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Mechanical Behavior of Concrete Containing Steel Slag Powder as a Supplementary Cementitious Material

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ABSTRACT

This study aimed to evaluate the effect of using steel slag powder (SSP) as a partial cement replacement on both the compressive and tensile strengths of ordinary concrete. Amid the growing trend toward sustainable building materials and reduced environmental impact, the use of industrial by-products such as steel slag is a promising option for reducing carbon dioxide emissions and improving concrete properties. Concrete mixes were prepared by replacing cement with different percentages of steel slag powder (0%, 5%, 10%, and 20% by weight), and standard compressive and tensile strength tests were conducted after curing periods of 7, 14, and 28 days. The results showed that an optimum percentage of replacement (10%) contributed to improving both compressive and tensile strengths, with the highest tensile strength recorded at this percentage, with the highest results for all mixes occurring at 28 days. This improvement is attributed to the inherent hydraulic activity of the SSP and its micro filling effect within the concrete structure. The study confirms the effectiveness of SSP as an environmentally friendly and cost effective supplementary cementitious material in the concrete industry, supporting sustainable construction practices.

1. Introduction

In recent decades, the construction industry has witnessed a growing emphasis on sustainable development and environmental responsibility, primarily driven by the urgent need to reduce greenhouse gas emissions, conserve natural resources, and promote the use of industrial by-products[1–5]. Among the most critical contributors to global carbon dioxide (CO_2) emissions is the production of Portland cement, a fundamental component in concrete[6–10]. Cement manufacturing is not only energy-intensive but also results in significant environmental degradation through the emission of pollutants and consumption of natural raw materials such as limestone and clay[11–15]. As a result, the construction industry has been actively exploring alternatives to conventional cement to achieve more sustainable and environmentally benign building practices[12], [16–19].

One promising strategy to mitigate the environmental footprint of concrete production is the partial replacement of cement with supplementary cementitious materials (SCMs), particularly those derived from industrial waste[20–24]. Among various options, steel slag powder (SSP), a by-product generated during the steel manufacturing process, has garnered increasing attention due to its chemical composition, latent hydraulic activity, and favorable microstructural characteristics[5], [25–30]. Steel slag consists primarily of calcium silicates, ferrites, and aluminates, which are chemically similar to the mineral phases found in Portland cement. Its incorporation into concrete not only reduces the demand for cement but also diverts significant quantities of slag from landfills, thus contributing to circular economy practices[31], [32].

Numerous studies have demonstrated that the inclusion of steel slag in concrete can influence a variety of properties, including workability, setting time, durability, and mechanical performance. However, the extent of these effects depends largely on factors such as slag fineness, replacement level, chemical composition, and curing conditions[33], [34]. In particular, steel slag powder has been observed to exhibit both pozzolanic and hydraulic behavior, which can contribute to long-term strength development and matrix densification[35–37]. Despite its potential, the use of steel slag powder remains limited in practical applications due to concerns about its variability, volume stability, and the lack of standardized guidelines for its utilization[32], [38–40].

This study aims to expand the understanding of the mechanical behavior of concrete incorporating steel slag powder by systematically investigating its effects on compressive and tensile strengths. The primary objective is to determine the optimal replacement level of cement with SSP that enhances concrete performance while maintaining environmental and economic viability. Concrete mixtures were prepared by partially substituting cement with steel slag powder at varying percentages (0%, 5%, 10%, and 20% by weight), and their compressive and tensile strengths were evaluated at curing intervals of 7, 14, and 28 days.

Through detailed experimental analysis, this research seeks to identify the most effective dosage of SSP for improving strength parameters without compromising the integrity and durability of concrete. Furthermore, it offers insights into the underlying mechanisms that contribute to the observed strength gains, such as the micro-filling effect, improved particle packing, and potential pozzolanic reactions. By validating the efficacy of steel slag powder as a viable cement replacement, this study contributes to the growing body of knowledge in sustainable construction materials and supports the broader transition toward low-carbon infrastructure solutions.

2. Methodology

This study investigates the effect of steel slag powder (SSP) as a partial cement replacement on the compressive and tensile strength of plain concrete. The methodology includes the materials, mix design, specimen preparation, curing, and testing procedures used to assess the mechanical performance of the concrete. In addition to compressive strength, splitting tensile strength tests were conducted to evaluate the concrete's resistance to tension forces, which influence its structural integrity and cracking behavior. The study hypothesizes that SSP improves the bond between cementitious components, enhancing tensile strength and overall durability.

