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Research Article

Strength Behavior of Prestressed Concrete Sleepers with Steel Slag Partial Replacement

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ABSTRACT

Prestressed concrete sleepers (PCS) are very popular and commonly used by Indian Railways. This research is aimed at studying the behavior of concrete sleepers made with steel slag as a partial replacement for traditional cement concrete. A pre-stressed concrete railway sleeper was made using energy-optimizing furnace (EOF) steel slag, a byproduct in the steel manufacturing process, partially in the place of coarse aggregate, following the Indian Railways Standard (T39-85) for sleepers. EOF steel slag coarse aggregates were subjected to a few tests, including those for chemical resistance, soundness and alkali reactivity and the results were found to be satisfactory. Compared to the traditional concrete mix, the compressive strength is increased by about 20%. It paves the way to utilize the discarded steel slag for manufacturing cost-effective prestressed railway sleepers.

Keywords: EOF steel slag; Railway sleepers; Pre-stressed concrete.

1. INTRODUCTION

A crucial part of railway tracks is railway sleepers, also known as railway ties in some places. They are essential to preserving the tracks' stability, alignment, and gauge. Additional details on railway sleepers are provided below: Rails are supported and held at the proper gauge (distance between the two rails) by railway sleepers, which are positioned horizontally beneath the rails. They disperse the weight and forces of the passing trains to the subgrade and ballast below. A variety of materials, including wood, concrete, steel and composites can be used to make railway sleepers. Cost, durability and environmental considerations are only a few examples of the variables that influence material selection. Sleepers made of wood were frequently employed in the past; to extend their life and guard against deterioration and pest infestations, they were frequently treated with preservatives. However, because of wear and tear, wooden sleepers need routine upkeep and replacement. Compared to wooden sleepers, concrete sleepers are more robust and survive longer. They are not susceptible to decay, insects, or bad weather. Monoblock (one-piece) and twin-block (two-piece) sleepers are two examples of the several designs available for concrete sleepers. Steel sleepers offer a high level of strength and durability and are employed in some applications. They are frequently utilized in heavy-duty or fast train lines. Composite Sleepers are constructed from a variety of materials, including recycled plastics. They try to strike a balance between cost and durability.

Sleepers are transverse beams that rest on ballast supports. The rail must sustain the force, and the track gauge must be maintained. The ballast can distribute and transfer the load from the rail (Taherinezhad *et al.* 2013). Indian railway sleepers are currently built of cement concrete. The demand for coarse aggregate rises in tandem with the demand for concrete as a construction ingredient.

Steel mills now produce a huge volume of steel slag. Steel slag waste is being reused in several ways (Raj *et al.* 2016). Indian Railways' Research, Design and Standards Organization (RDSO) is experimenting with cost-effective sleepers for railway lines. It would likely be part of their ongoing efforts to enhance the durability and performance of railway tracks while minimizing costs. This could involve exploring alternative materials, construction techniques and maintenance practices for sleepers, which are critical components of the railway track infrastructure. Now sleepers are made using conventional materials. The utilization of steel slag in sleepers will also reduce environmental pollution. Nowadays, all sleepers are made of high-strength concrete of M-55 to M-60; in this project, high strength is achieved by using steel slag (Ngamkhanong *et al.* 2017). The main feature of sleepers is that they should be free from sulfate and chlorides to increase durability. The steel slag is free from sulfates and chlorides. Hence the usage of steel slag in sleepers is a good innovative idea. It has been envisioned that leftover steel slag will be used to create affordable railway sleepers. (Guoqing *et al.* 2021; Sadeghi and Bababee, 2006; et al, Ruilin, *et al.* 2017). The cost-effectiveness of sleepers will be achieved by eliminating the usage of conventional coarse aggregate**.** The primary concern is how substituting steel slag for coarse aggregate can enhance the mechanical characteristics of prestressed concrete sleepers. It will be more useful for manufacturing cost-effective and eco-friendly railway sleepers.

