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INNOVATIVE APPROACH FOR WATERPROOF CONCRETE PRODUCTION USING INDUSTRIAL STEEL SLAG AND POLYPROPYLENE FIBERS

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ABSTRACT

The present study investigates the utilization of industrial steel slag as a partial replacement for fine aggregates in concrete, combined with polypropylene (PP) fibers to improve mechanical performance and waterproofing properties. Industrial steel slag, being a by-product of steel manufacturing, poses environmental disposal challenges; however, its latent hydraulic reactivity and high density make it suitable for sustainable concrete production. The experimental program assessed compressive strength, splitting tensile strength, flexural strength, and water absorption at 7, 14, and 28 days. A series of mixes incorporating 0%, 10%, and 20% slag with varying fiber content (0.25% and 0.50%) were designed and tested. Results revealed that slag densified the matrix through secondary C–S–H gel formation, while fibers improved crack resistance and toughness. The optimized mix of 20% slag with 0.50% fiber demonstrated enhanced compressive strength (56.8 MPa), tensile strength (4.4 MPa), and reduced water absorption (1.42%) at 28 days compared to control specimens. Beyond mechanical improvements, the study highlights the potential of slag-fiber synergy to reduce concrete porosity, thereby producing waterproof, durable, and eco-friendly concrete. This research contributes to sustainable construction by valorizing steel industry waste and minimizing the long-term deterioration of concrete structures due to water ingress.

Keywords: Steel Slag, Polypropylene Fiber; Waterproof Concrete, Mechanical Properties, Sustainable Construction.

1. INTRODUCTION

Concrete is the most widely used construction material across the globe, with annual production exceeding 10 billion tonnes. However, its durability and long-term performance are often compromised by high porosity and susceptibility to water ingress. This has led to premature deterioration of concrete infrastructures such as bridges, pavements, dams, and high-rise buildings. Enhancing the impermeability and service life of concrete is therefore an urgent priority for sustainable construction (Mehta & Monteiro, 2014).

Simultaneously, the steel manufacturing industry generates a significant quantity of industrial steel slag, estimated at **150–250 kg per tonne of steel produced** (Shi, 2004). A large fraction of this waste ends up in landfills or is stockpiled, leading to land degradation, leachate problems, and environmental pollution. Steel slag is rich in calcium, silica, and iron oxides, and it possesses latent hydraulic reactivity, making it a promising supplementary material for concrete production. Several studies have reported that replacing aggregates with slag enhances density, reduces permeability, and contributes to long-term strength due to pozzolanic reactions (Manso et al., 2005; Motz & Geiseler, 2001).

On the other hand, the incorporation of **polypropylene (PP) fibers** has been widely recognized as an effective technique to mitigate shrinkage cracks, enhance toughness, and improve post-cracking behavior in concrete (Bentur & Mindess, 2007). PP fibers, being chemically inert, non-corrosive, and hydrophobic, act as crack arrestors by bridging microcracks and delaying their propagation. Their role in reducing capillary water movement through microchannels makes them highly beneficial in producing waterproof concrete.

While the individual benefits of steel slag and polypropylene fibers are well-documented, research on their **synergistic effects** is still limited. The hypothesis is that steel slag will refine pore structure through matrix densification, while polypropylene fibers will reduce crack widths, thereby collectively enhancing both the strength and impermeability of concrete.

The present study aims to address this research gap by:

1. Investigating the mechanical performance (compressive, tensile, flexural strength) of concrete mixes incorporating steel slag and polypropylene fibers.
2. Evaluating the waterproofing capacity through water absorption tests.
3. Identifying the optimal slag-fiber combination that balances strength and durability.

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This work not only contributes to sustainable construction practices by recycling industrial waste but also develops a cost-effective strategy for producing durable and waterproof concrete for infrastructure applications.

2. MATERIALS AND METHODOLOGY

2.1 Materials

2.1.1 Cement: Ordinary Portland Cement (OPC) of 43 grade conforming to IS 8112:2013 was used as the primary binder. The cement was fresh, free from lumps, and stored in airtight containers to prevent moisture ingress. The physical properties of OPC such as specific gravity, standard consistency, initial and final setting time, and compressive strength at 28 days were verified in accordance with IS 4031 (Part 1–6). The cement exhibited a standard consistency of 32%, initial setting time of 115 minutes, final setting time of 285 minutes, and a specific gravity of 3.14, which satisfied the requirements of IS 8112:2013.

2.1.2 Fine Aggregate: Natural River sand conforming to IS 383:2016 was used as the fine aggregate. The sand was washed, oven-dried, and sieved to remove silt and organic matter. The sand was categorized under Zone II as per IS 383:2016 with a fineness modulus of 2.65, bulk density of 1580 kg/m³, and water absorption of 1.2%.