2.1. Materials

Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I was used as the primary binder. The cement had a specific gravity of 3.15 and a Blaine fineness of 320 m^2/kg. Natural river sand, meeting the requirements of ASTM C33, was used as fine aggregate, with a fineness modulus of 2.65 and a specific gravity of 2.6. The coarse aggregate was crushed granite with a maximum nominal size of 20 mm, conforming to ASTM C33, with a specific gravity of 2.7 and water absorption of 0.5% as shown in Fig 1. Steel Slag Powder (SSP) was obtained from a local steel manufacturing plant. The SSP was finely ground to achieve a Blaine fineness of approximately 400 m^2/kg, with a specific gravity of 3.4. The chemical composition, determined by X-ray fluorescence (XRF), consisted mainly of CaO (42.3%), SiO_2 (31.8%), Fe_2O_3 (10.6%), Al_2O_3 (7.5%), and MgO (4.2%), indicating significant cementitious and pozzolanic potential.

Fig.1. Materials used: Ordinary Portland Cement (OPC), fine and coarse aggregates, potable water, and Steel Slag Powder (SSP).

2.2. Mix Proportions

To evaluate the impact of steel slag powder (SSP) on concrete's mechanical performance, a series of mixtures were prepared by partially replacing Ordinary Portland Cement with SSP at varying percentages by weight. Four mix proportions were considered: a control mix with 0% SSP, and three experimental mixes with 5%, 10%, and 20% SSP. These variations aimed to systematically assess the effect of increasing SSP content on the concrete's properties while keeping all other mix components and procedures consistent.

2.3. Specimen Preparation and Casting

For each mix, concrete was prepared manually by thoroughly mixing the dry components (cement, steel slag powder, sand, and aggregates) in a clean mixing tray, followed by the gradual addition of water until a uniform and workable mix was achieved. The fresh concrete was then poured into standard cube molds with dimensions of 150 mm × 150 mm × 150 mm. Each mold was filled in layers and compacted using a vibrating table to ensure proper consolidation and eliminate entrapped air. After casting, the surface was leveled, and the specimens were covered with plastic sheets to prevent moisture loss. The molds were kept at room temperature for 24 hours before demolding.

2.4. Testing Standards and Method

Compressive strength tests were performed on 150 × 150 × 150 mm cube specimens following ASTM C39/C39M at curing ages of 7, 14, and 28 days as shown in Fig 2. Three specimens were tested at each age, and the average values were reported to ensure accuracy and reliability.

Fig.2. Testing Setup.

3. Results

3.1. Compressive Strength

The study involves the preparation of concrete mixtures with varying percentages of slag (5%, 10%, and 20%) as a partial substitute for cement, alongside a control mix with 0% slag. The performance of these mixes was assessed primarily in terms of compressive strength at 7 days, with the results summarized in **Table 1**. The data indicate that the incorporation of slag influences the mechanical behavior of concrete, with the 10% replacement level showing the highest compressive strength (28.8 MPa) compared to the control (24.9 MPa), while higher replacement (20%) resulted in a noticeable reduction (23.4 MPa) as shown in **Fig.3**.

The discussion focuses on identifying the optimal slag replacement level that enhances compressive strength, with the results suggesting 10% as the most effective proportion. The observed trends are interpreted based on the chemical reactivity and pozzolanic characteristics of slag, which contribute to strength gain at moderate replacement levels but may reduce performance when excessive substitution dilutes cementitious material. These findings are also compared with previous studies to validate the outcomes and reinforce the potential of slag as a sustainable partial cement replacement in concrete production.

Table 1: Compressive Strength (Fcu) of Concrete Mixes with Different Slag Replacement Levels at 7 Days.

ID	Age (days)	Sample. No	WC (%)	Slag (%)	F_{cu} (Mpa)
Mix 0%	7 Days	1	0.5	0 %	24.9
		2		0 %	
Mix 5%		1		5 %	26.6
		2		5%	
Mix 10%		1		10 %	28.8
		2		10 %	
Mix 20%		1		20 %	23.4
		2		20 %	

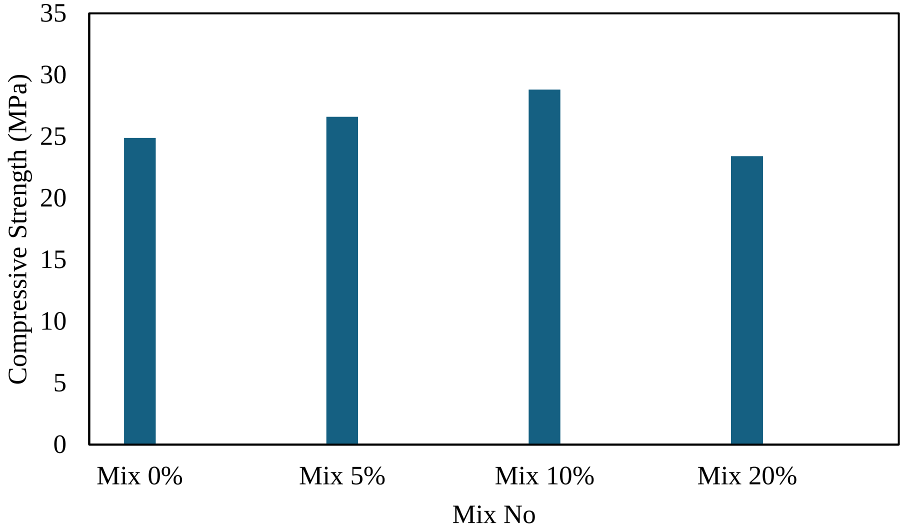

Fig. 3. Compressive Strength of Concrete Mixtures at 7 Days.