2. METHODOLOGY

The first step was to visit the Bommidi sleeper plant, Tamilnadu, India, to study the present sleeper production methods to replace the coarse aggregate with steel slag. Testing was conducted on the steel slag properties. The specimens were cast, cured and tested. Fig. 1 illustrates the methodology of this paper.

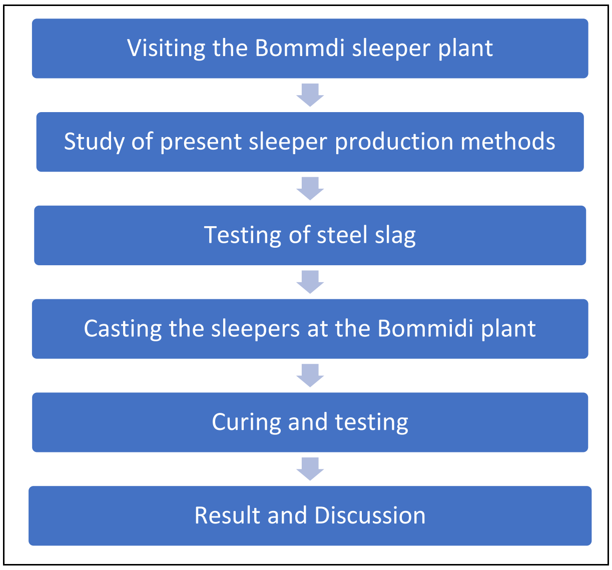

Fig. 1: Methodology of testing steel slag-based sleeper specimens

3. STEEL SLAG ORIGIN

3.1 Energy Optimizing Furnace

The main steelmaking furnace is an energy-optimizing furnace (EOF). Willy Korf, a pioneer of micro steelworks, and his colleagues created this method. This method is now being used in India at the JSW SISCOL factory and the Mukand Hospet Steel plant. In 1982, the first unit was produced.

3.2 Process

The EOF is a liquid steel smelting and refining furnace. It comes with a scrap preheater. Working with a combination of submerged and atmospheric oxygen blasted into an initial charge, including hot metal, warmed solid scrap, and fluxes for slag formation is the core idea. Scrap is warmed to roughly 850 °C in one or two chambers above the furnace roof, based on the observable heat in the off gas. Submerged blown oxygen combines with the carbon in heated metal to produce bubbles of CO that go through the liquid bath and into the furnace's atmosphere. The oxygen blasted by atmospheric injectors and supersonic lances burns CO to CO_2 (Li *et al*. 2017; Fisseha *et al*. 2016). CO bubbling causes much churning and surface area in the bath. This permits a substantial quantity of heat to be transferred to the bath. De-slagging and the creation of secondary slag are also part of the process (Abdeldayem *et al*. 2021; Silva *et al*. 2020; Kaewunruen *et al*. 2016).

It is possible to use a large proportion of solid charge in this technique (even greater than 40%). The following elements contribute to the process's thermal efficiency:

i) Chemical energy created as a result of exothermic reactions between injected oxygen and the bath's different constituents, including added carbon.

ii) Chemical energy created by gaseous oxidation processes involving CO and H_2 discharged from the bath in the furnace environment.

iii) Sensible heat transmitted from the furnace to the cold scrap placed into the pre-heater by hot gases

4. MATERIALS USED

4.1 Cement

Dalmia 53 S cement is uniquely developed to give additional protection and strength. It is made with cutting-edge CVRM technology. As a result, the cement has an ideal particle size distribution, allowing for denser concrete. The strong concrete prevents fractures and water leaks, assuring the roof's longevity. Cement's specific gravity is 3.15.

4.2 Fine Aggregate

Clean, dry sand was utilized as fine aggregate (sand). The sand was sieved in a 4.75 mm sieve to eliminate any stones. Table 1 presents the fine aggregate's specific gravity, fineness modulus and bulk density.