2.1.3 Steel Slag: Industrial steel slag was collected from a local steel manufacturing unit. The slag was air-cooled, crushed, and ground to pass through a 4.75 mm sieve to match Zone II fine aggregate grading. Before incorporation, the slag was washed thoroughly to remove any free lime or deleterious compounds. Its physical properties such as specific gravity (2.82), water absorption (2.8%), and fineness modulus (2.75) were measured. The pozzolanic activity and chemical composition were confirmed through X-ray fluorescence (XRF), revealing major oxides of CaO, SiO_2, Fe_2O_3, and Al_2O_3.

2.1.4 Coarse Aggregate: Crushed granite aggregate with a maximum nominal size of 20 mm was used. The aggregate was angular in shape, with a specific gravity of 2.68 and water absorption of 0.9%. It satisfied the grading requirements of IS 383:2016 for coarse aggregate.

Water: Potable water free from organic matter, oils, or deleterious salts was used for mixing and curing, satisfying the requirements of IS 456:2000. The pH value of the water was maintained at around 7.2.

2.1.5 Polypropylene Fiber (PPF): Polypropylene fibers of length 12 mm were used to improve crack resistance and water resistance of concrete. The fibers had a density of 0.91 g/cm³, tensile strength of 400 MPa, modulus of elasticity 3.5 GPa, and melting point around 160°C. The fibers were uniformly dispersed during mixing to avoid balling or clumping.

Fig 2.1: Material Used in this study

2.2 Mix Proportions

A total of six mixes were prepared, including a control mix and fiber/slag modified mixes.

- **Control Mix (M0):** Conventional concrete using cement, sand, coarse aggregate, and water without slag or fibers.
- **Slag Replacement Mixes:** Steel slag replaced fine aggregate at 10% (M1) and 20% (M2) by weight.
- **Fiber Addition:** Polypropylene fibers were added at dosages of 0.25% and 0.50% by volume in both M1 and M2, resulting in mixes M1F0.25, M1F0.50, M2F0.25, and M2F0.50.
- **Water–Cement Ratio:** Maintained constant at 0.40 across all mixes to ensure comparability.

The mix design followed IS 10262:2019 guidelines, targeting a characteristic strength of 40 MPa at 28 days. The proportioning was adjusted to account for the higher water absorption of steel slag, ensuring adequate workability. A polycarboxylate ether (PCE)-based superplasticizer was also used at 0.8% by weight of cement to maintain slump within 75–100 mm.

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Table 2.1: Mix design

Mix ID	Cement (kg)	Water for w/c (kg)	Extra Water for Absorption (kg)*	SP (kg)	Coarse Agg (kg)	Sand (kg, SSD)	Steel Slag – Fine (kg, SSD)	PP Fiber (% vol.)	PP Fiber (kg)
M0 (Control)	400	160	0.0	3.2	1200	680	0	–	0.00
M1F0.25 (10% slag + 0.25% PP)	400	160	**1.09**	3.2	1200	**612**	**68**	0.25%	**2.28**
M1F0.50 (10% slag + 0.50% PP)	400	160	**1.09**	3.2	1200	**612**	**68**	0.50%	**4.55**
M2F0.25 (20% slag + 0.25% PP)	400	160	**2.18**	3.2	1200	**544**	**136**	0.25%	**2.28**
M2F0.50 (20% slag + 0.50% PP)	400	160	**2.18**	3.2	1200	**544**	**136**	0.50%	**4.55**

3. EXPERIMENTAL PROGRAM

3.1 Compressive Strength

Compressive strength was measured on 150 × 150 × 150 mm cube specimens at 7, 14, and 28 days in accordance with IS 516:1959 and ASTM C39. A total of three cubes per mix per age were tested, and the average was reported. Specimens were tested in a compression testing machine (CTM) of 2000 kN capacity under a loading rate of 140 kg/cm²/min. The test aimed to evaluate the influence of slag-induced matrix densification and fiber crack-bridging on compressive behavior.

3.2 Splitting Tensile Strength

Splitting tensile strength was evaluated using cylindrical specimens of 150 mm diameter and 300 mm height according to IS 5816:1999 and ASTM C496. The specimens were cured for 7, 14, and 28 days before testing. The load was applied along the vertical diameter of the cylinder at a uniform rate until failure. This test was particularly significant to assess fiber contribution in bridging micro-cracks and enhancing tensile performance, which directly influences durability.

