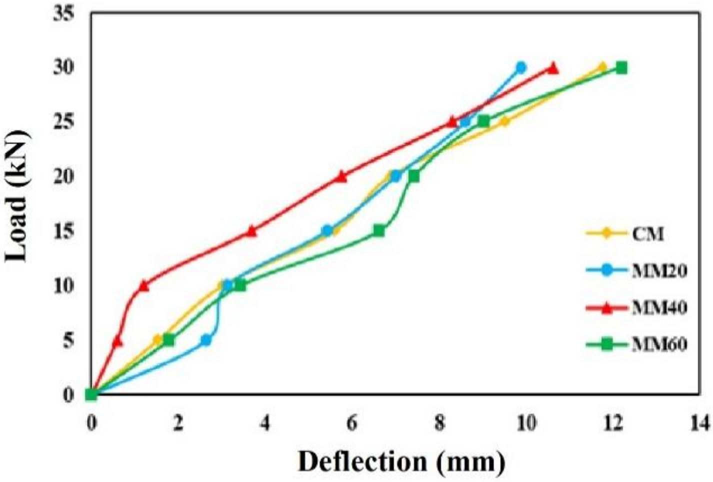

Fig.7. Load - deflection response of RCC Beams

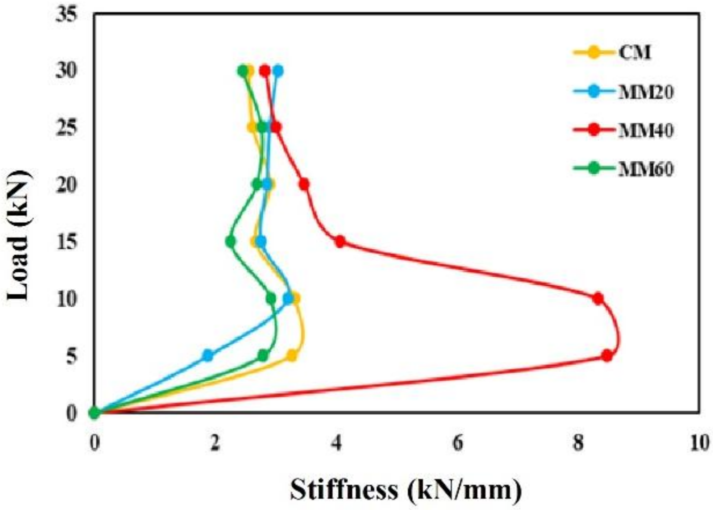

Fig.8. Load-Stiffness response of RCC beams

3.4 Flexural Strength of PCC

The flexural strength results of the plain cement concrete (PCC) beams are presented in Table 6 and Figure 9. The beams that used steel slag had greater flexural strength than the control mix, and the strength increased gradually with the replacement of slag up to 60 percent. The control mix (CM) recorded an average flexural strength of 4.14 MPa, whereas MM20, MM40, and MM60 recorded an average flexural strength of 4.72 MPa, 5.36 MPa, and 5.83 MPa, respectively. These values represent strength improvements of about 14%, 29%, and 41%, respectively, compared to the control mix. The angular shape of the particles and rough surface texture of the steel slag were observed to enhance the resistance to tensile cracking under flexural loading due to the enhancement of the aggregate interlocking and the bond between the aggregate particles and cement paste. Differences in the final load of specimens in the same mix were found due to the natural heterogeneity of the material, slight variations in the casting and compaction of the specimen, and natural variation in crack initiation and propagation, which are common in experimental concrete testing.

Table 6. Flexural Strength Results of PCC Beam

Mix	Load (kN)	Effective span (cm)	Flexural strength (MPa)	Average flexural strength (MPa)
CM	14.0	11.2	4.70	**4.14**
	9.0	15.5	3.64	
	8.5	16.0	4.08	
MM20	13.5	12.7	5.14	**4.72**
	11.5	12.3	4.24	
	12.0	11.6	4.17	
MM40	16.5	11.0	5.44	**5.36**
	15.5	12.8	5.62	
	16.0	10.5	5.04	
MM60	17.0	11.7	5.96	**5.83**
	20.0	9.5	5.70	
	13.0	15.0	5.85	

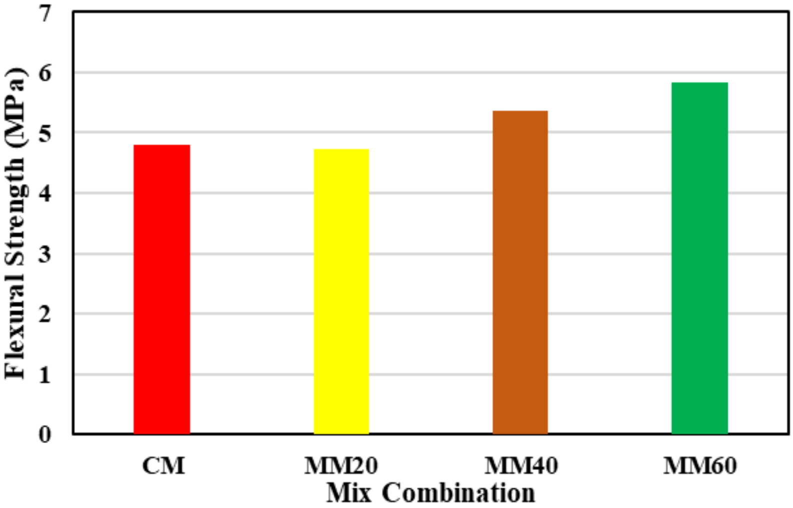

Fig.9. Flexural Strength of PCC beams

However, at higher steel slag replacement levels, the increased water absorption, surface roughness, and potential microporosity may have adverse effects on workability and long-term durability, which may limit performance beyond the investigated replacement range. Thus, before large-scale structural applications, an optimized mix design and durability-based investigations are suggested.

3.5 Failure mode of beams

PCC and RCC beams failed mostly in flexure, and the first cracks were developed in the tension zone at the mid-span and extended upwards as the load increased (Figure 10). The steel slag modified beams showed retarded crack initiation, narrower crack widths and more dispersed cracking than the control mix, which indicated better redistribution of tensile stress and ductility. The failure patterns observed proved that the addition of steel slag did not change the basic failure mechanism of concrete beams but increased the flexural resistance.

Fig.10. Flexural failure of RCC and PCC beams.

4 Conclusion

This paper experimentally tested the flexural behaviour of reinforced and plain concrete beams with the use of steel slag as a partial substitute of natural fine aggregates. The results indicated that the flexural performance was significantly affected by the steel slag and the strength and stiffness increased progressively to the maximum replacement percentage of 60 percent, which was the highest percentage that was experimented in this study. The angular shape of the particles and roughness of the surface of the steel slag are observed to have improved the situation, as they facilitate better mechanical interlocking and interfacial bonding between the cement paste and the aggregate particles. Beams with steel slag had less midspan deflection, delayed crack initiation, and better crack distribution than the control mix. According to the experimental results, it was found that a 60 percent substitution of natural fine aggregates with steel slag was the best percentage in the range of experimentation to enhance the flexural performance and sustainability in the use of materials. The results confirm the feasibility of using steel slag as an alternative to structural fine aggregate, especially for applications that require higher flexural resistance and resource efficiency.

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Conflicts of Interest

The authors have no conflicts of interest to declare.

Data Availability

The data generated and analysed during the current study are not publicly available due to institutional restrictions and ongoing related research. However, the datasets used in this study can be obtained from the corresponding author upon reasonable request

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