4.3 Coarse Aggregate

4.3.1 Steel Slag

4.3.1.1 Physical Properties

Steel slag particles (Fig. 2) can be recognized by their angular form and abrasive surface. As presented in Table 2, they have a low water absorption rate (less than 3%) and a high bulk-specific gravity (Jokubaitis *et al.* 2016).

Table 1. Physical properties of fine aggregate

S. No.	Description	Value
1	Specific gravity	2.64
2	Bulk density	1667 kg/m^3
3	Fineness modulus	2.53

Table 2. Physical properties of steel slag

S. No.	Property	Value
1	Specific gravity	2.9
2	Unit weight, kg/m^3	1600-1920
3	Absorption	Up to 3%

Fig. 2: Coarse aggregate (Steel slag)

4.3.1.2 Chemical Properties

Elemental analysis and X-ray fluorescence are used to identify the simple oxides of makeup slag's chemical composition. The components of steel slag from a standard base oxygen furnace are listed in Table 3. However, even though almost all steel slags meet these chemical specifications, not all of them can be used as aggregates. The mineralogical shape of the slag, which is more significant, is greatly influenced by the rate of cooling it experiences during steel production (Alexey *et al*. 2011).

It is more important to consider the slag's mineralogical shape, which is significantly influenced by how quickly it cools during the steel-making process (Rozli *et al*. 2018).

Most steel slags tend to be expansive, according to technical literature, and this is because the steel slag does not completely utilize the free calcium and magnesium oxides. This is because the unslaked lime and magnesium are in contact with moisture hydrate. Magnesium hydrates gradually aid in long-term expansion, the development of which can take years. In just a few short weeks, free lime can drastically alter volume due to its fast hydration. Steel slag is mildly alkaline, with a pH range of 8–10 in solution (Rozli *et al*. 2018).

Table 3. Typical chemical composition of steel slag

Constituent	Composition (%)
CaO	40 – 52
SiO_2	10 – 19
FeO	10-40
MnO	5-8
MgO	5-10
Al_2O_3	1-3
P_2O_5	0.5-1
S	<0.1
Metallic Fe	0.5-10

4.3.1.3 Mechanical Properties

Because of its outstanding bearing strength, soundness and abrasion resistance, processed steel slag makes an excellent aggregate. Table 4 lists a few mechanical parameters of steel slag.

Table 4: Mechanical properties of Steel slag

S. No.	Property	Value
1	Los Angeles Abrasion (ASTM C131), %	20-25
2	Sodium Sulfate Soundness Loss (ASTM C88), %	<12
3	Angle of Internal Friction	40°-50°
4	Hardness (measured by Scale mineral hardness) *	6-7
5	California Bearing Ratio (CBR), % top size 19 mm (3/4 inch) **	up to 300

***** Hardness of dolomite measured on the same scale is 3 to 4.
****** Typical CBR value for crushed limestone is 100%.

4.3.1.4 Thermal Properties

Steel slag aggregates have a higher heat capacity than natural aggregates, which allows them to hold heat for a lot longer (Rozli *et al*. 2015). The heat retention property of steel slag aggregates may be advantageous for hot mix asphalt repair projects in cold weather.

4.4 Water

Distilled water was used for the manufacture of the sodium hydroxide solution and potable water was used throughout for excess water supply to provide workability, as per IS:456 -2000.

4.5 High Tensile Steel

IS: 1785 Part-I and IS: 6006 apply to high tensile steel in plain wire or strand. It must be obtained exclusively from BIS-certified manufacturers who must provide proof of approval by BIS with the initial shipment and for any new support during the validity of the license (Grassé *et al.* 2013). A test certificate identifying the serial number of coils must accompany each shipment of high-tensile steel. According to the IS requirements, each loop must have a tag (Fig. 3 and Fig. 4).