3.3 Flexural Strength

Flexural strength was determined by two-point loading on prism specimens of size 100 × 100 × 500 mm in accordance with IS 516:1959 and ASTM C78. The test was conducted on specimens cured for 7, 14, and 28 days. The span length between supports was 400 mm, and the load was applied at one-third points. The test was essential to quantify the crack resistance provided by polypropylene fibers under bending, as well as the stiffening effect of steel slag on the cementitious matrix.

3.4 Water Absorption

Water absorption was measured as per ASTM C642:2013 using 100 mm cube specimens. The specimens were oven-dried at 105°C until a constant weight was achieved, then immersed in water for 48 hours. The increase in mass was recorded, and water absorption percentage was calculated. This test provided insight into the pore structure modification due to slag substitution and fiber reinforcement. Lower water absorption values indicate reduced capillary porosity and improved impermeability, directly correlating with durability.

4. RESULTS AND DISCUSSIONS

4.1 Compressive Strength (MPa)

The compressive strength results (Table 1) reveal a consistent improvement with both slag substitution and fiber incorporation. At 28 days, the control mix achieved **49.0 MPa**, while the optimum mix (20% slag + 0.50% fiber) reached **56.8 MPa**, representing a **15.9% improvement**. The observed enhancement is attributed to:

- **Secondary hydration**: Steel slag contributes CaO and SiO_2, leading to the formation of additional calcium silicate hydrate (C–S–H) gels that densify the microstructure (Shi, 2004).
- **Crack-bridging effect of PP fibers**: Fibers resisted stress concentrations, delaying crack propagation and contributing to improved load-bearing capacity.
- **Improved interfacial transition zone (ITZ)**: The rough surface of slag particles enhanced mechanical interlocking with the cement paste, improving bond strength.

Compared to similar studies, the performance enhancement in this study is consistent with results reported by Li et al. (2012), who observed a 12–18% strength increase with steel slag replacements up to 20%.

Table 4.1: Compressive Strength

Mix ID	7 days	14 days	28 days
M0 (Control)	32.5	41.2	49.0
M1 (10% Slag + 0.25% Fiber)	34.8	44.1	52.6
M1 (10% Slag + 0.50% Fiber)	35.6	46.4	54.2
M2 (20% Slag + 0.25% Fiber)	33.9	43.8	51.8
M2 (20% Slag + 0.50% Fiber)	34.5	45.2	56.8

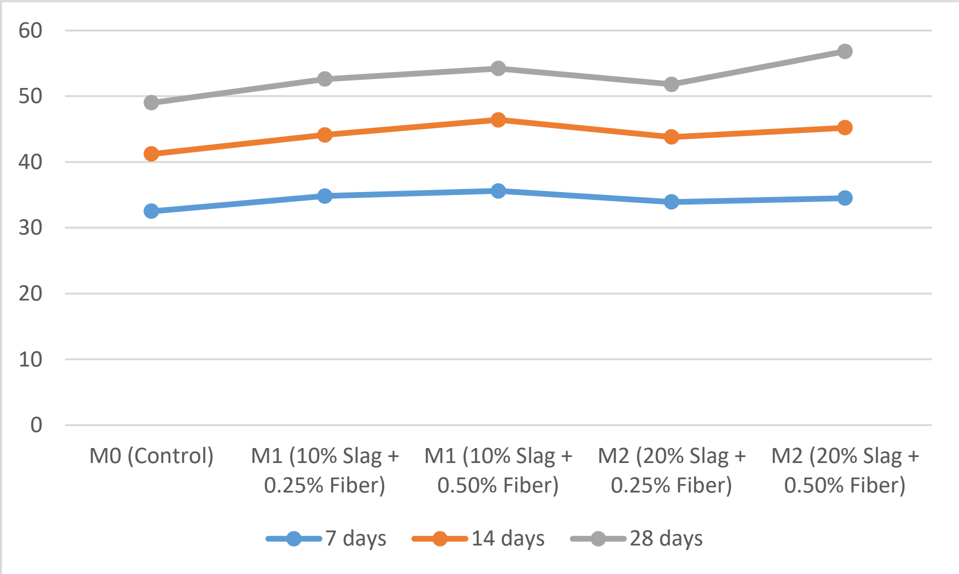

Fig 4.1: Compressive strength graph

Strength gain was progressive with curing age. Slag improved hydration due to latent pozzolanic activity, while fibers restrained microcracks, yielding superior performance.