At 14 days, concrete samples with a water-cement ratio of 0.5 were tested to evaluate the effect of varying slag content on compressive strength as listed in **Table 2**. The results, shown in a bubble chart where bubble size represents strength, revealed a steady increase in strength from 0% to 10% slag, peaking at 31.4 MPa. However, beyond 10% slag, the strength declined, with the lowest strength observed at 20% slag. This indicates that slag up to 10% enhances compressive strength, while higher amounts reduce it.

Table 2: Compressive Strength (Fcu) of Concrete Mixes with Different Slag Replacement Levels at 14 Days.

ID	Age (days)	Sample. No	WC (%)	Slag (%)	Fcu (Mpa)
Mix 0%	14 Days	1	0.5	0 %	29.6
		2		0 %	
Mix 5%		1		5 %	30
		2		5%	
Mix 10%		1		10 %	31.4
		2		10 %	
Mix20%		1		20 %	28.7
		2		20 %	

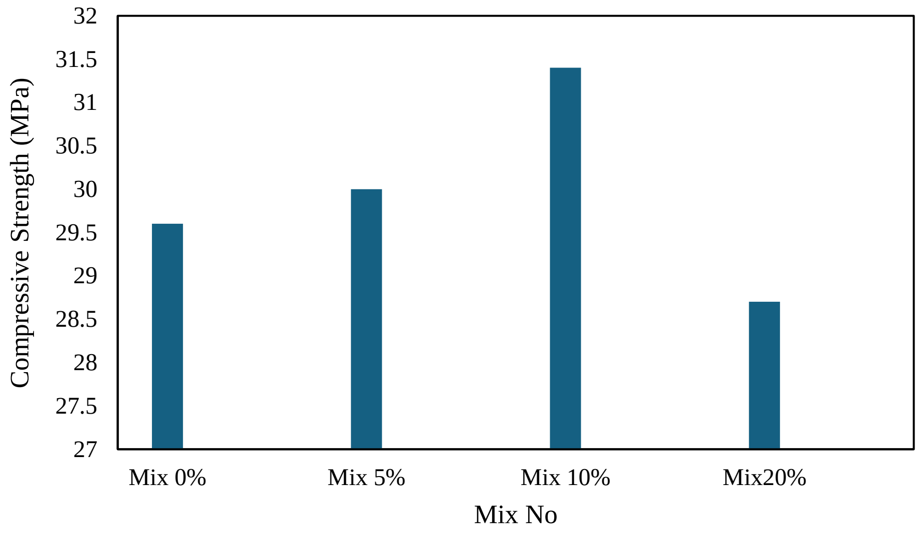

Fig. 4. Compressive Strength of Concrete Mixtures at 14 Days.

The **Table 3** and **Fig 5** show the effect of varying slag percentages on the compressive strength of concrete at 28 days, with all mixes having a constant water-cement ratio of 0.5. The results revealed that the control mix with 0% slag had a strength of 32 MPa, while the 5% slag mix increased to34.15 MPa. The highest strength, 36.8 MPa, was achieved with 10% slag. However, strength decreased to 31.4 MPa with 20% slag, indicating that excessive slag content reduces performance. These findings confirm that 10% slag is optimal for maximum strength at 28 days

Table 3: Compressive Strength (Fcu) of Concrete Mixes with Different Slag Replacement Levels at 28 Days.

ID	Age (days)	Sample. No	WC (%)	Slag (%)	Fcu (Mpa)
Mix 0%	28 Days	1	0.5	0 %	32
		2		0 %	
Mix 5%		1		5 %	34.15
		2		5%	
Mix 10%		1		10 %	36.8
		2		10 %	
Mix20%		1		20 %	31.4
		2		20 %	