Fig. 3: Steel bars (3 mm diameter)

The dimensions of the specimens are:

Volume	0.1089 m^3
Length	2.75 m
At the ends	
Width at bottom	0.27 m
Width at top	0.13 m
Height	0.23 m
At the centre	
Width at bottom	0.31 m
Width at top	0.31 m
Height	0.18 m
Slope	1 in 20

Table 5. Time duration and curing temperature

S. No.	Type of curing	Time duration (h)	Temperature (°C)
1	Pre-streaming	2 h	28
2	Rising temperature	2 h	Above 75
3	Constant temperature	4 h	75
4	Cooling temperature	2.5	Up to 28

Fig. 4: Sleeper mold

5. IMPORTANT MEASURES

1. Concreting must begin within 2 h of wire stressing, and if required, de-tensioning is done.
2. At the two different locations of the sleeper, the vibrators should be normally fixed. The concrete should be properly mixed and vibrated at least 9000 times per minute.

De-tensioning of wires

A mechanism for progressive wire de-tensioning must be included in the anchoring system. Back tugging of wire to release a wedge is strictly forbidden (Ferdous and Allan, 2014).

6. CURING

In this process, both stream curing and water curing take place. This type of concrete is cured for 11 h at the temperature of 75 °C (Kumaran *et al*. 2003). This is used to achieve an early development of strength and is easy for demolding. The curing procedure is presented in Table 5. After stream curing, the sleeper will be kept in water for 15 days.

7. TESTING OF SPECIMENS

7.1 Compressive Strength Test

The cubes were formed using steel slag, and compression testing equipment (CTM) was employed to inspect them. The cubes were allowed to be steam cured for a maximum of 11 h at 75 °C, after which they were cured in a pond for the specific amount of time mentioned above. Then, with the compacted side facing us, the cubes are positioned between the testing device's steel plates. Starting from zero load, the load is delivered gradually and evenly at 40 N/mm^2/min. By dividing the greatest force applied to the cube by its cross-sectional area, the observed compressive strength of the cubes was computed. It should be at least 40 N/mm^2 after 11 h of curing the cubes. This is required as the sleeper will be stressed while de-moulding.

7.2 Static Bending Strength-Central Top

This is the primary test for sleepers to be approved by the Indian Railways. This test involves the application of loads simultaneously on both the rail seats, steadily and uniformly, to measure the tension at the sleeper's centre top. The tension causes the central top section of the sleeper to split when the weights are applied. The loads should be applied at 30-40 kN/min. The reading is taken when the cracks are visible up to 2 mm from the top of the sleeper. This can take place on both sides of the sleeper. As in the case above, if one sleeper fails, two randomly selected sleepers should compulsorily pass for the batch to be accepted. As mentioned above, until cracking, the sleeper should withstand at least 230 kN of load in each rail seat. Fig. 5 illustrates the test set-up of the prestressing specimen.

7.3 Test for a Moment of Failure

This is the final test to accept the sleeper batch. It is the same as the bending strength test, for the rail seat bottom, except that it is done until the sleeper completely fails. In this test, the load rate per rail seat is uniformly increased from 0, at the rate of 30-40 kN/min. Once the sleeper completely fails or the loading reduces, the reading is taken. The basic requirement for this test is 370 kN. The values are taken from the Indian Railways Manual. Once the sleeper clears the above tests, the Railways could accept the batch of about 320 sleepers. Fig. 6 depicts the test set-up.