4.2 Splitting Tensile Strength (MPa)

Tensile strength values (Table 2) displayed significant improvements with fiber inclusion. The optimum mix reached **4.4 MPa**, which was 15.7% higher than the control mix (3.8 MPa). Fibers contributed more strongly to tensile strength than compressive strength, underscoring their crack-bridging role. This aligns with observations by Nili and Afroughsabet (2010), who reported that synthetic fibers enhanced tensile strength by up to 20%.

Table 4.2: Splitting Tensile Strength (MPa)

Mix ID	7 days	14 days	28 days
M0	2.6	3.2	3.8
M1 (10% Slag + 0.25% Fiber)	2.8	3.5	4.0
M1 (10% Slag + 0.50% Fiber)	2.9	3.6	4.2
M2 (20% Slag + 0.25% Fiber)	2.7	3.4	4.1
M2 (20% Slag + 0.50% Fiber)	2.8	3.5	4.4

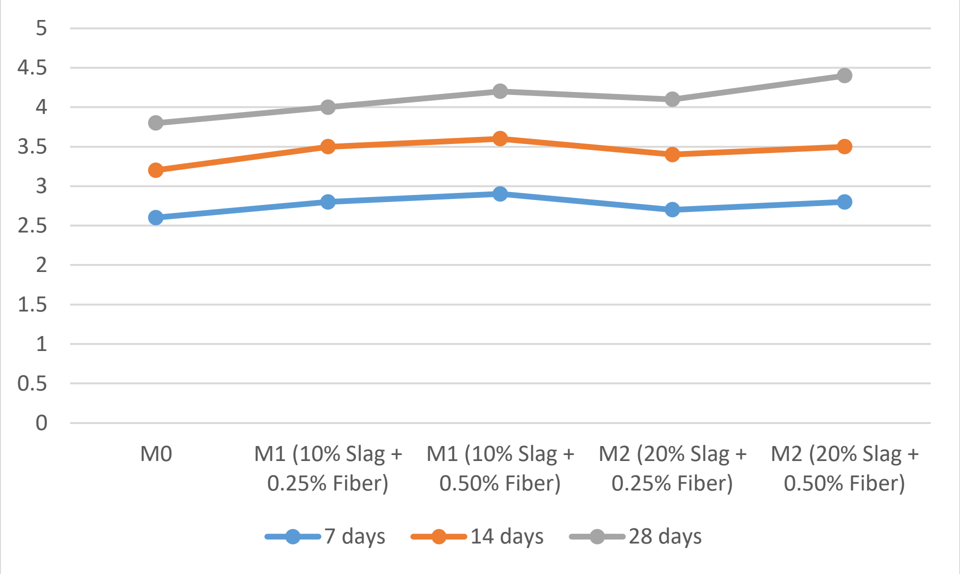

Fig 4.2: Tensile strength graph

Fibers significantly enhanced tensile capacity by bridging cracks, particularly noticeable at 28 days.

4.3 Flexural Strength (MPa)

Flexural strength values (Table 3) showed improvements similar to tensile results. At 28 days, the optimum mix achieved **7.1 MPa**, about 14.5% higher than the control. The fibers provided energy absorption capacity after initial cracking, enhancing toughness and ductility. This is particularly important for structural applications such as pavements, slabs, and hydraulic structures subjected to flexural stresses.

Table 4.3: Flexural Strength (MPa)

Mix ID	7 Days	14 Days	28 Days
M0	3.9	5.0	6.2
M1 (10% Slag + 0.25% Fiber)	4.1	5.4	6.7
M1 (10% Slag + 0.50% Fiber)	4.2	5.5	6.9
M2 (20% Slag + 0.25% Fiber)	4.0	5.3	6.8
M2 (20% Slag + 0.50% Fiber)	4.3	5.6	7.1