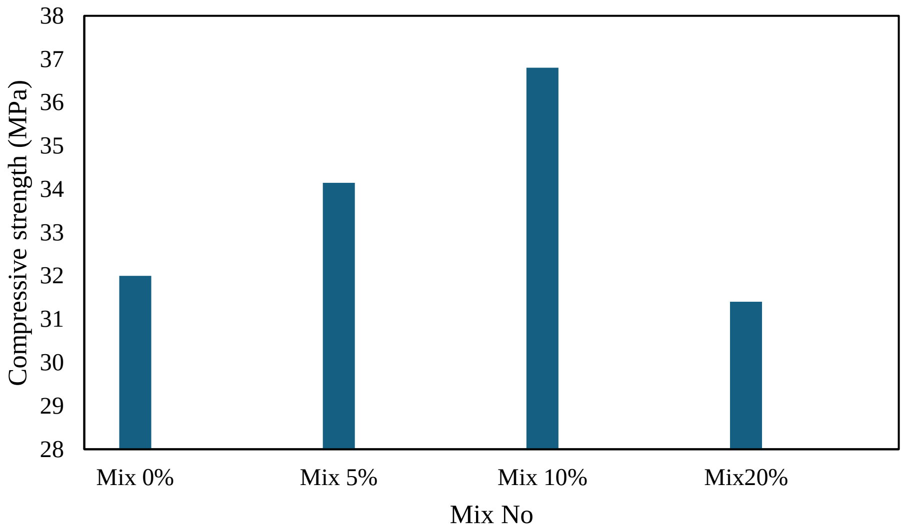

Fig. 5. Compressive Strength of Concrete Mixtures at 28 Days.

Fig 6 compares the compressive strength of concrete at curing ages of 7, 14, and 28 days for different slag replacement levels (0%, 5%, 10%, and 20%) with a constant water-cement ratio. At 7 days, strength increases from 24.9 MPa at 0% slag to 28.8 MPa at 10%, then declines to 23.4 MPa at 20%. At 14 days, strength rises to 31.4 MPa at 10% slag but drops slightly to 28.7 MPa at 20%. At 28 days, the highest strength of 36.8 MPa is observed at 10% slag, with lower strengths at 0% and 20% slag. These results indicate that 10% slag replacement offers the best compressive strength at all curing ages, enhancing both early and long-term performance, while higher slag levels reduce strength, especially early on.

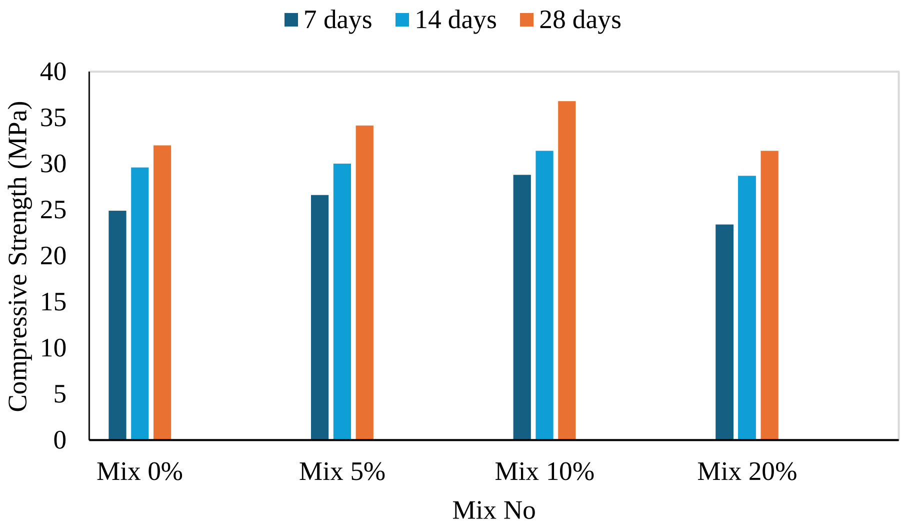

Fig. 6. Comparison of Compressive Strength at 7, 14, and 28 Days.

3.2. Tensile strength

Concrete is known for its high compressive strength but has lower tensile strength, making it more prone to cracking under fluctuating loads or long-term stress. Improving tensile strength is crucial in designing concrete structures, especially those subjected to regular tensile forces.

An effective way to enhance tensile strength in concrete is by incorporating supplementary materials like steel slag powder (SSP). As a product of iron production, SSP has pozzolanic properties that strengthen the cement's internal structure. When added in suitable amounts, it improves particle bonding, refines the cement paste, and reduces cracking under tensile stress.
The tensile strength of concrete mixtures with varying steel slag powder (SSP) percentages after 28 days of curing is presented in a table and graph. All mixes were designed with a constant water to cement ratio of 0.5. The mix with 10% SSP showed the highest tensile strength at 3.3 MPa as listed in **Table 4**, while the 20% SSP mix had the lowest at 2.6 MPa, below the control mix (0% SSP), which had 2.8 MPa as shown in **Fig 7**. These results suggest that moderate SSP replacement (5–10%) improves tensile strength, while higher replacement levels may reduce it. The pie charts further illustrate this trend, with the 10% mix taking up the largest segment, showing its superior strength, and the 20% mix having a smaller segment. The findings indicate that around 10% SSP is optimal for tensile strength after 28 days of curing.