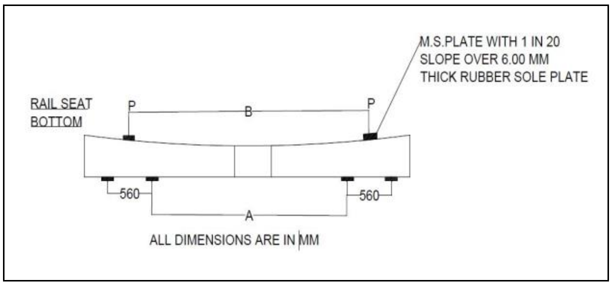

Fig. 5: Static bending strength test set-up (Central top)

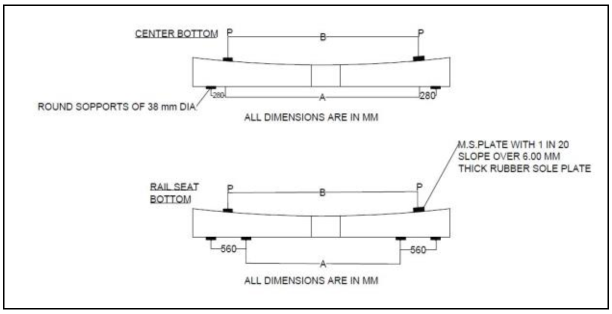

Fig. 6: Static bending strength test set-up (Rail seat bottom)

Table 6. Compressive strength of concrete cube specimens

Cube No.	Percentage of Replacement			
	100% F.A. Replacement	100% C.A Replacement	50% F.A. & 50% C.A. Replacement	100% F.A. & 100% C.A. Mix
1	36.4 N/mm^2	45.7 N/mm^2	41.4 N/mm^2	26.1 N/mm^2
2	36 N/mm^2	37.6 N/mm^2	35 N/mm^2	23.1 N/mm^2
Average	36.2 N/mm^2	41.65 N/mm^2	38.2 N/mm^2	24.6 N/mm^2

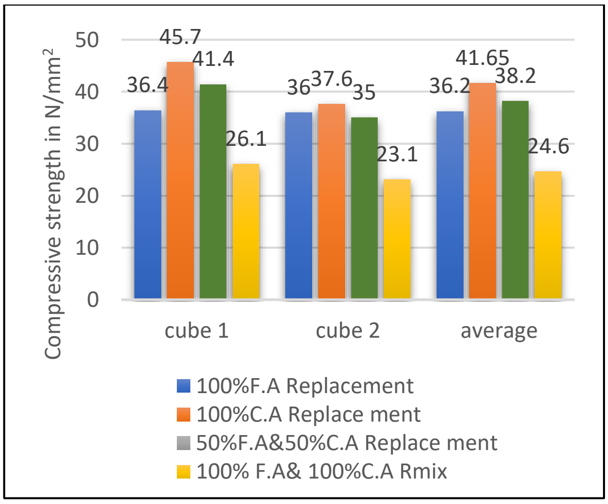

Fig. 7: Comparison of Compressive strengths of the specimens

8. RESULTS

8.1 Cube Strength after Stream Curing

The results shown in Table 6 indicate that the maximum compression strength is exhibited by 100% coarse aggregate replacement. After the stream curing, it reaches the minimum value of 40 N/mm^2 as per code provisions. Hence high strength is achieved within one day after stream curing so this concrete should withstand the pre-stressing wires. Fig. 7 shows a comparison of the compressive strengths of the specimens.

9. CONCLUSION

The study has shown that steel slag can successfully replace conventional coarse aggregate, which is cost-effective and highly useful in a variety of applications. When compared to conventional concrete, compression strength is 20% better and environmental pollution is 20% less when steel slag is used in buildings. This is a positive outcome since there is a lower need for coarse material, coupled with the fact that industrial leftovers like steel slag are getting recycled. The use of steel slag in the production of sleepers has reduced costs, maybe because it is more affordable or readily available than the typical coarse aggregate. Using steel slag will improve the performance of the concrete sleepers, as evident from the findings, where the maximum compressive strength was reached when coarse aggregate was replaced with steel slag by 100%.

The novel strategy proposed in this work has significant potential for use in actual sleeper production. The benefits include producing stronger concrete and effectively using steel slag, both of which help in minimizing costs and mitigating environmental damage.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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