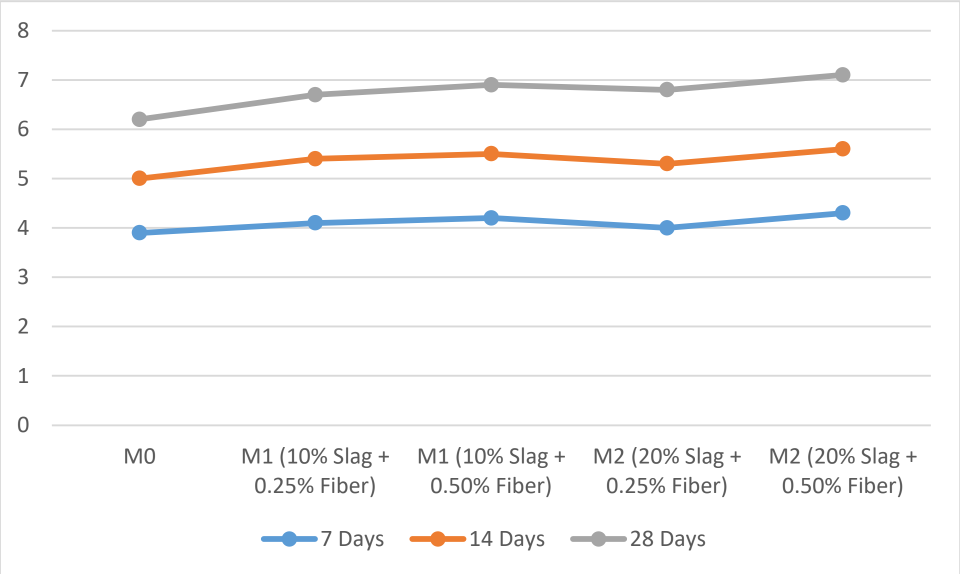

Fig 4.3: Flexural strength graph

The presence of fibers enhanced post-cracking behavior, improving flexural toughness.

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4.4 Water Absorption (%)

Water absorption (Table 4) decreased substantially with slag and fiber addition. The control mix showed **2.40%** absorption at 28 days, while the optimum mix (M2F0.50) exhibited **1.42%**, a **40.8% reduction**. This demonstrates the waterproofing effect of slag-fiber synergy:

- Slag particles refine pore structure, reducing capillary porosity.
- Fibers disrupt continuous microchannels, limiting water migration pathways.
- Together, they enhance impermeability, thereby improving resistance against chloride penetration, freeze–thaw cycles, and sulfate attack.

These results suggest that the developed slag-fiber concrete has the potential for applications in **marine environments, water-retaining structures, and underground construction**.

Table 4.4: Water Absorption (%)

Mix ID	7 Days	14 Days	28 Days
M0	3.12	2.85	2.40
M1 (10% Slag + 0.25% Fiber)	2.95	2.60	2.00
M1 (10% Slag + 0.50% Fiber)	2.85	2.40	1.90
M2 (20% Slag + 0.25% Fiber)	2.90	2.55	1.85
M2 (20% Slag + 0.50% Fiber)	2.80	2.35	1.42

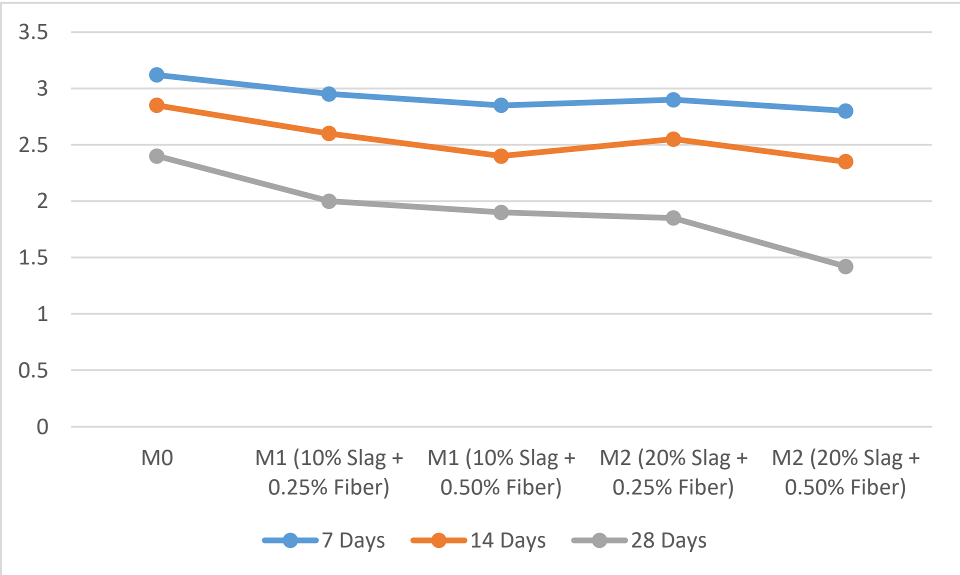

Fig 4.4: Water absorption graph

Steel slag densified the microstructure, while PP fibers-controlled cracking, leading to reduced water absorption and improved waterproofing properties.

5. CONCLUSION

This study confirms that industrial steel slag and polypropylene fibers can be effectively utilized in concrete to enhance strength and durability while reducing permeability. At 28 days, the mix containing 20% slag and 0.50% fibers achieved compressive strength of 56.8 MPa, tensile strength of 4.4 MPa, flexural strength of 7.1 MPa, and lowest water absorption (1.42%). These results validate the potential of slag-fiber synergy in producing eco-friendly, high-performance, and waterproof concrete.

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