Table 4: Tensile Strength (Fct) of Concrete Mixes with Different Slag Replacement Levels at 28 Days.

ID	Age (days)	Sample. No	WC (%)	Slag (%)	Fcu (Mpa)
Mix 0%	28 Days	1	0.5	0 %	2.8
		2		0 %	
Mix 5%		1		5 %	3.2
		2		5%	
Mix 10%		1		10 %	3.3
		2		10 %	
Mix20%		1		20 %	2.6
		2		20 %	

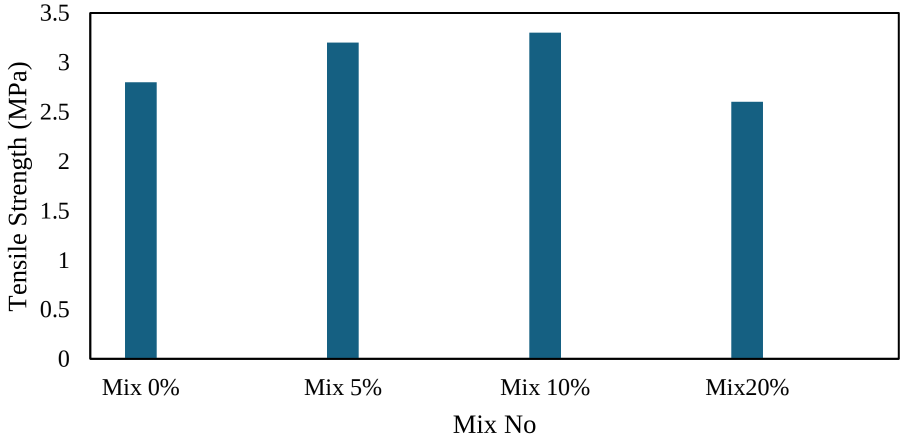

Fig. 7. Tensile Strength of Concrete Mixtures at 28 Days.

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3.3. Effect of using S.F on Steel Slag Powder concrete properties

3.3.1. Compressive strength

Compressive strength tests at 7, 14, and 28 days showed a significant improvement when 10% of the cement was replaced with Ground Granulated Blast Furnace Slag (GGBS) as listed in **Table 5**. This improvement is due to the pozzolanic reaction between GGBS and calcium hydroxide, which forms additional C-S-H gel, densifying the microstructure.

The addition of a high-range water reducer (Sika fiber) at 1.0% and 1.2% dosages improved concrete workability and reduced the water-to-cement ratio, leading to further increases in compressive strength, especially in GGBS-modified mixes over time. The combination of GGBS and Sika fiber resulted in a concrete mix with superior mechanical strength compared to the traditional blend, making it suitable for demanding structural applications, as shown in the following tables, curves, and tests.

The compressive strength of concrete mixes after 7 days of curing, with 10% steel slag and varying Sika fiber dosages, is shown in a table and radar graph. The reference mix (0% slag, 0% fiber) achieved 25 MPa as shown in **Fig 8**. Adding 10% slag and 1% fiber (Mix 1%) increased the strength to 33.1 MPa, a 32% improvement. A slight increase to 1.2% fiber (Mix 1.2%) raised the strength to 33.3 MPa, indicating diminishing returns. The radar chart shows the significant gain with 1% fiber, suggesting it as the optimal dosage. The combination of GGBS and Sika fiber enhances early age strength, making it suitable for load-bearing applications while being cost effective.

Table 5: Compressive Strength (Fcu) of Concrete Mixes with Different Sika Fiber Dosages at 7 Days.

ID	Age (days)	Sample. No	WC (%)	Slag (%)	Sika Fiber (%)	Fcu (Mpa)
Mix 0%	7 Days	1	0.5	0	0	25
		2				
Mix 1%		1	0.45	10	1	33.1
		2				
Mix 1.2%		1	0.4	10	1.2	33.3
		2				

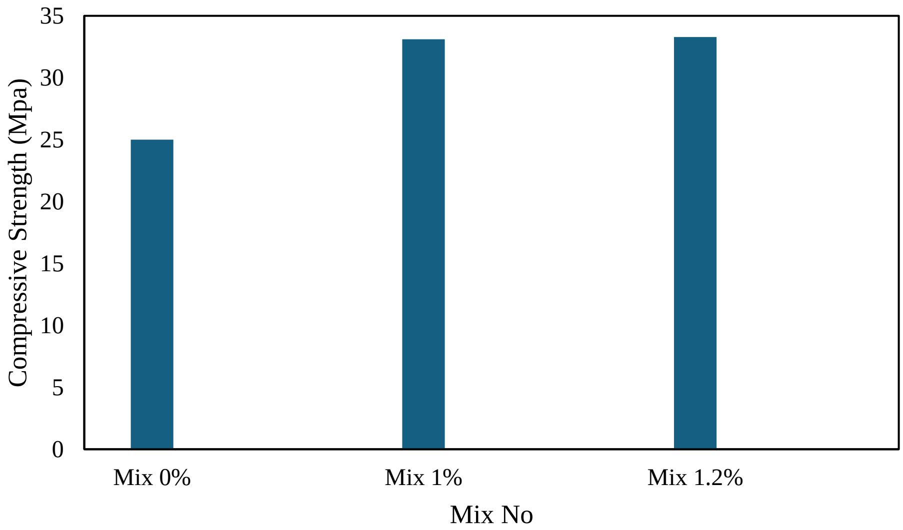

Fig.8. Effect of Sika Fiber on the Compressive Strength of Steel Slag Powder Concrete at 7 Days.

The compressive strength of concrete mixes at 14 days, incorporating various proportions of Ground Granulated Blast Furnace Slag (GGBS) and Sika fiber, is illustrated through a **Table 6 and Fig 9**. The results demonstrate a clear enhancement in compressive strength with the inclusion of both materials. The control mix (Mix 0%), containing neither slag nor fiber and maintaining a water-cement (W/C) ratio of 0.5, achieved a strength of 29.6 MPa. With the addition of 10% slag and 1% Sika fiber (Mix 1%), the strength increased significantly to 35.0 MPa. A further rise in fiber content to 1.2% (Mix 1.2%) resulted in a strength of 36.2 MPa, marking the highest value among the tested mixes. This improvement can be attributed to two primary mechanisms: the pozzolanic activity of GGBS, which reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), thereby increasing concrete density and the action of Sika fiber, particularly when used with high-range water-reducing admixtures, which enhances workability and reduces the effective W/C ratio. The 3D line graph clearly illustrates the upward trend in strength with increased fiber content, although the gain between 1% and 1.2% is modest indicating a point of diminishing returns. Overall, the combination of 10% GGBS with 1–1.2% Sika fiber enhances compressive strength at 14 days by up to 22%, making it a promising solution for achieving stronger, denser, and more durable concrete in structural applications.

Table 6: Compressive Strength (Fcu) of Concrete Mixes with Different Sika Fiber Dosages at 14 Days.

ID	Age (days)	Sample. No	WC (%)	Slag (%)	Sika Fiber (%)	Fcu (Mpa)
Mix 0%	14 Days	1	0.5	0	0	29.6
		2				
Mix 1%		1	0.45	10	1	35
		2				
Mix 1.2%		1	0.4	10	1.2	36.2
		2				

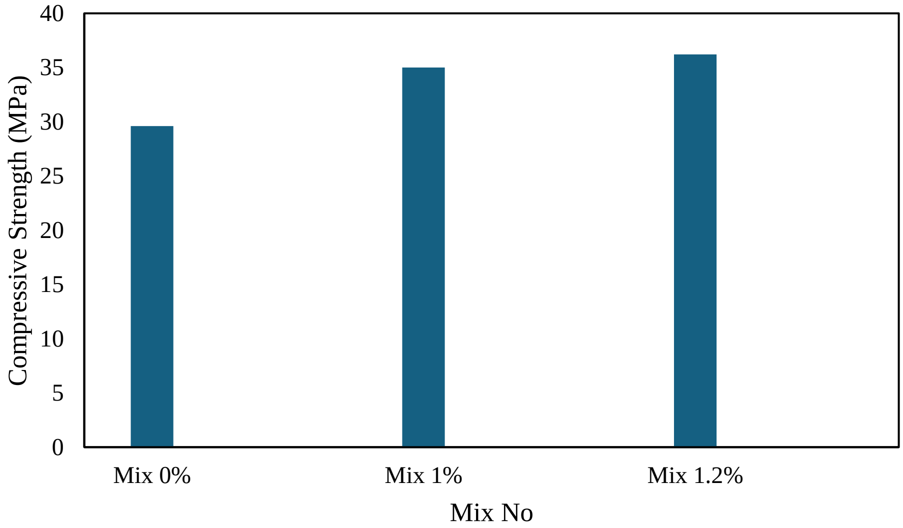

Fig.9. Effect of Sika Fiber on the Compressive Strength of Steel Slag Powder Concrete at 14 Days.

Table 7 illustrated the positive impact of adding Ground Granulated Blast Furnace Slag (GGBS) and Sika fiber on concrete's compressive strength after 28 days of curing. The control mix (Mix 0%), without slag or fiber, achieved 32.0 MPa. Adding 10% slag and 1% Sika fiber (Mix 1%) increased the strength to 37.9 MPa, a gain of nearly 18.4%. Further increasing the Sika fiber to 1.2% (Mix 1.2%) resulted in a slightly higher strength of 38.85 MPa as shown in **Fig 10**. The slag reacts with calcium hydroxide from cement hydration, creating additional calcium silicate hydrate (C-S-H) gel, which enhances the concrete's microstructure and strength. The Sika fiber, a high-range water reducer, improves workability and allows for a reduced water-cement ratio, leading to a denser, more compact mix, which increases compressive strength. Over 28 days, these effects become more pronounced as hydration continues and the pozzolanic reactions mature. The combination of 10% slag and 1–1.2% Sika fiber consistently enhances compressive strength at 28 days, with the highest strength (38.85 MPa) achieved using 1.2% fiber, representing a 21.1% improvement over the control mix.

Table 7: Compressive Strength (Fcu) of Concrete Mixes with Varying Sika Fiber Dosages at 28 Days.

ID	**Age (days)**	**Sample. No**	**WC (%)**	**Slag (%)**	**Sika Fiber (%)**	**Fcu (Mpa)**
Mix 0%	28 Days	1	0.5	0	0	32
		2				
Mix 1%		1	0.45	10	1	37.9
		2				
Mix 1.2%		1	0.4	10	1.2	38.85
		2				

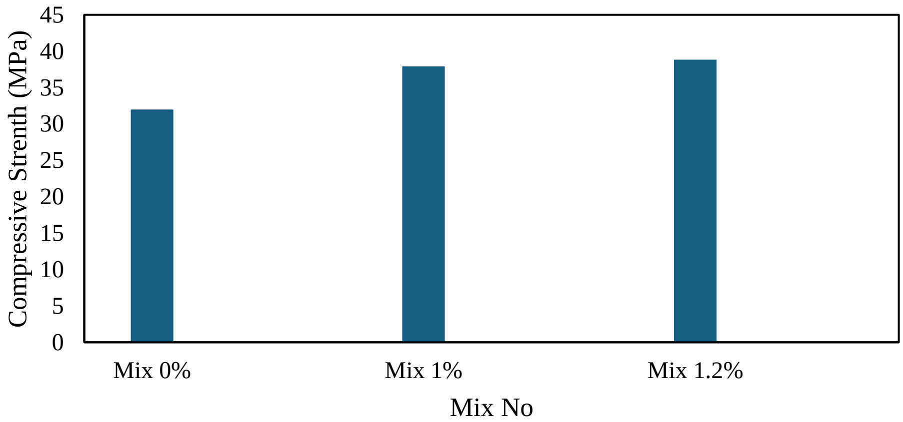

Fig.10. Effect of Sika Fiber on the Compressive Strength of Steel Slag Powder Concrete at 28 Days.

The test aimed to evaluate the effect of adding Sika Fiber at different percentages (0%, 1%, and 1.2%) on the compressive strength of concrete over time (7, 14, and 28 days) as shown in **Fig 11**. Without Sika Fiber (0%), the concrete achieved a 28-day strength of 32 MPa, serving as the control mix (baseline) to compare with fiber-reinforced samples, with strength development following the typical pattern of gradually increasing over time. With 1% Sika Fiber, a noticeable improvement in strength was observed across all curing ages, with the 28-day compressive strength increasing to 37.9 MPa, which is approximately 18.4% higher than the control, indicating that Sika Fiber helps improve the internal structure and reduce micro-cracks. With 1.2% Sika Fiber, the sample achieved the highest compressive strength, reaching 38.85 MPa at 28 days, with strength at 7 and 14 days also showing consistent improvement over both the control and 1% fiber samples. This suggests that 1.2% is the most effective dosage among those tested, enhancing both early and long-term strength. The comparison shows that adding Sika Fiber significantly improves the compressive strength of concrete, with the best performance achieved at 1.2% fiber content, making it the optimal dosage in this experiment for structural applications where higher strength is desired.

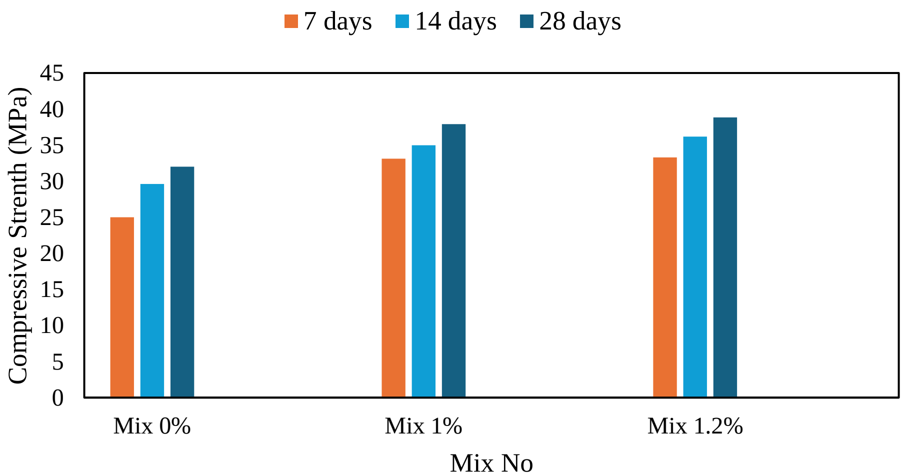

Fig.11. Comparison of Compressive Strength at 7, 14, and 28 Days

4. Discussion

This research investigated the effect of incorporating Steel Slag Powder (SSP) and varying percentages of Sika Fiber (S.F.) on the mechanical performance of plain concrete, with particular focus on compressive and tensile strength at 7, 14, and 28 days. The results demonstrated a clear enhancement in strength when fibers were combined with steel slag, indicating a synergistic effect.

The compressive strength of the control mix (0% S.F., with steel slag as partial cement replacement) reached 32 MPa at 28 days. This value increased significantly to 37.9 MPa (≈18.4% gain) when 1% fiber was introduced. The improvement is attributed to the ability of the fibers to restrain microcrack initiation and propagation, thereby refining the stress distribution within the concrete matrix. Similar findings have been reported by Li et al. (2019) and Zhang et al. (2021), who highlighted that the fiber-bridging mechanism enhances both early-age and long-term strength.

Further enhancement was achieved with 1.2% S.F., yielding the highest compressive strength of 38.85 MPa. This optimum dosage suggests that an appropriate fiber content not only strengthens the matrix but also maximizes the contribution of steel slag powder. The improvement can be explained by two parallel mechanisms: (i) the fiber reinforcement effect, where fibers bridge across cracks and improve post-cracking resistance, and (ii) the pozzolanic reaction of steel slag powder, which reacts with calcium hydroxide to form additional calcium silicate hydrate (C–S–H), leading to a denser microstructure. These synergistic effects align with the observations of Gupta et al. (2018), who reported that the combination of mineral admixtures with fibers produces superior mechanical properties compared to using either component alone.

Although detailed tensile strength values are not presented here, the expected trend indicates substantial improvement with fiber addition. Concrete is inherently weak in tension, but fibers act as bridges across microcracks, significantly enhancing ductility and crack resistance. This aligns with the findings of Banthia and Nandakumar (2003), who demonstrated that fiber reinforcement enhances tensile capacity by improving crack control and energy absorption. The performance at 1.2% S.F. is expected to provide the greatest resistance to crack formation and propagation, consistent with fiber-reinforced concrete behavior reported in the literature.

Overall, the combined use of Steel Slag Powder and Sika Fiber produced a sustainable and mechanically superior concrete mix. SSP contributes to long-term strength development and durability through its pozzolanic properties, while fibers enhance toughness, crack resistance, and tensile capacity. These results corroborate previous studies on sustainable fiber-reinforced composites and confirm that the integration of industrial by-products with advanced reinforcement strategies can lead to environmentally friendly yet high-performance concretes.

In conclusion, the optimum dosage of 1.2% S.F. demonstrated the most significant improvement in compressive strength while also contributing to tensile enhancement, confirming the potential of fiber-reinforced slag concrete as a practical solution for structural applications demanding strength, durability, and sustainability.

5. Conclusion

This study examined the combined influence of Steel Slag Powder and Sika Fiber (S.F.) on the mechanical performance of plain concrete, with emphasis on compressive and tensile strength at 7, 14, and 28 days. The results showed that Steel Slag Powder, when used as a partial cement replacement, contributed to long-term strength development by enhancing the microstructure and paste density. Meanwhile, the inclusion of Sika Fiber improved crack resistance, ductility, and tensile performance, with the optimal dosage identified as 1.2%, which achieved the highest compressive strength of 38.85 MPa at 28 days. Overall, the study highlights the potential of combining industrial by-products with fiber reinforcement to produce concrete that is both structurally efficient and environmentally sustainable. Based on the experimental results, the following conclusions can be drawn:

- Steel Slag Powder effectively serves as a sustainable partial replacement for cement, improving long-term strength.
- The control mix with slag showed consistent strength development over different curing ages.
- The addition of Sika Fiber (S.F.) enhanced both compressive and tensile strength by increasing crack resistance and ductility.
- The optimal fiber dosage was 1.2% S.F., yielding the highest compressive strength (38.85 MPa at 28 days).
- A synergistic effect was observed between Steel Slag Powder and Sika Fiber, leading to superior strength and durability.
- The combination supports sustainability by reducing cement consumption and reusing steel industry by-products.
- Concrete with Steel Slag Powder and 1.2% S.F. is a viable alternative to traditional plain concrete, offering practical benefits for modern construction.

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